

Machinability of Aerospace Tooling Materials for Composite Repairs

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A dissertation

submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington 2014

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Program Authorized to Offer Degree:

Mechanical Engineering

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Abstract

Machinability of Aerospace Tooling Materials for Composite Repairs

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Tooling used to cure composite laminates in the aerospace and automotive industries must provide a dimensionally stable geometry throughout the thermal cycle applied during the part curing process. This requires that the Coefficient of Thermal Expansion (CTE) of the tooling materials match that of the composite being cured. The traditional tooling material for production applications is a nickel alloy. Poor machinability and high material costs increase the expense of metallic tooling made from nickel alloys such as 'Invar 36' or 'Invar 42'. Currently, metallic tooling is unable to meet the needs of applications requiring rapid affordable tooling solutions. In applications where the tooling is not required to have the durability provided by metals, such as for small area repair, an opportunity exists for non-metallic tooling materials like graphite, carbon foams, composites, or ceramics and machinable glasses. Nevertheless, efficient machining of brittle, non-metallic materials is challenging due to low ductility, porosity, and high hardness. The machining of a layup tool comprises a large portion of the final cost. Achieving maximum process economy requires optimization of the machining process in the given tooling material. Therefore, machinability of the tooling material is a critical aspect of the overall cost of the tool.

In this work, three commercially available, brittle/porous, non-metallic candidate tooling materials were selected, namely: (AAC) Autoclaved Aerated Concrete, CB1100 ceramic block and Cfoam carbon foam. Machining tests were conducted in order to evaluate the machinability of these materials using end milling. Chip formation, cutting forces, cutting tool wear, machining induced damage, surface quality and surface integrity were investigated using High Speed Steel (HSS), carbide, diamond abrasive and Polycrystalline Diamond (PCD) cutting tools. Cutting forces were found to be random in magnitude, which was a result of material porosity. The abrasive nature of Cfoam produced rapid tool wear when using HSS and PCD type cutting tools. However, tool wear was not significant in AAC or CB1100 regardless of the type of cutting edge. Machining induced damage was observed in the form of macro-scale chipping and fracture in combination with micro-scale cracking. Transverse rupture test results revealed significant reductions in residual strength and damage tolerance in CB1100. In contrast, AAC

and Cfoam showed no correlation between machining induced damage and a reduction in surface integrity.

Cutting forces in machining were modeled for all materials. Cutting force regression models were developed based on Design of Experiment and Analysis of Variance. A mechanistic cutting force model was proposed based upon conventional end milling force models and statistical distributions of material porosity. In order to validate the model, predicted cutting forces were compared to experimental results. Predicted cutting forces agreed well with experimental measurements. Furthermore, over the range of cutting conditions tested, the proposed model was shown to have comparable predictive accuracy to empirically produced regression models; greatly reducing the number of cutting tests required to simulate cutting forces. Further, this work demonstrates a key adaptation of metallic cutting force models to brittle porous material; a vital step in the research into the machining of these materials using end milling.

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ACKNOWLEDGEMENTS

I would like to acknowledge the University of Washington Department of Mechanical Engineering for providing me with the opportunities, resources and encouragement to achieve my academic goals. I have called this department my home for many years and I am truly grateful to have been given the chance to earn my undergraduate, masters and doctorate degrees from such a prestigious department and program. I would like to thank all the faculty and staff of the UW ME department.

My deepest gratitude is extended to my advisor Professor M. Ramulu. Without his belief in me, encouragement, and generosity I would not be where I am today. His constant dedication to his students and their success and learning is unmatched. The self sacrifice that Professor Ramulu performs in service of others day in and day out is awe inspiring. He has had a profound impact on my life for the better and I will be forever in his debt.

I would like to thank Jeff Miller of the Boeing Company for his help in starting this research project and technical advice during the project. As the project focal for Boeing, Jeff helped guide the research and provided valuable insight throughout. I am also grateful to Dr. Paul Edwards for taking the time to mentor and guide me through my research and professional career. His precise and profound feedback has been a valuable learning tool in my development. I would also like to thank the Boeing Company for their financial and technical support.

I would like to thank all the members of the UW MSTL laboratory and all my friends and family who have supported me over all the years.

DEDICATION

This work is dedicated to my mother and father.

Chapter 1: Introduction

Carbon Fiber-Reinforced Polymer (CFRP) composite materials are characterized by a combination of high specific strength and stiffness, which makes them uniquely suited to aerospace and automotive applications [1]. The ability to tailor material properties to fulfill differing application requirements has made Fiber Reinforced Polymer (FRP) composites the fastest growing group of structural materials in these industries. Unfortunately heterogeneity, anisotropy, as well as thermal and electrical properties often causes significant manufacturing difficulty. Heterogeneity and anisotropy complicate the prediction and understanding of behavior during dynamic processes such as machining. The high material hardness of many fiber reinforcements accelerates tool wear. Obtaining high quality finished parts with close tolerances requires diligent planning and engineering. The fabrication of FRP components has unique manufacturing requirements specific to this family of materials. In the processing of FRP, the desired material system is selected and placed upon a tool or mold. Heat and pressure are then applied to cure the laminated material into its final geometry. Exact thermal cycles are specified by the manufacturer of each composite material system. The tool must remain dimensionally stable throughout the thermal cycle in order to ensure accurate final part geometry and minimal residual stress. This requires the Coefficient of Thermal Expansion (CTE) of the tool to match the CTE of the composite material system being cured. Carbon fiber reinforced epoxy composite materials have a CTE of approximately $0.9 - 2.2 \times 10^{-6} \text{ m/m K}$ [2], depending upon the specific chemistry of the constituents. A mismatch between the CTE of the component and tool has been shown to have a strong influence on the residual stress developed during autoclaving [3]. Residual stresses lead to distortion, resulting in inaccurate parts which are ultimately rejected during post curing inspection. The use of tooling materials with a CTE

matching the composite material system is an effective method of ensuring minimal distortion and residual stress. However, tooling materials with desirable thermal and mechanical properties, ease of manufacture, and cost effectiveness are rare.

1.1 Composite Layup Tooling

A comparison of typical tooling materials used to manufacture composite component tooling in the aerospace and automotive industries along with their performance ratings are shown in Table 1-1 [4]. Metallic tooling materials offer fair to excellent durability with good thermal performance. However, as thermal performance and durability increase, metallic tooling fabrication costs increase sharply. Non-metallic tooling materials include: ceramics, FRPs, and composites. These materials offer fair to poor durability but good to excellent CTE performance and low fabrication costs. Different applications require different combinations of performance and properties. Each material is suited for a separate range of applications depending upon their properties.

Table 1-1: Tooling Material Guide [4].

Tooling Material	Process Capability	CTE	Heat Conductivity	Material Cost	Fabrication Cost	Durability	Notes:
Aluminum	Press Diaphragm	Poor	Good	Good	Good	Fair	Not suitable for high temperature
Steel	Autoclave Hot Press Diaphragm	Good	Good	Good	Fair	Good	High density Warping at high temperatures
Titanium	Autoclave Press Diaphragm	Good	Good	Poor	Poor	Good	Poor machinability leads to high production costs
Invar	Autoclave Press Diaphragm	Excellent	Good	Poor	Poor	Excellent	Long lead time on materials and components Very fine surface finishes
Monolithic Graphite	Autoclave Diaphragm	Excellent	Good	Good	Good	Poor	Fragile Poor vacuum integrity Possible dust hazard Porous

Table 1-1 Cont'd.

Tooling Material	Process Capability	CTE	Heat Conductivity	Material Cost	Fabrication Cost	Durability	Notes:
Ceramics	Autoclave Diaphragm	Excellent	Poor	Good	Fair	Fair	High density Can be porous Difficult to repair
Fiberglass Polymer Composite	Autoclave Diaphragm	Poor to Good	Fair	Good	Good	Poor	Low density High temperature strength is problematic
Graphite Epoxy Composite	Autoclave Diaphragm	Excellent	Fair	High	Fair	Poor	Low density High temperature strength is problematic

1.1.1 Metallic Composite Tooling Materials

Metallic tooling solutions provide the strongest tools; making them suitable for use in high mechanical loading processes such as matched-die molding. Metallic tools may be used for hundreds of production cycles with minimal regular maintenance but are time consuming and expensive to manufacture. Traditional metallic based layup tools are primarily constructed from aluminum, steel, or invar. Often, these tools are complex welded structures requiring multiple forming, welding, machining, and heat treatment operations to bring the tool to final geometry, Figure 1-1.



Figure 1-1: (a) Example of a metallic based composite layup tool [5] with (b) bottom view of a large metallic tool substructure [6].

Aluminum based tooling is capable of producing high quality surfaces and is easily machined; often yielding finished tooling utilizing only a single machining operation and minor secondary processing or finishing. Low principal material cost is another advantage. However,

aluminum's durability is inferior to steel and invar. Further, aluminum has a poorly matched CTE of 23.0×10^{-6} m/m K [7]. Aluminum's CTE is too high to allow for accurate high-tolerance parts to be produced at elevated cure temperatures required by many modern high-performance composite material systems.

Steel is less machinable than aluminum but is more durable; offering a longer lifespan. Steel based tooling also offers affordability while possessing a lower more compatible CTE: 13.0×10^{-6} m/m K [7]. In addition, fine surface finishes are also achievable. Unfortunately, high tolerance aerospace applications still require tooling with lower CTE than what steel and aluminum can offer. Nickel based alloys such as invar offers the best performance of all metallic based tooling materials in terms of durability and thermal properties. These expensive metals are the accepted standard metallic tooling material when high tolerance and long service life are required. With an ideal CTE of 1.3×10^{-6} m/m K [8], nickel based alloys such as invar offers exceptionally fine surface finishes. However, the current practice of using metallic tooling based on nickel alloys is uneconomical due to high material cost and poor machinability [9]. Machining of nickel alloys is challenging due to: a propensity to work harden, develop surface scale, and form continuous "gummy" chips that adhere to the machined surface and the tool [9]. Utilization of nickel alloys is prohibitively expensive in applications where limited service life is required. With fewer parts produced by the tool, a sufficient return on investment of invar based tools is hard to achieve.

Time critical applications require rapid manufacturability. Metallic tooling materials with low CTEs are not capable of such rapid fabrication. Furthermore, the increased density of metallic tooling solutions over non-metallic solutions lead to more weight, more thermal mass, complicated handling and high costs. Non-metallic tooling solutions offer large performance

gains when durability can be sacrificed. Applications that require short service life tools include: prototype tooling, short production run tooling, and Foreign Object Damage (FOD) or other in-service damage repair tooling. Many non-metallic tooling solutions offer rapid manufacturability through a combination of simplified tooling designs and increased machinability of novel materials.

1.1.2 Nonmetallic Tooling Materials

Standard production tooling is required to produce large numbers of parts with a minimum of mandatory maintenance or repair. Thus, the durability of a production tooling system is paramount. Non-production tooling such as prototype tools and tooling made for repair applications are expected to yield far fewer parts than production tooling. When few part cycles are expected, less durable and more cost efficient options can be considered. In these applications non-metallic tooling materials such as composites, ceramics or graphite are not excluded by their lack of durability.

Graphite based tools have been an established practice for several years [10], are the most widely used non-metallic substrate material in small scale tooling, and can rapidly produce low cost tooling due to the fact that it is easily machined and has a low raw material cost. Graphite has a well matched CTE to carbon fibers and has been shown to produce high tolerance composite parts at cure temperatures up to 427°C [11]. The low density and good thermal conductivity of graphite reduces thermal mass, total energy and time required to heat the tool to the required temperature. Unfortunately, graphite also has several drawbacks as a tooling material. Graphite tooling has poor durability and frequently requires surface repairs before subsequent use due to low impact strength and a tendency to fracture during curing. The dust created while machining graphite based materials is a possible health and safety hazard and must

be contained or controlled to limit both human and machine exposure [12-14]. Graphite is a porous material, making it difficult to maintain vacuum integrity through the tool. A common solution is to apply a surface sealer directly to the tool's surface to help seal the pores and improve surface finish.

Ceramic tooling materials are more durable than graphite and are capable of producing fine surface finishes while maintaining low CTE's compatible with modern composite material systems. However, the majority of ceramic materials is too hard for normal machining operations, and frequently are machined using abrasive type cutting tools and processes such as grinding, abrasive water-jet machining, or ultrasonic machining. Erosive processes of this nature do not achieve high material removal rates. Therefore, machining time, fabrication time, and costs are increased. Further, ceramics suffer from poor thermal conductivity which increases the time required to heat the tool. This can be overcome through the use of embedding heating elements within the tool. Nevertheless, this adds to the complexity and weight as well as the cost of the finished tool. Properties of ceramics vary with the density of the material and chemical composition. Ceramics with low density or special formulations that increase machinability can be machined using traditional machining processes and offer increased process economics. However, decreased density coincides with increased porosity which can present several challenges to machining. Careful consideration of the properties the material offers and how they affect machining and final part performance is necessary.

Layup tools fabricated from composite materials are made from the same or similar material to the part being cured, therefore, the CTE mismatch is nearly zero. Composites systems used for aerospace tooling typically consist of an epoxy or bismaleimide matrix reinforced with carbon or graphite fibers. These composite systems offer poor to fair durability.

Although quality surface finishes can be achieved from tooling made from composite materials, increased finishing (sanding/polishing) and maintenance are required to sustain the surface quality. Composite systems containing carbon or graphite fibers are abrasive in nature when machining. The high hardness and strength of the fibers along with their small diameter induce localized stress concentrations on the cutting tool edge. High tool wear rates are avoided through the use of expensive Polycrystalline Diamond (PCD) cutting tools or diamond based coatings.

1.2 Tooling and Fabrication Approaches

Traditional tooling approaches often do not have the required CTE or are cost prohibitive for low quantity part production. Layup tooling systems that can be rapidly produced to the desired geometry and which satisfies dimensional and thermal performance requirements, provides a desirable alternative to traditional tools for those applications requiring limited part quantities. These approaches are referred to as Rapid Tooling (RT) solutions. RT methods have been in use for several years and are generally composed of a metal tooling surface, made by thermally spraying metal onto a male pattern, and a support structure fabricated either from low CTE metals or composites [15 - 18]. Wimpenny and Gibbons [19-20] reported a 40% production cost savings over machined Invar tooling using thermally sprayed Invar tooling techniques.

Despite developments in RT approaches, metallic based tooling is often still cost prohibitive in many applications. Further, the high costs associated with implementing new advanced techniques may significantly offset the gains. However, metallic tools offer more durability than is needed for one-off prototypes or producing parts for emergent needs such as incident repair due to FOD. In such applications, the tool is required to produce a limited number of parts. The speed of delivery of these tools is a higher priority than durability since the

need to resolve a repair or evaluate a prototype part is often time critical. Currently the use of carbon fiber based composites has become common place for short service life and repair tooling.

Tools fabricated from composites require a complex design and manufacturing process. Composite based tooling designs typically consist of a carbon/polymer composite tooling surface with an “egg-crate” substructure used for support, Figure 1-2. Design, fabrication, and assembly of egg-crate type support structures, Figure 1-2, are costly and time consuming [21]. An alternative tooling approach, which simplifies the need of support, involves the use of a machined monolithic substrate. Post machining, the appropriate coating or laminate is applied as the final tooling surface.



Figure 1-2: Example of composite based layup tool "egg-crate" backup structure made from CFRP [23].

Two composite layup tools which use a monolithic substructure approach are shown in Figure 1-3 and Figure 1-4. Substrates may be initially built from bonded blocks of material or cast to rough geometry. Subsequently, they are machined to their final form before the final tooling surface, which is made from a composite laminate or sealant/filler, is applied. This

provides the net geometry of the tool and final form of the part. The strength of the bond between the laminate and the substrate and the amount of sealers/fillers are dependent upon the surface quality and integrity of the substrate. Surface quality and integrity are primarily controlled by the material properties and the machining process used. If the surface integrity has deteriorated the tooling surface may crack or separate from the substrate during the curing cycle. Higher roughness and porosity requires a larger amount of sealers and/or fillers to achieve a uniform fill. Further, the more material that is applied the greater the chance that thermal mismatch in properties will lead to cracks or failures.

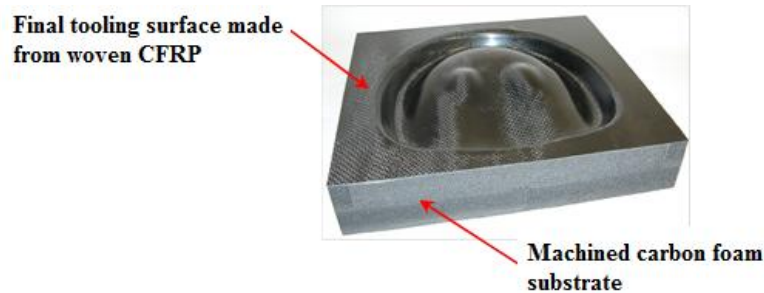


Figure 1-3: Example of Cfoam® rapid tooling system using Cfoam substrate with woven CFRP final tooling surface [24].

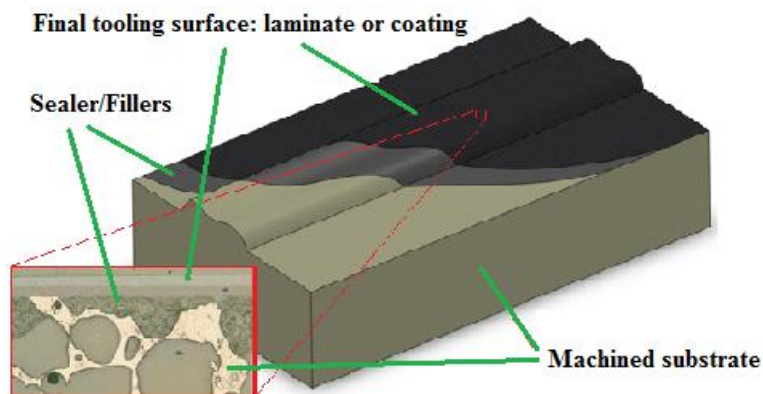


Figure 1-4: Schematic diagram of rapid tooling system based upon a machinable substrate material with inset: cross sectional view of material layers.

1.3 Summary

Current common practice for fabrication of large scale composite tools is to use either metals or composite materials for fabrication. Generally, metallic tools may be used for hundreds of processing cycles, but are time consuming and expensive to produce. Composite based tools offer reduced manufacturing costs compared to high performance metallic tools. Nevertheless, composite based tooling designs are complex requiring time consuming fabrication and are not capable of supporting all needs. Many applications such as incident repair tooling require a tooling solution that can be rapidly fabricated affordably with a sufficient capability to produce only a limited number of parts. Applications of this nature may preclude more traditional tooling solutions, such as metallic or composite based tools due to their cost and lead time.

The documentation or published literature available on the machinability of non-metallic tooling materials is limited. The need to evaluate the machinability of tooling substrate materials has motivated a series of experiments conducted at the University of Washington which investigated three candidate commercially available, brittle, porous, non-metallic materials. These materials were evaluated based upon their advertised ability to improve process simplicity and economics while maintaining the physical and thermal properties required. Evaluation of the machinability of these novel materials is a key step in optimizing the fabrication process. During this study three novel tooling materials underwent several experiments in order to determine the machinability and optimal cutting parameters for using in end milling. The optimal machining conditions, cutting forces, cutting mechanism, surface finish generation, surface integrity and tool wear were investigated, characterized, and reported.

Chapter 2: Background and Literature Review

Composite components are manufactured to near net shape using various techniques such as wet layup, Resin Transfer Molding (RTM) and autoclaving [21]. The commonality between all these methods is the requirement of a mold or tool to provide the desired geometry of the cured part. These tools often contain complex compound geometry which is difficult to accurately produce. The most common process used to achieve the desired net shape of a given composite tool is Computer Numeric Control (CNC) end milling. End milling is a universal/flexible process capable of accurately producing complex geometries such as compound curvature over large areas while achieving high material removal rates. The end milling process is highly dynamic and sensitive to cutter geometry and cutting conditions such as cutting velocity, feed rate, depths of cut in both axial and radial directions as well as machine tool and workpiece rigidity. In order to achieve the best possible results in terms of accuracy and process economy an understanding of how each variable affects the process is necessary. A review of the available literature related to the machinability of brittle porous materials are presented and discussed in the following sections. In addition, key topics related to machinability such as tool wear, surface quality, and the mathematical modeling of cutting forces are presented.

2.1 The End Milling Process

The end milling process utilizes a rotating cutting tool (end mill) with one or more cutting edges of defined geometry mounted into a machine tool spindle. The workpiece is mounted on a pallet or table. The table and spindle are capable of translating in one or more axis of movement. A diagram of a typical 3-axis vertical milling machine is given in Figure 2-1. As the tool moves through the workpiece, material is cut from the workpiece by each cutting edge in the form of a chip. End milling can be divided into three basic categories: peripheral milling, slot milling, and

surface milling. Each type of milling process defines the nature in which contact between the tool and the workpiece occurs. During peripheral milling, the cutting tool travels around the edge or perimeter of a feature. The depth of cut in the radial direction is always less than the full diameter of the tool. When slot milling, the radial depth of cut is equal to the full diameter of the tool. A schematic representation of slot and peripherally milling is shown in Figure 2-2. The third form of end milling is surface milling, used when a three dimensional compound surface is required. A radiused end mill or 'Ball-nose' end mill is used in order to contour the machined surface. Fine steps between cutting paths (stepover) are required when surface milling in order to minimize the surfaces irregularity. The larger the stepover, the larger the peaks of the material left over due to the curvature of the nose of the tool. Requiring tightly spaced tool paths makes surface milling the slowest and least efficient form of end milling. Although these three categories of end milling vary in their use, approach, and tooling, the basic cutting mechanism and principals are the same.

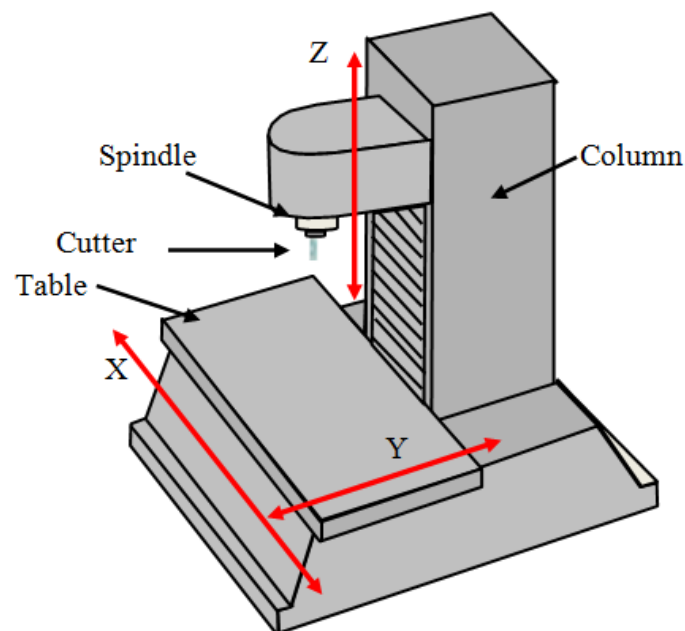


Figure 2-1: Vertical milling machine.

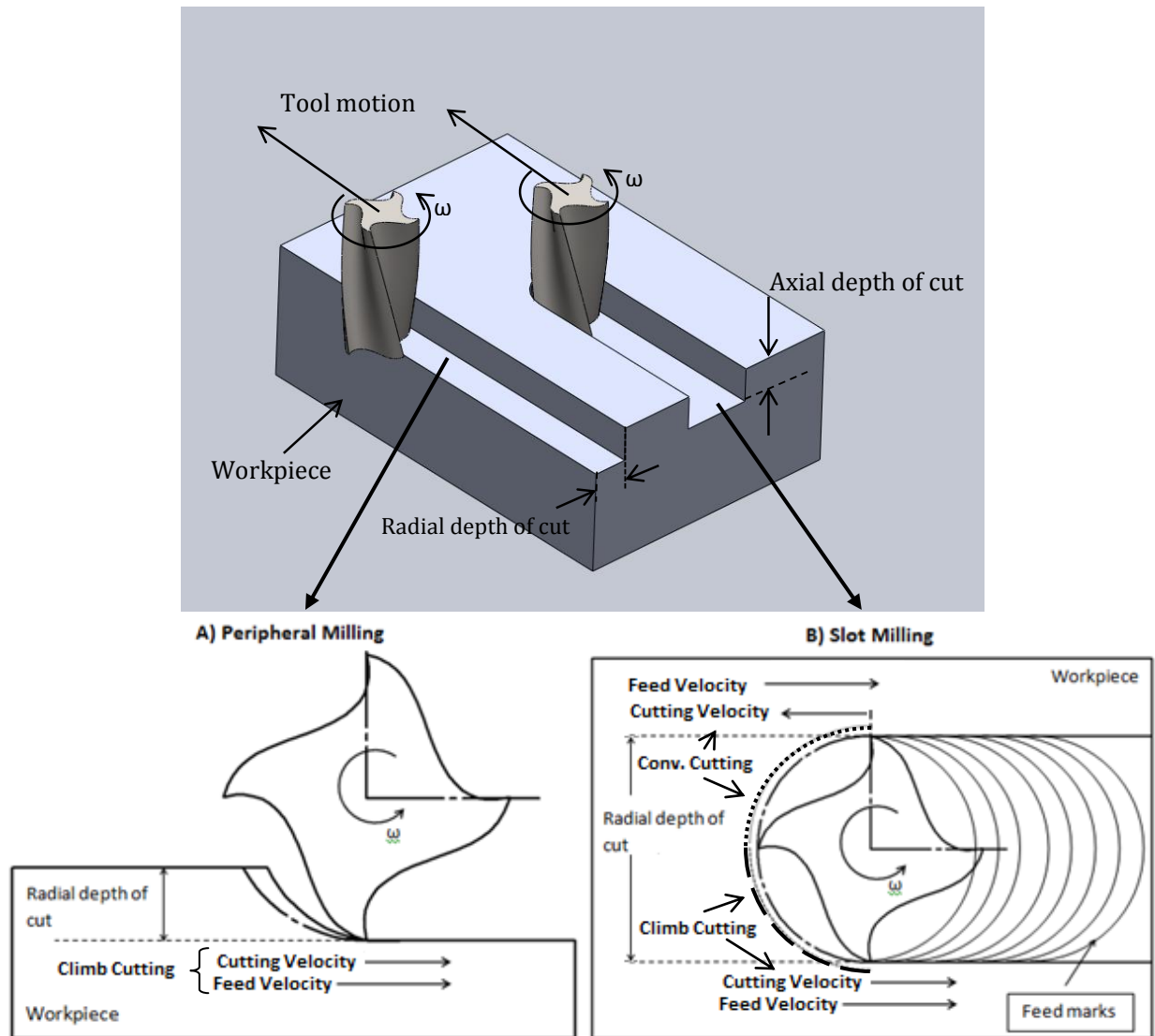


Figure 2-2: A) Peripheral milling and B) Slot milling.

2.2 Machinability of materials

Machinability can be challenging to predict because machining has so many variables [25]. Many industries utilize a machinability index or scale. Index's are commonly specific to a class of metals such as steels, aluminum alloys, ect. Indexes are formulated to take into account variables such as: hardness, cutting forces, tool wear, and cutting velocity. American Iron and Steel Institute (AISI) determine the machinability of materials by conducting cutting tests at a specific cutting velocity, 54.9 m/min [26]. Cutting forces, surface quality and tool life are

measured. Results are then compared to those of 160 Brinell B1112 steel which is designated as the baseline and given the rating of 100% [26]. Any value below 100% is said to be less machinable. However, the ratings are highly subjective and intended as a rough estimation of a material's behavior during machining. A full discussion of a material's machinability requires inclusion of six key areas of knowledge:

- Microstructure
- Cutting Forces
- Tool Wear
- Chip Formation
- Surface Topography
- Surface Integrity

Inclusion of all six areas is necessary for a *complete* characterization of a given material's machinability. Microstructure and composition of the material affects many mechanical and thermal properties which in turn alter machinability such as ductility, hardness, CTE and thermal conductivity, ect. Cutting forces determine the strength of the required machine tool, cutting tool stiffness, cutting tool geometry and power requirements. The rate of tool wear that can be expected in given material is key to determining the expected tool life. Chip formation and the type of chips which will be formed aids in early identification of difficulties which arise from problematic chip evacuation. For example continuous type chips can form tangled masses of chips referred to as 'birds nests' which can collect on the tool obstructing cutting action, coolant flow, and inevitably lead to tool failure. Materials like stainless steels can also form chips which have a high propensity to adhere to the workpiece and tool. Understanding how the machining parameters affect the resulting surface topography assists the user in determining the required parameters in order to achieve the desired surface finish and accuracy. Machining induced damage may have a detrimental effect on the resulting residual strength of the workpiece.

Knowing how the machining parameters affect the amount of induced damage and how that damage affects the surface quality is key to ensuring the final part quality, particularly in brittle materials.

2.3 Machinability of brittle, porous materials

The machining of brittle materials is challenging due to the high hardness and low toughness of the material. The machining of hard and brittle materials such as ceramics is most commonly accomplished through abrasive type processes such as grinding or ultrasonic machining. End milling of ceramics is largely avoided, reducing research in the subject and the available literature. During cutting processes such as turning or milling controlling fracture and cracking is challenging. Low ductility does not allow deformation and shear to form a chip. Like composites, cutting of brittle materials is a series of localized small scale fracture. If fracture can be controlled, cutting processes such as end milling are feasible.

2.3.1 Machinable glasses and ceramics

Glass has many applications due its desirable mechanical, thermal, and dielectric properties. However, shaping glass with high precision at rapid rates is difficult. The brittle nature of glass requires grinding processes which have low material removal rates. Difficulty in machining is regarded as one of the major shortcomings for the widespread applications of most ceramics [27]. The need to increase the achievable material removal rates of ceramics led to the development of machinable glasses and ceramics.

Macor® machinable glass ceramic was developed and produced by Corning Inc. Machining of Macor® was studied by Grossman [28, 29]. Macor® processes high temperature capabilities, stable up to 1000°C, and can be machined using traditional machining processes and

cutting tools [28]. Addition of mica crystals into a glassy matrix gives the material the machinable characteristics. The primary role of the mica is to contain the brittle fracture to the vicinity of the cutting edge by deflecting and blunting cracks [30], Figure 2-3. As a result, the traveling fracture removes the glassy matrix contained between mica crystals. Therefore, the achievable accuracy is directly proportional to the size of the mica crystals [28].

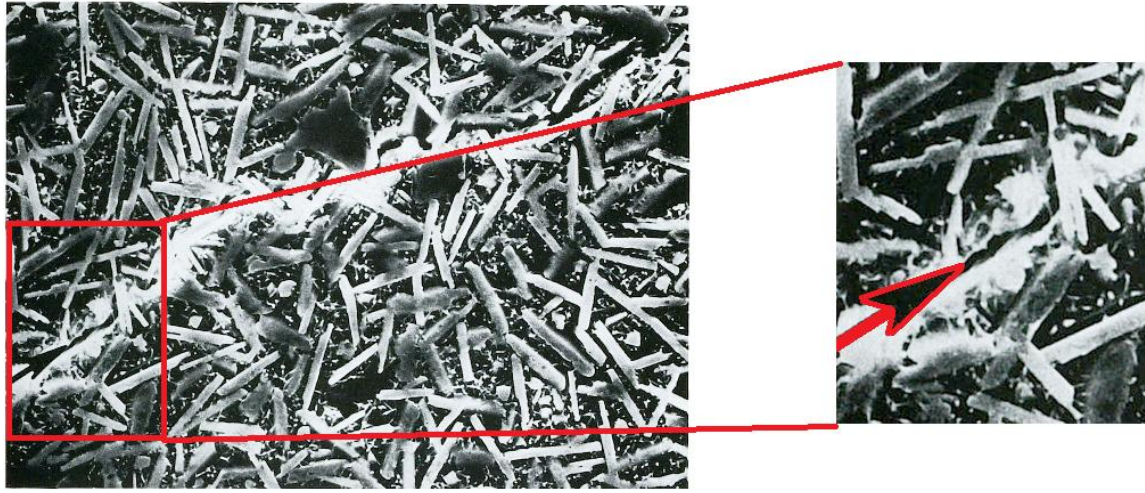


Figure 2-3: Crack deflection by mica crystals in Macor machinable glass ceramic [28].

Most machinable glass-ceramic materials have a mica crystal size of approximately $20\mu\text{m}$ [29]. Along with achievable accuracy, strength and hardness increase with mica crystal size [29]. Machinable glass-ceramics with fine mica crystal sizes of approximately $4.5\mu\text{m}$ or less have been shown to increase in mechanical strength with the $1/5$ power of the average mica plate diameter [29]. Size is not the only important characteristic of the mica crystals. Aspect ratio has a significant effect on the mica's ability to arrest cracks and contain the fracture [28]. *The ability to arrest and contain fracture to within the cutting tool region is an important ability of a machinable brittle material. Not only does the process of controlled small scale fracture serve as the material removal mechanism it also provides a damage tolerance mechanism for the material.*

An additional example of a machinable ceramic is aluminum nitride (AlN), hexagonal boron nitride (hBN) composite ceramic which was studied by Beck et al in 2008 [31]. It was shown that in AlN-hBN the hBN platelets act as the crack deflecting mechanism, Figure 2-4. The hBN platelets provide both a preferential failure path and crack resistance to transverse fractures. Planar fractures occurring along the plane of the hBN platelets can be seen in Figure 2-4a. Fractures coalesce to form particles of loose material which are subsequently removed. Thus, damage is controlled and contained within a localized region surrounding the cutting edge.

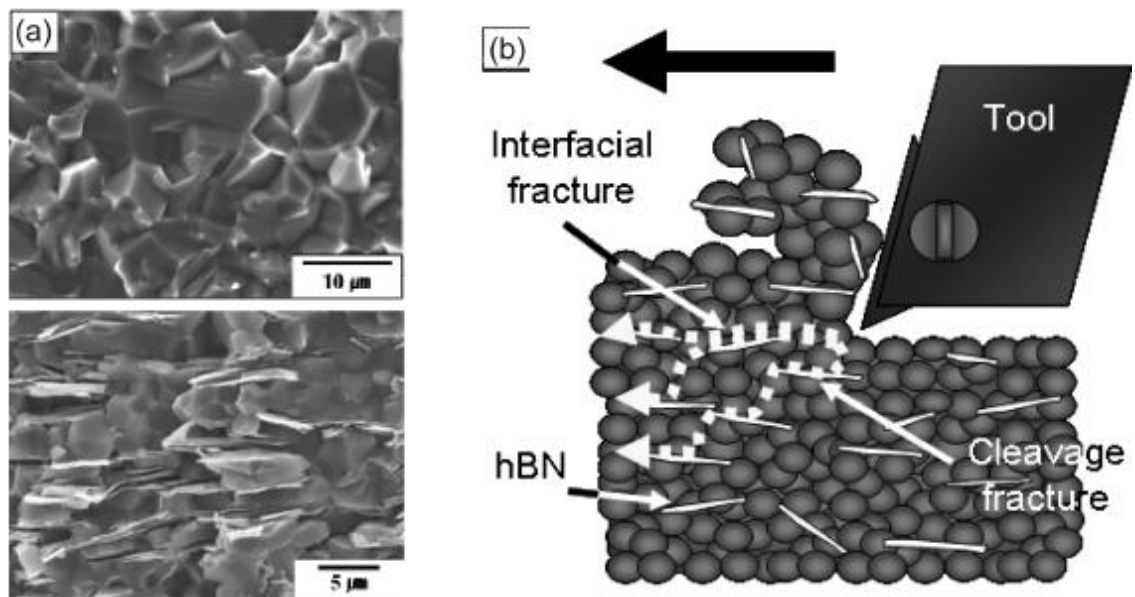


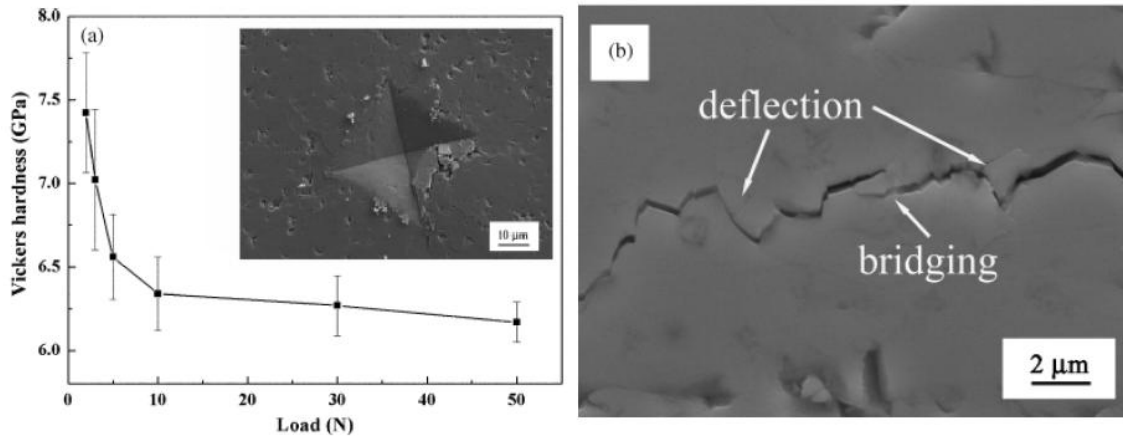
Figure 2-4: (a) SEM micrographs of fracture surface in AlN-hBN ceramic and (b) crack behavior during cutting process in AlN-hBN [31].

Yet another machinable ceramic, γ - $\text{Y}_2\text{Si}_2\text{O}_7$, has been studied extensively by Sun et al [32]. The silicate ceramic studied is unique in that it is a single phase machinable ceramic. Despite being single phased, the material possesses low shear modulus and good damage tolerance [32]. A comparison of the mechanical properties of several ceramics including γ - $\text{Y}_2\text{Si}_2\text{O}_7$ is given below in Table 2-1.

Table 2-1: Properties of γ -Y₂Si₂O₇ along with other machinable ceramics [32].

	Y ₂ Si ₂ O ₇	LaPO ₄ ^{5,29}	Macor ²⁸	SiO ₂ ³⁰	Y ₂ O ₃ ³¹
Young's modulus, E (GPa)	155 ± 3	134	66	73	169
Shear modulus, G (GPa)	61	53	25	31	65
Poisson ratio ν	0.27	0.275	0.29	0.17	0.304
Bulk modulus, B (GPa)	112	99.3	52	41	143
Flexure strength, σ_b (MPa)	135 ± 4	101.82	94	55	145
Compressive strength, σ_c (MPa)	650 ± 20	/	345	1100	1100
Fracture toughness, K_{Ic} (MPa · m ^{1/2})	2.12 ± 0.04	1 ± 0.1	1.4 ± 0.5	0.79	2.3
Vickers hardness, H (GPa)	6.2 ± 0.1	4.86	3	7.0	6.8
Machinability	Good	Good	Good	Poor	Poor

To understand the underlying mechanism of machinability drilling tests and Hertzian contact tests were conducted. Sun et al found that intrinsically weak interfaces within the material allowed for a localized damage mechanism referred to in the paper as “quasi-plastic” behavior. Weakly bonded planes contributed to the containment of damage to a localized region and low shear modulus [32], Figure 2-5. Material removal is accomplished through a series of controlled small scale fracture and removal of loose grains.

**Figure 2-5: (a) Plot of Vicker hardness of machinable silicate vs. load and (b) high magnification SEM image of crack deflection and bridging [32].**

From the studies of the three machinable ceramics discussed, several similarities are apparent. The foremost commonality is the presence of a crack deflection or damage tolerance mechanism. Secondary phases in the form of fiber like mica crystals [28-30] or plate like crystals of hBN [31] deflect or hinder crack travel. Intrinsically weak bonds can also achieve a

fracture controlling affect [32]. In all three materials a separate mechanism of controlling fracture or deflecting cracks is present. *The presence of a fracture or damage controlling mechanism is vital to the machinability of brittle materials for two reasons. First, the damage tolerance mechanism limits fracture to an area closely surrounding the cutting edge preventing large scale fracture of the workpiece. Secondly, the containment of the fracture leads to coalescence of the cracks to form a region of highly localized damage which in turn is removed.* Therefore, the damage tolerance mechanism at work in machinable brittle materials is not just a form of controlling cracking; it is also a key part of the material removal mechanism and process.

The control and deflection of cracking can be achieved through methods other than those presented thus far. The methods previously discussed approach the problem by deflecting the crack either by introducing secondary phases or intrinsically weak interfaces. The next section will discuss an alternative approach through the use of porosity.

2.3.2 Porous materials and foams

As a crack travels through a material, if a pore is encountered, the crack will essentially lose the sharp geometry at the tip. The crack tip radius will be equal to the pore radius. This results in reducing the stress concentration which in turn arrests the propagating crack. Porosity can therefore be used in brittle materials as a damage tolerance mechanism to increase machinability. However, porosity adds additional complexity to the machining process. Pores can cause a localized unloading effect as the cutting edge passes through them; resulting in high frequency loading and unloading of the cutting edge. The role of unloading in machining of brittle materials was investigated by Chandra et.al [33]. It was shown that material removal was accomplished in the form of small scale chipping. Chipping was found to initiate upon

unloading of the cutting edge. Induced cracks were initiated when the force reached the peak indentation force. It was shown that unloading could induce chipping regardless of whether the peak indentation force had been reached or not. A method of unloading to induce material removal while reducing cutting forces below the indentation force and reducing cracks was proposed. Although the unloading effect during the study was induced mechanically through the tool, possible similar effects due to the presence of pores may be possible.

A brittle foam material commonly machined in many industries is carbon foam. Carbon foams have been used in heat exchangers, space structures, naval applications, acoustics, radar-selective shielding, as well as dental and orthopedic scaffolds [34-40]. Many of these applications require machining. Carbon foams span many applications due to the fact their mechanical and thermoelectric properties can have a large span and can be tailored through additives, coatings, and infiltrations [41]. Carbon foams were first developed in the late 1960's, through the pyrolysis of thermoset polymer foams which created a weak carbon skeleton. Development of a thermodynamic flash technique utilizing meso-phase pitch precursors came in the 1990's. These foams greatly improved on the strength and reliability of previous foams [42]. This process was later extended to coal based precursors as a low cost alternative [43, 44]. Carbon foams have been in use as sandwich core materials and as low cost alternatives to metallic materials in composite tooling applications in recent years. The use of a composite laminate applied to a machined carbon foam substrate to provide the final tooling surface of a composite tool was demonstrated by R. Lucas et al [45] and L. Carver [46]. Reductions of 20-40% in the final tooling cost when compared to tools fabricated from Invar36 were reported [45]. G.D. Skives et al [47] showed that the application of sealants to the foam substrate prior to curing the final tooling surface over the foam prevents the matrix material from infiltrating and

cracking the foam near the surface, improving reliability. Khairul et al. [48] has shown that components produced using carbon foam tooling have less residual stress and distortion than those manufactured from Invar 36. He accounted this to the lower bulk modulus of the carbon foam which was not capable of inducing higher residual stresses.

Carbon foams have a cellular structure that is considered open-celled with the majority of the mass of the foam concentrated in the ligaments. The main parameter describing the degree of porosity of cellular materials is the relative density

$$\rho = \rho^* / \rho_s \quad \text{Eq.(2.1)}$$

Where, ρ^* is the density of cellular medium and ρ_s the solid density. Solid density is defined as the density of the material that constitutes the struts or ligaments of the cell. Many of the material's properties depend on the relative density which is a measure of the material solidity. Thin cell walls exist between ligaments which have been shown to increase the overall energy absorbed during ballistic testing by Janszen et al. [49]. Janszen showed that the damage induced during ballistic impact testing was kept localized and did not deeply extend into the material in any direction [49]. The mechanism behind the energy absorption is not fully characterized at this point. However, these studies indicate the possibility that brittle porous materials can be machined without inducing damage which would otherwise be detrimental. Much of the damage tolerance of brittle porous materials comes from the fact that open pores affect crack propagation. In an attempt to apply linear elastic fracture mechanics to these materials Choi and Sankar [50] investigated the Mode I fracture toughness of carbon foams. A finite element model based upon a number of different representative unit cells was developed. This model was used in order to estimate the Mode I fracture toughness. High correlation was found between

experimentally measured values obtained using three point and four point single edge notch bend tests.

Recently much effort has been put toward the application of Finite Element Analysis (FEA) to foam materials in order to better understand their behavior. The most common method of applying FEA to these open cell structures is based on the development of a representative unit cell. The development of representative unit cells can be traced to the work of Anderson, Maruyama, and Hagar [51-53]. Sarzynski et al. [54] also showed that a multi-scale FEA model can be used to characterize the response of multifunctional hybrid carbon foams while taking into account ligament anisotropy and functional coatings. A recent study using the finite element based approach to determine fracture toughness was published by Thiyyagasundaram et al [55]. The model used by the authors was based on a tetrakaidecahedral unit cell, Figure 2-6. The structure of the unit cell was selected specifically by the authors to closely resemble the structure of carbon foams. A close semblance is visible in Figure 2-6. Mode I, Mode II and mixed mode fracture toughness values were all determined using a convergence method. Mode I and Mode II fracture toughness for a foam model with a relative density of 0.16% was found to be $622 \text{ Pa}\sqrt{\text{m}}$ and $522 \text{ Pa}\sqrt{\text{m}}$, respectively.

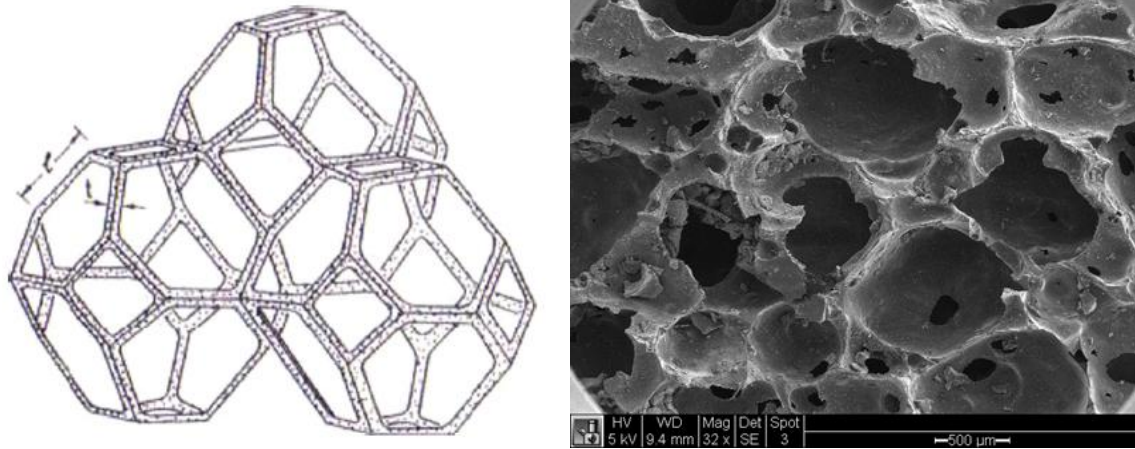


Figure 2-6: Side by side comparison of tetrakaidecahedral unit cell with strut length l and thickness t in a BCC lattice [55] and carbon foam.

2.3.3 Brittle material effects

The machining and finishing of brittle materials is often accomplished through the use of grinding techniques involving abrasive particles. Diamond based abrasive particles are often required in order to ensure acceptable tool life in brittle materials due to their high hardness and frequently abrasive nature. These embedded particles penetrate into the workpiece surface causing a combination of plastic flow and fracture in even the most brittle materials [56]. This was identified by Hockey, B.J. [56] in 1971. High plastic dislocation densities were induced and identified near the surface of single and polycrystalline aluminum oxide. Evans et al. [57] found similar results and confirmed Hockey's finding in 1978. This behavior was found to exist on a highly localized basis at the small scale.

The existence of process induced cracks which has been established in many studies and may affect strength, especially when cracks are oriented normal to the surface. Mecholsky et al. [58] in 1977 and Rice & Mecholsky [59] in 1979 showed that machining induced cracks lead the eventual initiation of failure and degradation of strength. Degradation in the strength of the material near the surface is commonly referred to as a reduction in residual strength or surface

integrity. An understanding of the machining induced damage in order to determine the integrity of the machined component is necessary. Initial attempts [58] were made to correlate flaw size to failure strength in accordance with traditional Griffith theory. However, subsequent indentation fracture studies suggested significant differences in crack propagation of ideal Griffith flaws and flaws created by a diamond indentation. This difference in crack behavior during subsequent loading was found to be effected by the resulting residual stress field. The failure stress expressed in terms of residual stress parameters, which is independent of initial flaw size, was found to be lower than that associated with stress free cracks of the same initial dimensions. Therefore, crack propagation is dominated by the effects of the residual stress field.

The fracture and deformation created by a single diamond particle during machining is assumed to be similar to the damage induced by sharp diamond indentations. Following this logic the crack formation and propagation of machining induced damage may be assumed to obey an equivalent residual stress dominated effects. This was affirmed by Kirchner & Isaacson [60] who showed that strength was reduced by residual stresses induced during single point machining of ceramics. Further investigation into the effects and in-situ monitoring of damage induced during machining of brittle materials was carried out by Marshall et al. [61]. It was further shown that residual stresses induced during machining had a significant effect on crack response in brittle materials.

2.4 Mathematical Cutting Force Models

An understanding of cutting forces during end milling is essential for determining cutting conditions, power requirements, cutter geometry and material, and the required machine rigidity. Depending upon the combination of variables, the mechanics of the cutting process will change. The most widely accepted text defining the principals of the metal cutting process was written by

Milton C. Shaw[62]; a thorough text to develop an in-depth, fundamental understanding of the metal cutting processes and their development. As understanding of the mechanics evolved over the years, more complex and powerful models were developed.

Modern metallic cutting force models use many assumptions which are not valid in brittle porous materials. However, the basic mathematical approach used to account for process parameters and geometry is adapted for use in brittle porous materials in the developed model presented in this research. Therefore, the modeling of metallic cutting forces is presented in the following sections as relevant background information.

2.4.1 The Orthogonal Cutting Model

Modern metal cutting theory began with the two-dimensional ‘idealized’ Orthogonal cutting model. The Orthogonal cutting model was first defined by Piispanen. Piispanen’s model led to the development of the modern ‘idealized’ Orthogonal cutting model by Merchant [63 - 66]. The ‘Idealized’ orthogonal cutting model, Figure 2-7, is based on a minimum energy principal which is defined as, “the shear angle ϕ will be oriented such that the total amount of work done in cutting will be minimum [64].” It is further assumed that the shear strength of the material being machined is equal to the shear stress acting on the shear plane; and is independent of the shear angle [64]. This leads to the following formulation:

$$shear\ angle = \frac{\pi}{4} - \frac{1}{2}(Friction\ angle - Rake\ angle) \quad Eq.(2.2)$$

In Merchant’s model the chip is assumed to be a separate body, Figure 2-7a in equilibrium. Therefore, the force exerted on the chip by the tool is equal to the resultant force exerted by the workpiece at the shear plane [64]. Dissolving these forces into component vectors

and adding a vector set to account for the shear force and placing the origin for these vectors at the tool tip lead to the development of the famous ‘Merchant’s Circle Diagram’, Figure 2-7b.

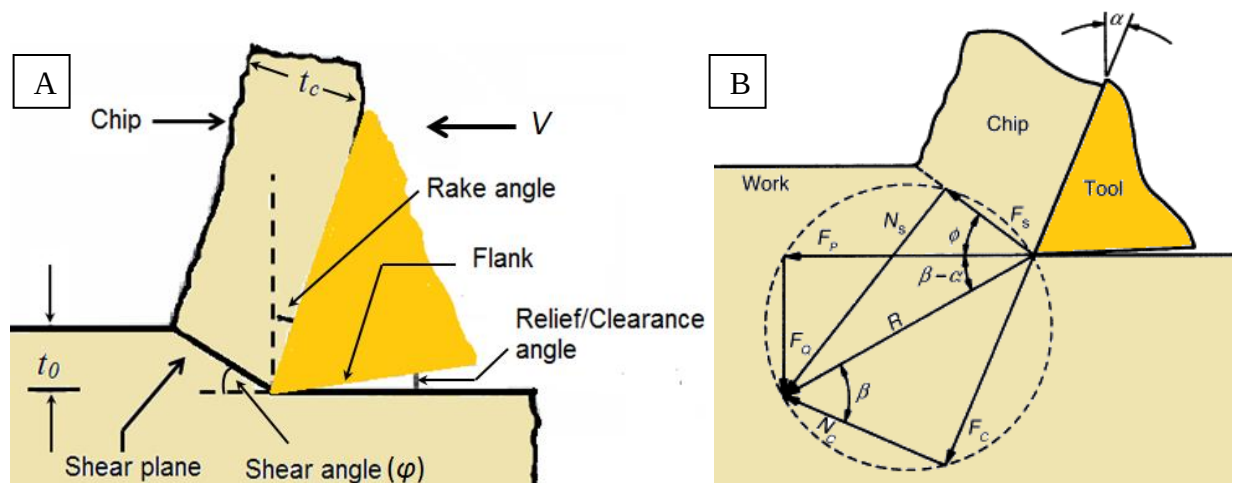


Figure 2-7: (a) Schematic diagram of two dimensional cutting edge and (b) ‘Merchant’s Circle’ diagram showing orthogonal cutting forces.

Orthogonal cutting assumes a two-dimensional state of plane strain. There are three deformation zones in the Orthogonal cutting model, Figure 2-8. The *primary shear zone* follows the shear plane and extends from the tip of the tool to the far edge of the chip. The majority of the chip deformation and acceleration occur here. As the chip travels up the tool face it further deforms in the *secondary shear zone*, which runs along tool rake face beginning at the tool tip. The final deformation zone is titled the *tertiary zone*, which is located on the machined surface where the flank of the tool contacts the machine surface.

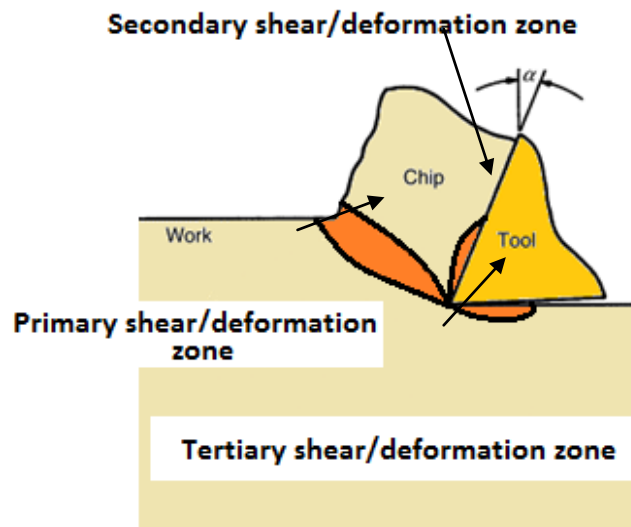


Figure 2-8: Shear/deformation zones diagram.

The equations and relationships describing the forces and values related to the Orthogonal cutting model are listed in Table 2-2. While a useful tool for understanding the mechanics of the Orthogonal cutting model, the Merchant circle is not inclusively accurate over a wide range of materials or conditions [67]. A lack of means to account for changes in machining behavior due to machining parameters such as cutting velocity is the primary source of error [67]. Over a wide range of cutting conditions, Oxley [68-71] found that there was poor correlation between the predicted shear angle and the experimentally determined quantities [68]. He contributed this to the lack of inclusion of rate dependent effects such as strain rate and strain hardening. Despite the inaccuracy of Merchant's model it was a fundamental milestone in the development of modern metal cutting principals.

Table 2-2: Principal relationships and equations

Value	Equation	Eq. Number
Shear force in primary shear zone	$F_s = F \cos(\phi + \beta_a - \alpha)$	Eq.(2.3)
Normal force in terms of tangential force	$F_n = F \sin(\phi + \beta_a - \alpha)$	Eq.(2.4)
Shear stress on shear plane	$\tau_s = \frac{F_s}{A_s}$	Eq.(2.5)
Shear plane area	$A_s = b \frac{h}{\sin \phi}$	Eq.(2.6)
Normal stress on the shear plane	$\sigma_s = \frac{F_n}{A_s}$	Eq.(2.7)
Shear velocity	$V_s = V \frac{\cos(\alpha)}{\cos(\phi - \alpha)}$	Eq.(2.8)
Shear plane length	$L_c = \frac{h}{\sin(\phi)} = \frac{h_c}{\cos(\phi - \alpha)}$	Eq.(2.9)
Chip compression ratio (r_c)	$r_c = \frac{h}{h_c}$	Eq.(2.10)
Shear plane angle (ϕ)	$\phi = \tan^{-1}\left(\frac{r_c \cos \alpha}{1 - r_c \sin \alpha}\right)$	Eq.(2.11)
Shear strain in chip (γ_s)	$\gamma_s = \frac{V \cos(\alpha)}{\sin(\phi) \cos(\phi - \alpha)}$	Eq.(2.12)
Frictional and normal force acting on the rake face	$F_n = F_{tan} \cos(\alpha) - F_{feed} \sin(\alpha)$ $F_u = F_{tan} \sin(\alpha) + F_{feed} \cos(\alpha)$	Eq.(2.13)
Average friction coefficient	$\mu_a = \tan(\beta_a) = \frac{F_u}{F_v}$	Eq.(2.14)
Friction angle (β)	$\beta_a = \alpha + \tan^{-1} \frac{F_{feed}}{F_{tan}}$	Eq.(2.15)
Chip velocity	$V_c = r_c V = \frac{\sin \phi}{\cos(\phi - \alpha)} V$	Eq.(2.16)
Frictional power	$P_t = F_u * V_c$	Eq.(2.17)
Frictional heat	$P_u = m_c c_s \Delta T_c$ where, T_c is the chip temperature	Eq.(2.18)

2.4.2 Predictive force modeling

Prediction of the forces experienced by the workpiece, cutting tool, and chip has been studied extensively. A survey of the force modeling process with respect to end milling was written by Smith and Tlustý [72]. Smith covers several of the more common early metal removal models being applied to the milling process as well as categorizes them according to

their force computation and deflection feedback methods. These model categories include: the *Average Rigid Force, Static Deflection (ARFSD) Model*, the *Instantaneous Rigid Force (IRF) Model*, the *Instantaneous Rigid Force, Static Deflection (IRFSD) Model*, and the *Regenerative Force, Dynamic Deflection (RFDD) Model*.

End milling simulation models are divided based upon the method used to calculate the force and tool deflection. Of these, the most basic model is the ARFSD model, which calculates the tool deflection through modeling the average cutting force as a point load located at the tool tip and using a cantilever beam approach. According to this model there exists a proportional relationship between the Material Removal Rate (MRR) and the amount of power (P) consumed in the cut. These quantities are related by the coefficient known as specific cutting power (P_{sp}). The specific cutting power of most common materials is available in literature.

$$P = P_{sp} * MRR \quad \text{Eq.(2.19)}$$

The average torque is given by the following equation:

$$Torque = P/\omega \quad \text{Eq.(2.20)}$$

The ARFSD model does not take deflection of the cutting tool into account in the determination of cutting forces. However, it has a simple approach which makes the model popular for rough estimation purposes. More accurate calculations can be found using the IRF model which no longer assumes that the force on the tool is simply proportional to the average power. This model computes the instantaneous force on the cutting edge at discrete locations as shown in Figure 2-9. The vector sum of these forces is equal to the cutting force acting on the tool edge in contact. As with the ARFSD model, the IRF model is designated *rigid* because tool deflection is not considered in the force calculation. The tangential cutting force for each

discrete location is taken as proportional to the frontal surface area of the chip in contact with the cutting edge. Incremental forces ($F_{s,i}$) are calculated from the following equation:

$$F_{s,i} = K_s W_i T c_i \quad \text{Eq.(2.21)}$$

K_s is an empirical value known as the cutting force coefficient where $s = (x, y, z)$ for Cartesian systems or $s = (tangential, radial, axial)$ for polar systems. W_i and $T c_i$ are the instantaneous chip width and thickness for the current incremental segment being computed. The formation of the model is an extension of Sabberwal's [73] observation that instantaneous tangential and radial cutting force is proportional to the frontal cutting area. Cutting force coefficients are most commonly static values empirically determined from cutting tests [74, 75].

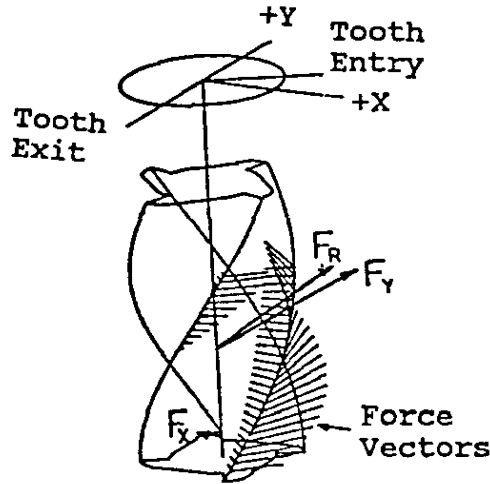


Figure 2-9: Instantaneous rigid force model [72].

The IRFSD model is similar to the original IRF model; the forces are computed in the same manner. However, IRFSD model also estimates cutter deflection to determine theoretical surface generation error plots. The 'static deflection' portion of the title of this model indicates that the deflection is taken as being proportional to the force. Ultimately, the deflection is not included in the calculation of force and plays no role in its determination.

Neglecting cutter deflection may lead to a source of error when compared to experimental values. Deflection of the cutting tool will lead to a change in the contact area of the cutting edge. Cutting force is assumed to be proportional to the frontal contact area of the tool and chip. Thus, the deflection of the tool will affect the cutting forces. Both of the previously discussed models do not take into account the deflection of the cutter in their computation of cutting forces. A form of feedback must be employed in order to include the deflection of the cutter in the calculation of cutting force.

The *Instantaneous Force with Static Deflection Feedback Model* utilizes a deflection feedback method in order to include the effect of tool deflection in the calculation of cutting forces. Because the deflection of the tool only affects t_{ch} , Equation 2.21 can now be described as

$$F_{s,i} = K_s W_i (T_{ci} - F/k) \quad \text{Eq.(2.22)}$$

, where k is the cutter stiffness and F/k is the deflection of the cutter. Deflection is assumed to be constant along the length of the cutter. Therefore, this model is only valid for small axial depths of cut where the curvature of the deflect tool can be neglected. The term: $(T_{ci} - F/k)$ represents the chip thickness of the given pass. Rearranging and solving the previous equation for force gives

$$F_{s,i} = \frac{K_s W_i}{(1 - K_s W_i / k)} T_{ci} \quad \text{Eq.(2.23)}$$

The deflection is taken to be directly proportional to force. Therefore, the deflection of the tool is given by:

$$\delta = \frac{K_s W_i / k}{(1 - K_s W_i / k)} T_{ci} \quad \text{Eq.(2.24)}$$

The RFDD models take an additional step further and account for excess material. If the cutter has deflected then there has been excess material left on the machined surface. Material will thus need to be removed by the following tooth making the total chip thickness for the second tooth equal to the sum of the nominal chip thickness and the deflection of the tool during the first pass. This principal is applied in a time stepped manner in order to map tool deflection, surface generation, and cutting forces. Many of these models also incorporate means to determine and predict chatter and the error in surface generation it produces through the incorporation of modal analysis of the tool. A summary comparison of the models discussed is offered in Table 2-3.

Table 2-3: Categories of end milling simulation models reference table.

Model:	Principal:	Basic Relations:	Tool Deflection	Surface Generation	Notes:
Average Rigid Force, Static Deflection Model	Relates material removal rate with power consumption.	$P = P_{sp}(MRR)$ $T = P/\omega$ $F_t \text{ avg} = P_{sp}(MRR)/v$ Deflection is calculated by modeling the average load as a point load at the end of the tool and using a cantilevered beam approach,	Yes, but not accounted for in the determination of forces.	No, deflection is treated as static.	Simplest model Popular for estimation due to its simplicity
Instantaneous Rigid Force Model	Force vectors acting on incremental sections of the cutting edge. The vector sum is taken as the cutting force.	$F_c = \sum_{i=1}^n F_i$ $F_i = K_s w_i T c_i$ Where, w_i and $T c_i$ are the instantaneous chip width and thickness for the i th segment	No, tool is assumed rigid	No, tool is assumed rigid	This model does not incorporate tool deflection or surface error calculations. Deviation from experimental values in 15 % – 25% range.
Instantaneous Rigid Force, Static Deflection Model	Forces are calculated in the same manner as the instantaneous rigid force model.	$F_c = \sum_{i=1}^n F_i$ $F_i = K_s w_i T c_i$ Where, w_i and $T c_i$ are the instantaneous chip width and thickness for the i th segment	This model assumes the deflection of the tool to be proportional to the cutting force vector sum.	Yes, surface error generation can be determined, but is assume static.	There is no deflection feedback for the force calculation in this model.
Instantaneous Force With Static Deflection Feedback Model	Tool deflection is calculated using the instantaneous force approach which assumes chip face area to be proportional to the cutting force.	$F = \frac{K_s * b}{1 + \frac{K_s * b}{k}} f$ Force is fed back into the force calculation in order to account for the loss in chip face area which is taken to be proportional to the cutting force.	Yes, The cutter deflection is given by: $\delta = \frac{\frac{K_s * b}{k}}{1 + \frac{K_s * b}{k}} f$	Yes, surface error generation can be determined, but is assume static.	This model includes surface generation and error estimation as well. It also directly leads to the time stepped approach of the regenerative force dynamic deflection model
Regenerative Force, Dynamic Deflection Model.	This model calculates force based upon not only the feed per tooth and deflection of the cutter but also the amount of area left by the previous tooth.	$F_{i+1} = K_s b (f + z_i - z_0)$ Where, z_i and z_0 represent the current deflection of the cutter and the previous time step deflection respectively	Yes, time based mapping of tool deflection is possible.	Yes, numerous formulations are available with surface error “mapping” capabilities.	Models of this type along with full development can be found in references: [1]

2.5 Tool life and wear

The determination of the wear rates of a tool is key to the determination of the tool's useful life. The cost of replacing cutting tools is a major portion of the total cost of machining [76]. Therefore, overall process economics is heavily influenced by cutting tool wear rates and characteristics. There are two main types of tool wear: "flank wear" and "crater wear." There are also less defined forms of wear such as: "nose wear" and "chipping" [77]. While not a material removal process, "built up edge," is considered a tool wear type due to the fact that it causes a *loss* in cutting geometry.

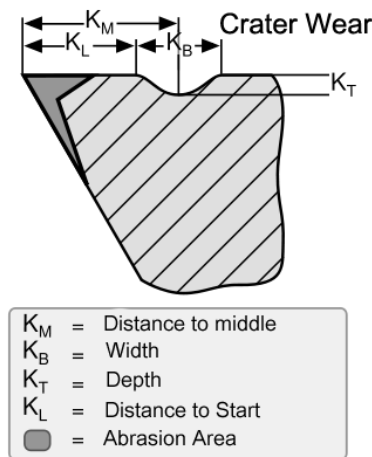


Figure 2-10: Schematic diagram of wear types.

Flank wear is the most detrimental type of tool wear. Fortunately, it is also the most predictable. Flank wear occurs as a result of a combination of abrasive and adhesive wear mechanisms possibly due to the presence of hard secondary phases [78, 79]. The most widely used estimation of tool life expectancy is the Taylor Tool Life Equation. The Taylor equation provides a simple means to estimate a tool's expected usable life within a moderate degree of accuracy under normal cutting conditions. It is based upon the amount of time it takes for a cutting tool's wear to increase to a predetermined point. The Taylor Tool Life equation is given in Equation 2.24.

$$V_c T^n X D^x f^y = C \quad \text{Eq.(2.25)}$$

The more common form is the following:

$$V_c T^n = C \quad \text{Eq.(2.26)}$$

Where,

$$\begin{aligned} V_c &= \text{Cutting Speed} \\ T &= \text{tool life} \\ D &= \text{depth of cut} \\ f &= \text{feed rate} \end{aligned}$$

The constants C , n , x , and y are empirically determined values. Although the Taylor Tool Life Equation provides a good approximation, it fails to account for critical factors such as thermal and other frictional energy effects. A number of other wear models exist and are in common usage today. Many wear models include a combination of effects due to thermal, frictional, and adhesion effects [80- 82].

2.6 Summary

As newly developed tooling materials are entering the industry, a need exists for research focused on the end milling of brittle porous materials in order to evaluate their potential. Currently, there is a lack of publicly available research on the machining of brittle porous tooling materials. In summary, the key points relevant to the machining of brittle porous materials that can be found in the literature are as follows: During the machining of brittle materials, material removal does not occur as a result of cutting, shear, and deformation as it does in metals. The machining of brittle materials consists of a series of controlled small scale fractures. Cracks and fracture in brittle machinable materials are controlled by various methods such as: crack deflection through the induction of secondary phases on the microstructural scale [28-32] or the introduction of porosity which blunts or arrests cracks. These methods are capable of controlling

crack propagation during machining of brittle material, and act as the material removal/chip formation mechanism, as well as serving as a damage tolerance mechanism during use.

Chapter 3: Research Scope, Goals, and Objectives

Novel tooling materials are one way to cut cost and significantly reduce production times associated with tooling used for composite component manufacture. The cost of machining can be a significant portion of the overall cost of a given composite layup tool. Therefore, the use of novel materials with increased machinability may offer significant cost savings. An understanding of cutting forces, tool wear, cutting tool material/geometry, surface quality, and surface integrity is needed to fully evaluate the benefits and drawbacks of a material and ensure maximum process economy.

Current data publicly available on the machinability of non-metallic materials is lacking. This dissertation will add to the available documentation on the machinability of brittle/porous materials by evaluating the machinability of three commercially available candidate tooling materials, namely: Xella/Hebel Autoclaved Aerated Concrete AAC-4/500, UMECO/Advanced Composites Group CB1100 Ceramic Tooling Block, and Touchstone Research Laboratory Cfoam®-20, carbon foam

Effects of cutting tool material, cutting edge type, and cutting conditions on: cutting forces, surface quality, surface integrity, and tool wear are investigated. A mathematical model of cutting forces in brittle porous materials is developed and investigated. The development in a mathematical model will aid in the reduction of the number of cutting tests that are required when investigating a novel brittle porous material.

3.1 Research Goals and Objectives

The machinability of the candidate tooling materials will be evaluated in order to:

- Determine average cutting force characteristics in all three materials using diamond abrasive, Polycrystalline Diamond (PCD), and High Speed Steel (HSS) cutting tools.
- Determine chip formation behavior of each material through study of machined material.
- Correlate machining conditions to cutting forces, surface finish, and surface quality.
- Report the tool wear behavior in each material for each cutting tool material and cutting edge type.
- Define the optimal feasible machining parameters for each material based upon cutting forces, surface quality and finish, and tool wear.
- Model cutting forces both empirically and analytically over the range of tested cutting conditions. Validate analytical model through comparison of results

In order to accomplish the stated goals and objectives the research will be carried out in the following stages:

Stage one: feasibility investigations

The first stage of the research will be an experimental investigation into the feasibility of the candidate tooling materials for use as composite component tooling substrate. Experimental investigation into the effects of cutting tool type and cutting conditions will aid in the selection of the parameters studied during the subsequent optimization study of Stage two.

- Fabrication of test setup, tooling, and material handling equipment.
- Preliminary determination of the cutting forces involved during machining of all three materials based upon the use of HSS, diamond abrasive, and PCD cutting tools.
- Investigation of surface finishes obtained using both diamond abrasive and polycrystalline diamond tools with varying machining conditions.

- Experimental investigation of tool wear in all three given materials for all cutting tools selected. Determine feasible conditions for machining each material based upon cutting forces, surface generation, and tool wear.

Stage two: experimentation optimization

Stage two of the research will build upon the results of Stage one. Microstructure, composition, and chip formation will be researched. Cutting force studies and analysis are based on Design of Experiments (DOE). Regression models based upon DOE and semi-analytical models of cutting forces are developed and evaluated. In addition, transverse rupture tests are also conducted in order to investigate effects machining induced damage on surface integrity.

- Full factorial design of experiment based upon results of preliminary investigations of cutting force and surface topography. Investigation of machining induced damage through Scanning Electron Microscopy (SEM) studies and correlation to surface roughness and topography.
- Evaluate chip formation mechanism and material composition and structure through optical and SEM studies.
- Investigation into surface integrity based upon the most and least optimal machining conditions determined during preliminary investigations. And, correlation of machining induced damage to surface integrity and residual strength.
- Analysis of Variance (ANOVA) and regression modeling of cutting force results.
- Develop semi-analytical modeling of cutting forces based upon material properties, porosity, and cutting conditions. Validation of semi-analytical model through comparison to experimental results.

Chapter 4: Candidate Tooling Materials and Experimental Methodology

This chapter will present the experimental approach and procedure as well as detail the three candidate tooling materials studied. The three candidate tooling materials were selected for their desirable characteristics of low CTE's, low costs, and rapid machinability for composite component manufacturing. In order to determine the machinability of the selected tooling materials: AAC-4/500, CB1100 and Cfoam, machining tests were conducted over a large range of cutting conditions. Cutting tool materials including: HSS, carbide, diamond abrasive, and PCD were studied to determine the effects of different types of cutting edges and materials. Surface roughness and topography investigations were conducted using surface profilometry as well as optical and SEM studies. Transverse rupture tests were also performed in order to determine the effects of machining induced flaws/damage on residual strength in each material.

4.1 Candidate Tooling Materials for Composite Part Manufacturing

AAC-4/500, simply referred to here after as AAC is an autoclaved aerated concrete manufactured by the Xella/Hebel company. AAC has a density of 500 kg/m³ and a CTE of 8.1×10^{-6} m/m/°C. An optical micrograph of AAC is given in Figure 4-2. The aggregate constituents of the solid material are clearly visible. The large variation in pore size is also evident. AAC is produced from abundant, natural materials including Portland cement, lime, water, sand gypsum, and aluminum paste. AAC is comprised of a typical aggregate microstructure observed in concrete. In addition to reduction in density due to porosity, chemical composition of AAC has been altered to increase machinability. AAC is light and brittle making transportation/handling challenging and difficult to avoid damage.

CB1100 is a low density open cell alumina based ceramic manufactured by the Advanced Composites Group®, and specifically engineered as a tooling substrate material. It is supplied in

block form and available in various sizes. An optical micrograph of CB1100 is given in Figure 4-1. Reflective surfaces in Figure 4-1a show the cross-sectional regions of the solid ligaments. CB1100 has high temperature capabilities and is thermally stable up to 1000°C. With a low CTE of $2.3 \times 10^{-6} \text{m/m/}^{\circ}\text{C}$ it is also capable of curing accurate parts using high temperature cure cycles.

The final material under investigation is a carbon foam product marked under the trade name Cfoam and manufactured by the Touchstone Research Laboratory. It is available in different block sizes that may be bonded together using standard thermoset resins to form larger workpieces. Optical micrographs of Cfoam are given in Figure 4-3. The large irregularly shaped pores and solid ligaments are clear and visible. Cfoam has a low CTE of $5.0 \times 10^{-6} \text{m/m/}^{\circ}\text{C}$ and is the lowest density of the tested materials. Cfoam is non-graphitic carbon foam which is characterized by highly amorphous crystal micro-structure. It should be noted that safety concerns exist regarding carbon dust which poses acute health and safety hazards.

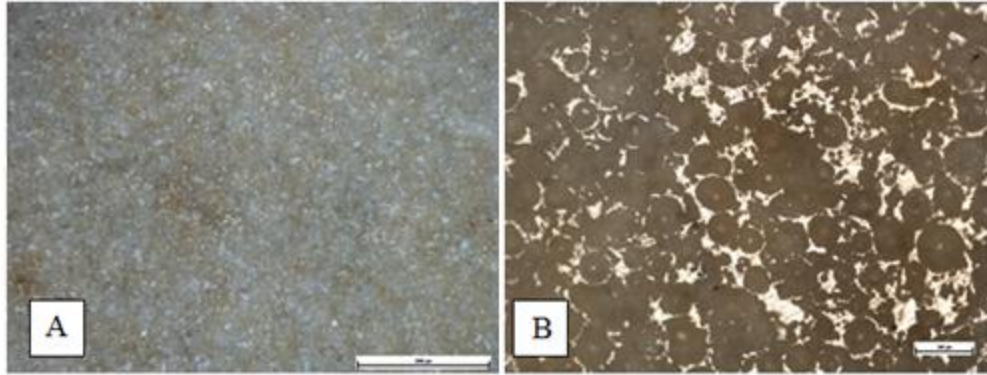


Figure 4-1: Low and High magnification of polished CB1100.

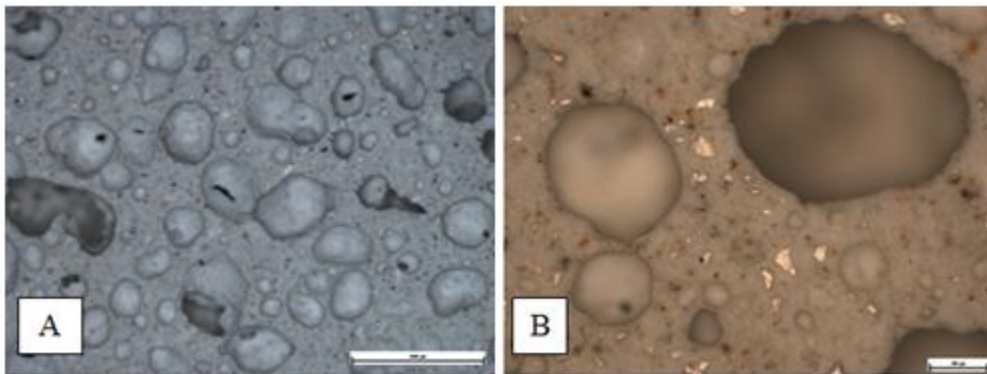


Figure 4-2: Low and High magnification of polished AAC.

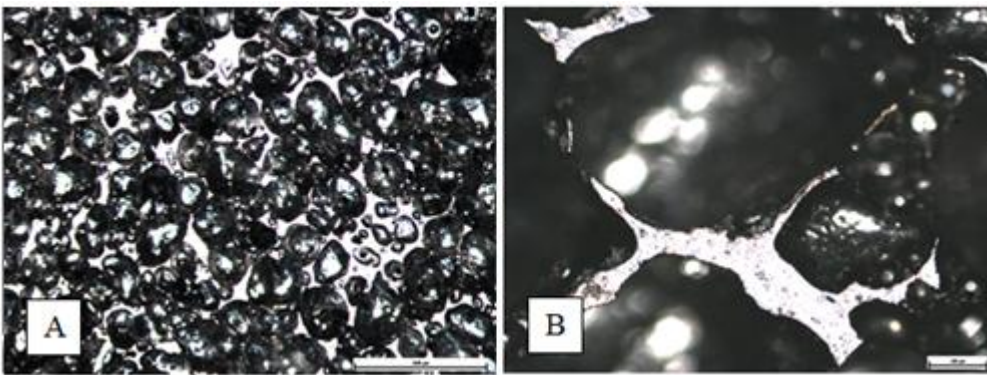


Figure 4-3: Low and High magnification of polished Cfoam.

The distribution and size of pores in each material affects mechanical, physical, and thermal properties thus greatly influencing the materials' machinability. SEM images of the three material systems are shown in Figure 4-4. CB1100 contains the smallest pores with an average diameter of approximately 100 μm and ranging from 50 – 200 μm . The shape of the pores in

CB1100 can be characterized the most spherical of the three investigated. AAC contains the largest variance in pore diameter with pores as small as 50 μm and as large as 3-4 mm intermittently. Mean pore diameter is approximately 1.8 mm AAC also has highly spherically shaped pores. However, there is an atypical tendency for adjacent pores to conjoin into ellipsoids. Cfoam has an average pore diameter of 800 μm , with pores ranging from 50-2000 μm . Cfoam has the most irregularly shaped pores which can be described as randomly distorted ellipsoids.

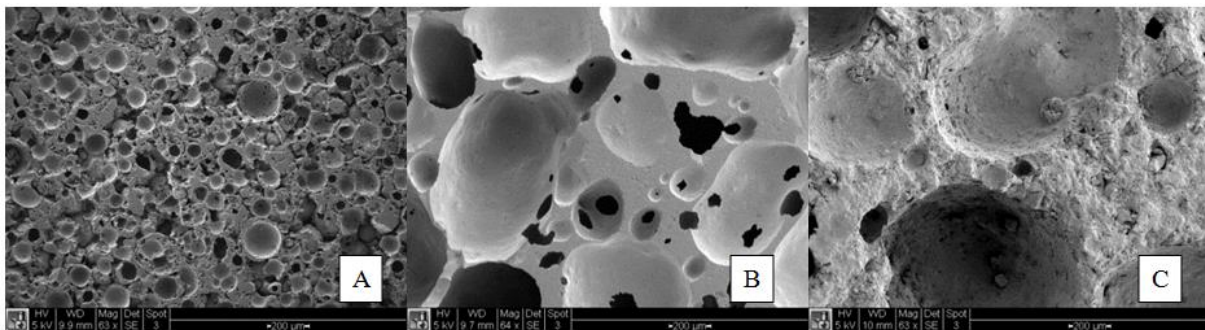


Figure 4-4: SEM Images of polished material samples: (a) CB1100 (b) Cfoam (c) AAC.

The density of the pores contained throughout each material has a significant effect on mechanical and thermal properties. CB1100 has a high pore density and combined with the small size of its pores, and has the highest bulk density at 1100 kg/m^3 . Cfoam also has a high pore density, but nevertheless, the large pore size gives Cfoam the lowest bulk density of the three materials at 320 Kg/m^3 . AAC has a comparatively low pore density but has large pores. This gives AAC a bulk density in between that of Cfoam and CB1100, 449 – 545 Kg/m^3 . Not all the properties are published by all the manufactures. Available properties provided from the manufacturer's literature for the tooling substrate materials evaluated in this study are listed in Table 4-1.

Table 4-1: Reported material properties.

Property	AAC	CB1100	Cfoam®
Density	449 – 545 Kg/m ³	1100 kg/m ³	320 Kg/m ³
Compressive Strength, Modulus	n/a, n/a	32 MPa, n/a	8.3 MPa, n/a
Tensile Strength, Modulus	n/a, 2040 Mpa	n/a , n/a	n/a, 500 MPa
Coefficient of Thermal Expansion	8.1x10 ⁻⁶ /°C	< 2.3x10 ⁻⁶ /°C	5x10 ⁻⁶ /°C
Thermal Conductivity	n/a	0.69 (RT) W/m K	0.25 – 25.0 W/m K
Flexural Strength, Modulus	n/a	5.6 MPa, 2.8 GPa	n/a

While the strength and durability of a potential tooling material is important it comes with certain compromises. CB1100 is the strongest and most durable of the materials tested. Higher strength is combined with higher density. This increased mass not only leads to a heavier physical weight, but also to an increase in the total thermal mass of the tool. Furthermore, the low thermal conductivity and large thermal mass can lead to non-uniform temperatures in the tool and damage the part or the tool itself. Slow and gradual heating cycles are often employed to compensate, but are not time or cost efficient.

4.2 CB1100 Microstructure

SEM images of polished samples of CB1100 are shown in Figure 4-5. Pores are highly spherical in shape and rarely conjoin to form ellipsoids. Cell walls are relatively thick and estimated to be in the range of up to 5-10 µm in thickness. The composition of CB1100 is a combination of alumina and silica. The Energy Dispersive Spectroscopy (EDS) spectrum of the overall material is given in Figure 4-6. The major constituents in the elemental composition are 47.6% Oxygen, 21% Silicone, 18.5% Aluminum, and 7.3% Carbon by weight.

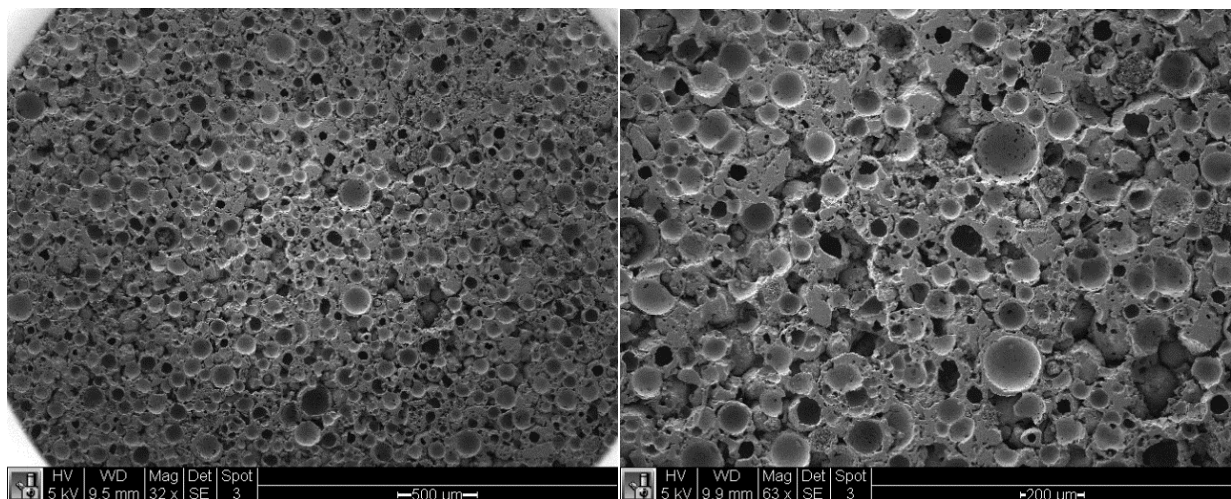


Figure 4-5: SEM images of polished CB1100.

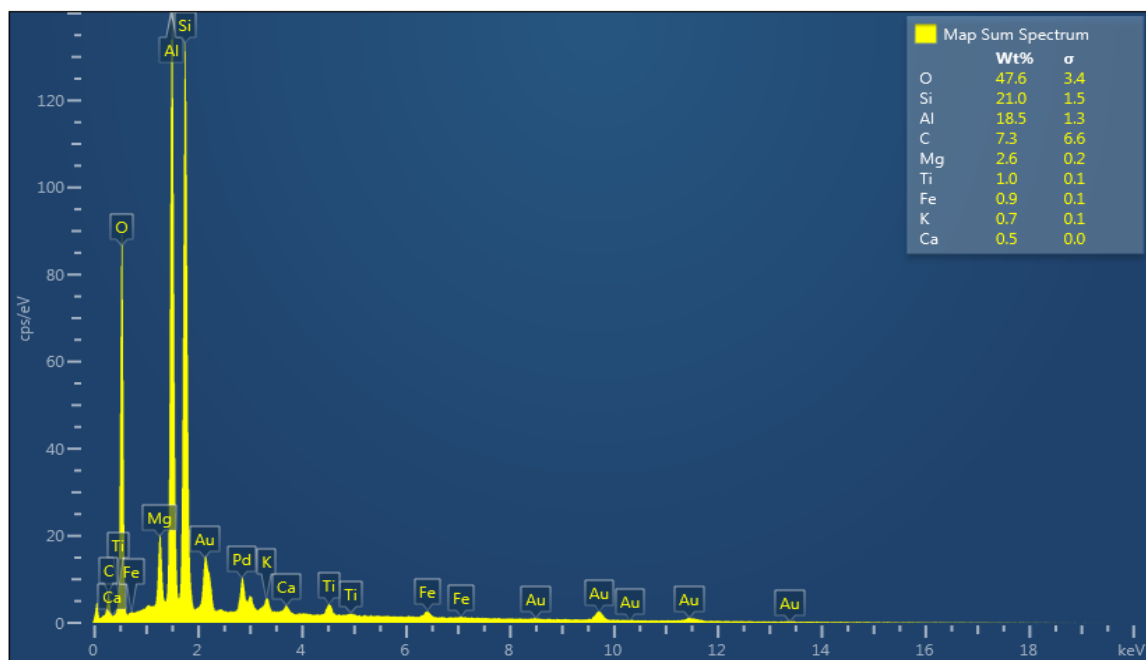


Figure 4-6: EDS spectrum of CB1100.

Multiple distinct microstructures which vary in composition have been observed under SEM and EDS investigations of CB1100. Results of the EDS analysis of these structures reveal an inhomogeneous composition and are shown in Figure 4-7.

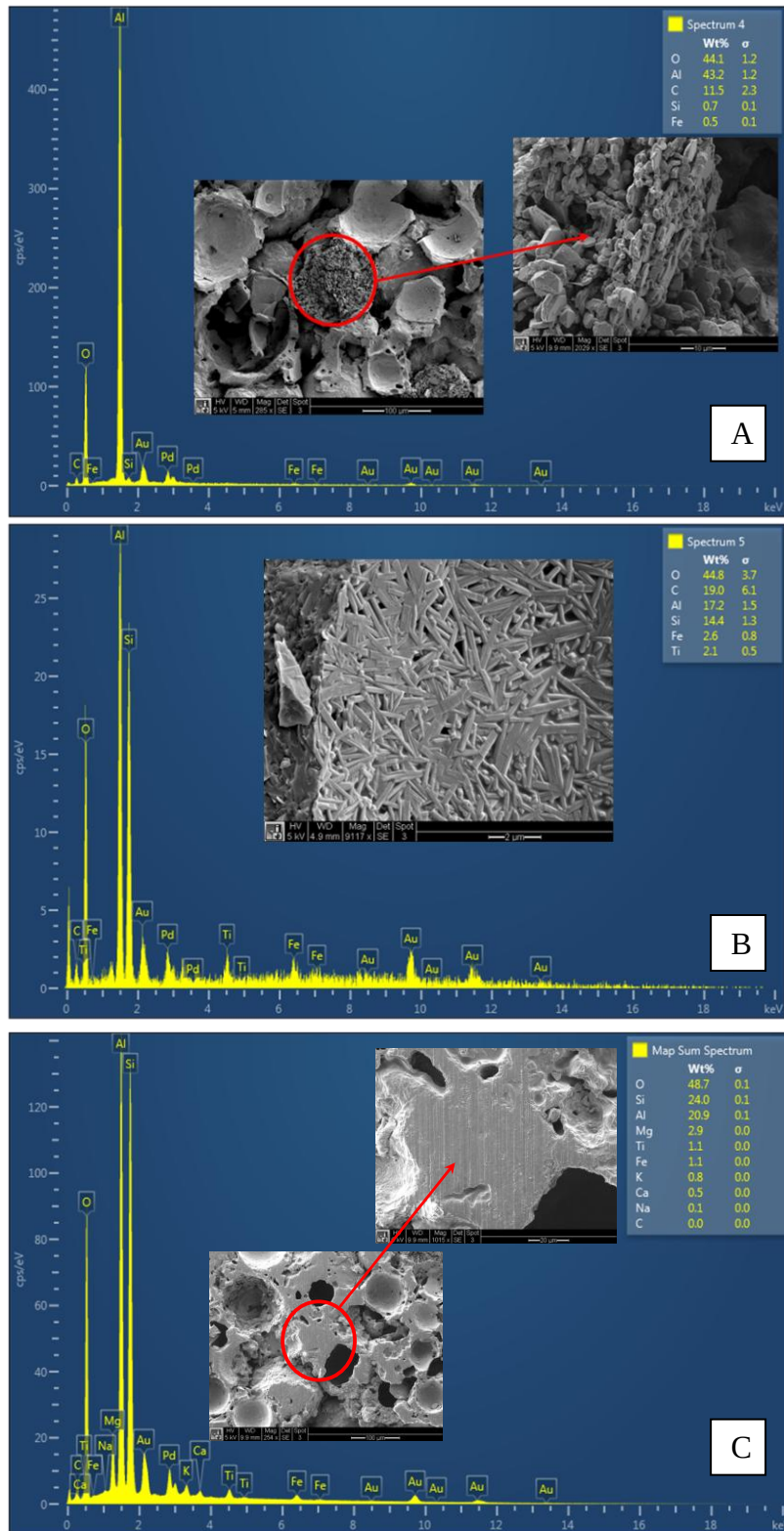


Figure 4-7: a) EDS spectrum and SEM image of granular alumina microstructure. b) EDS spectrum and SEM image of fiber like cell wall microstructure. c) EDS spectrum and SEM images of CB1100 ligaments

Regions like the one highlighted in Figure 4-7a have a rugged and random granular structure and their composition is dominated by alumina. Silicon is nearly absent. Conversely, in regions like the one shown in Figure 4-7b there is a high percentage of silicon. In these regions short randomly oriented fiber like structures exist in high density. This structure is predominantly present in cell walls and less frequently observed in ligaments. Ligament structures are more homogeneous in their composition and closely match the overall spectrum of the material, Figure 4-7c.

4.3 AAC Microstructure

AAC is manufactured using a steam curing process. Raw materials consisting of cement, lime, gypsum, fine siliceous materials and aluminum powder are mixed with water and cured. The aluminum powders cause a chemical reaction which results in the expansion of the material to approximately twice its original volume, creating the highly porous structure of AAC. SEM images of the typical microstructure found in AAC are shown in Figure 4-8. AAC is estimated to be comprised of approximately 80% pores by volume, 50% large pores and 30% micro-pores. Micro-pores are present throughout the material in both ligaments and cell walls. The solid constituent of AAC is mainly comprised of microcrystalline platelets of tobermorite, which forms the cells walls and ligaments.

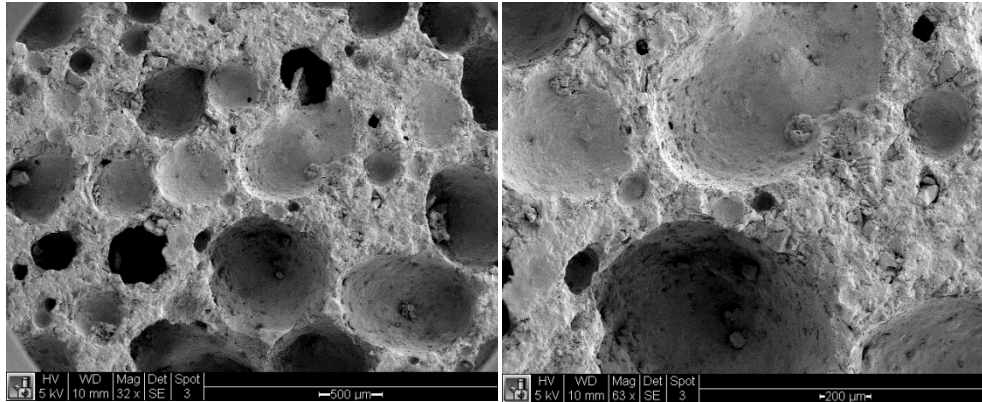


Figure 4-8: SEM images of AAC microstructure.

The chemical composition of the samples tested is shown in the EDS spectrum shown in Figure 4-9. The elemental composition is listed in Table 4-2. Main element in the composition both by concentration and by weight (%wt) is iron. Chromium is the second highest by %wt and third by apparent concentration.

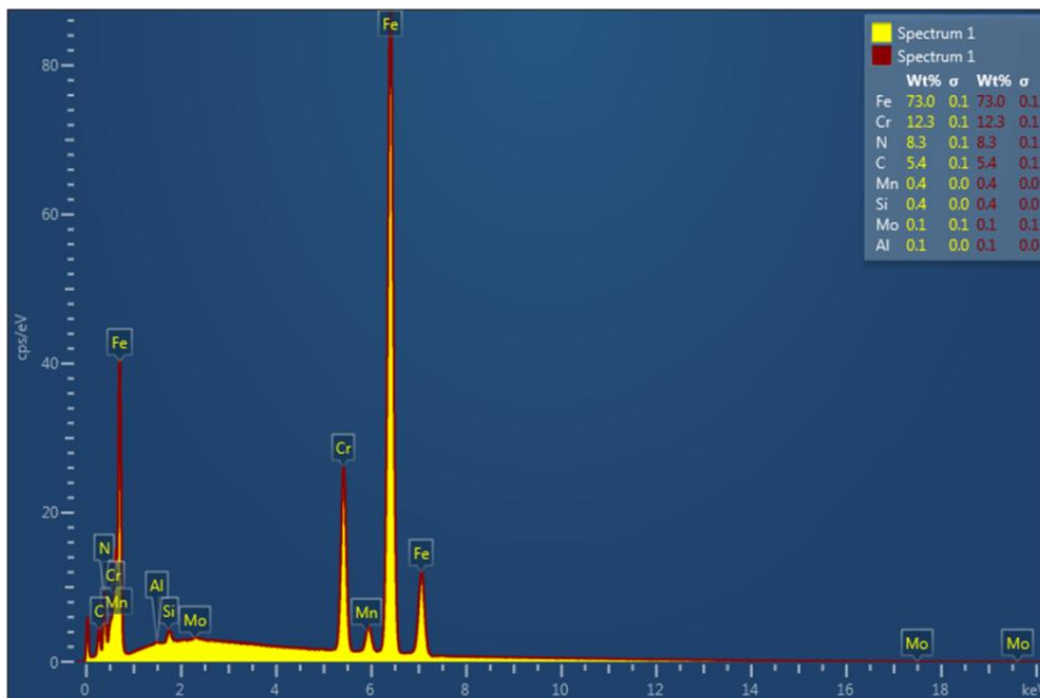


Figure 4-9: EDS spectrum of AAC.

Table 4-2: Elemental composition of AAC.

Element	Apparent Concentration	Wt%	Standard Label
C	0.98	5.37	C Vit
N	11.91	8.35	BN
Al	0.04	0.08	Al ₂ O ₃
Si	0.22	0.38	SiO ₂
Cr	11.78	12.28	Cr
Mn	0.31	0.39	Mn
Fe	58.45	73.00	Fe
Mo	0.10	0.15	Mo

As with any porous material, the properties of AAC can vary depending upon the density. Density of AAC may also vary significantly within the sample. Because the aeration occurs as a result of a chemical reaction the porosity and uniformity is difficult to control. Many mechanical and thermal properties are key in determining the machinability and behavior of the material during machining. Three properties which are important to machinability and the mechanics of cutting are elastic modulus, compressive strength, and fracture toughness.

As the density increases, the modulus, compressive strength, and fracture toughness all increase. Density is a function of the pore size and distribution. As density increases the pore size decreases. During machining this leads to an increase in theoretical contact area between the cutting edge and the material. Therefore, with an increase in material density there is an increase not only an increase in strength of the material but also the theoretical contact area between the cutting edge and material.

4.4 Cfoam Microstructure

Figure 4-10 shows an SEM images of the typical microstructure of the as received low density carbon foam supplied by Touchstone Research Laboratory Ltd. Closely packed large pores are shown as well as fractured ligaments and cell walls. Average shape of the pores ranges from spherical to ellipsoids. Thin ligaments exist between cells. Ligaments are the load carrying

member of the structure. The cell walls are not capable of supporting any significant load due to the low wall thickness. Smaller pores exist periodically within the ligaments as well. Smaller pores occur mostly in between intersections of several large pores.

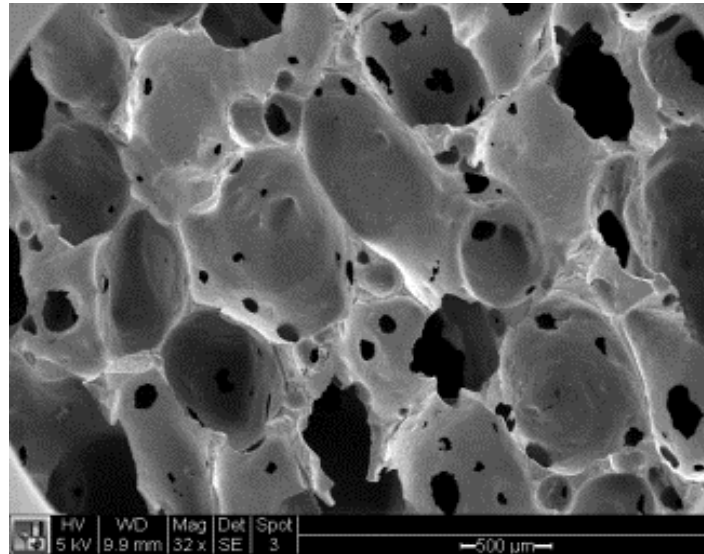


Figure 4-10: Typical SEM photomicrograph of as received Cfoam.

4.5 Experimental Feasibility Investigation

Although much of the equipment used during the feasibility investigation and experimental optimization portions of the study are the same, procedures and design of experiments differ. The following sections will describe the methods and procedures used to evaluate the three candidate materials during the feasibility investigation. The sample preparation, cutting tools, equipment, procedures and analysis methods will be discussed. The methodology used in the experimental optimization study will be discussed in Section 4.3.

4.5.1 Machining System

All experimentation was carried out using a Haas Automation TM1P milling machine. Table 4-3 lists the specifications of the milling machine used in this study. For the cutting force measurement study during the feasibility investigations the milling machining was equipped with a Kistler Instruments Type 9123C rotating dynamometer, shown in Figure 4-11. The 9123C dynamometer is capable of direct measurement of all four components of cutting forces: F_x , F_y , F_z , and M_z . Where, F_x , F_y and F_z are force in the X, Y, and Z axis respectively, and M_z is the applied torque. Figure 4-11 illustrates the relationship of these forces to one another and their relationship to tangential and radial cutting forces. Tangential and radial cutting force, the true forces of interest in this study, are calculated from the measured values of F_x , F_y , and M_z .

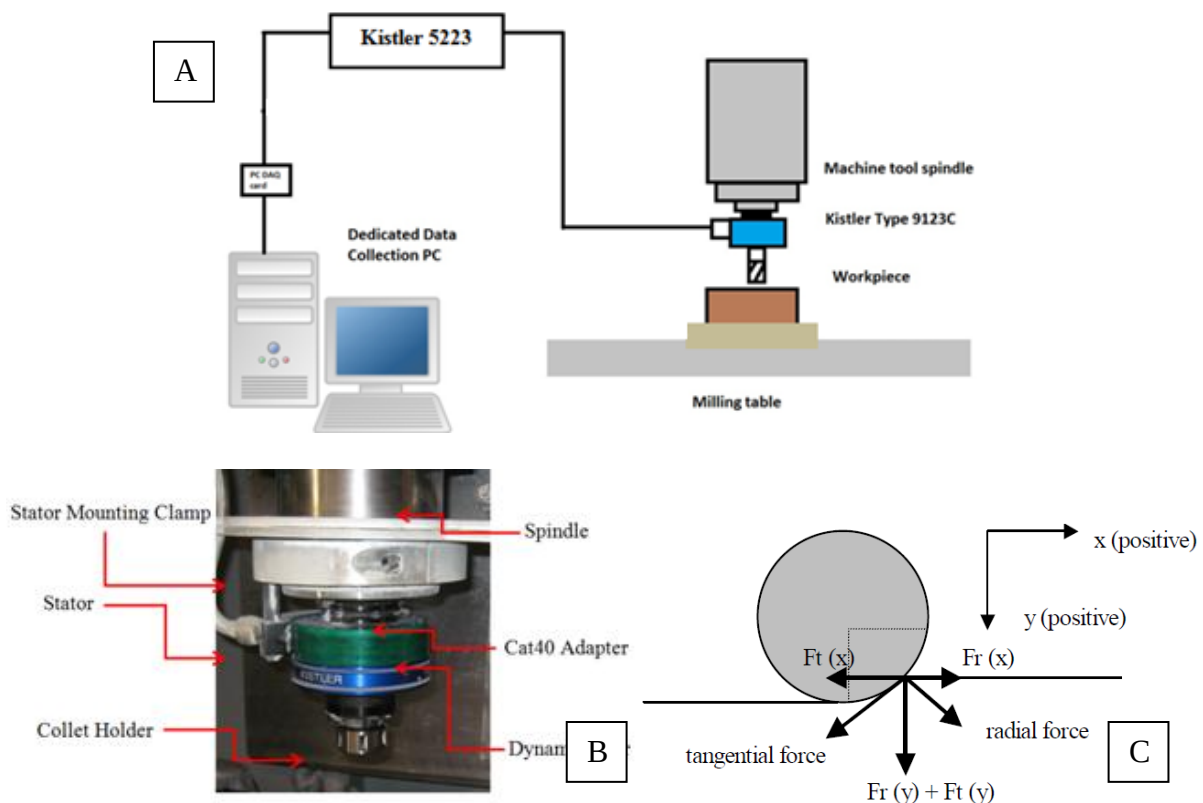


Figure 4-11: A) Schematic diagram of force measurement system B) 9123C Rotating Dynamometer C) Schematic diagram of cutting forces during milling.

Table 4-3: Haas Automation TM1P milling machining specifications.

Tool Holder Interface	40	n/a
Maximum Speed	6000	rpm
Maximum Torque	44.74 @1200 rpm	N-m
Spindle Power	5.6	kw
Maximum Thrust Force(Z)	8900	N
Maximum Feedrate	10.16	m/min
Accuracy	.01	mm
Repeatability	.005	mm

Signals are transmitted across the air gap from the dynamometer to a stationary stator, visible as the black semi-circular collar to the left of the unit in Figure 4-11. The 9123C is capable of outputting a singular synchronizing event per revolution on a dedicated channel. A dedicated synchronization channel allows direct correlation of rotational position to measured data. Signals were processed using a Kistler Instruments Type5223 signal conditioning system. Data was collected using a Data Acquisition (DAQ) card installed in a dedicated PC. Data post processing was carried out using Kistler Instruments' DynoWare® software, which allowed for simple filtration and manipulation of the data signal quickly and easily. The Type9123C is a rotating dynamometer which means the coordinate system of the dynamometer is not related to the static coordinate system of the milling machine. Therefore, F_x and F_y vary with rotation. This causes an oscillatory signal for measured values of F_x and F_y . Calibration of the dynamometer and special considerations for the tooling used are discussed in the Appendix A. Experiments were conducted within a dust enclosure contained within the milling machine in order to protect the milling machine from hazardous dust created during cutting, Figure 4-12. Further discussion and description of the dust enclosure are given in Appendix B.

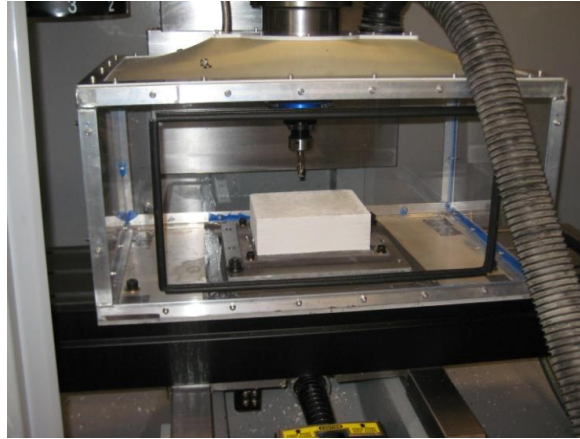


Figure 4-12: Dust Enclosure and Sample Platen.

4.5.2 Cutting Tools

Three types of cutting tools were selected for evaluation: HSS, PCD and diamond abrasive cutters and are shown in Figure 4-13. Tool wear studies were conducted using HSS cutting tools, Figure 4-13a, in order to provide a benchmark cutting tool material common in industry. Diamond abrasive tools such as the one shown in Figure 4-13c were selected due to the common usage for composite edge trimming as well as being a manufacturer suggested tool for the machining of Cfoam. PCD is commonly used in the aerospace industry for the machining of composites. The PCD cutter used in the feasibility investigation is shown in Figure 4-13. PCD and other diamond based tooling are used in applications requiring high abrasion resistance which may prove beneficial in the materials studied in this research.

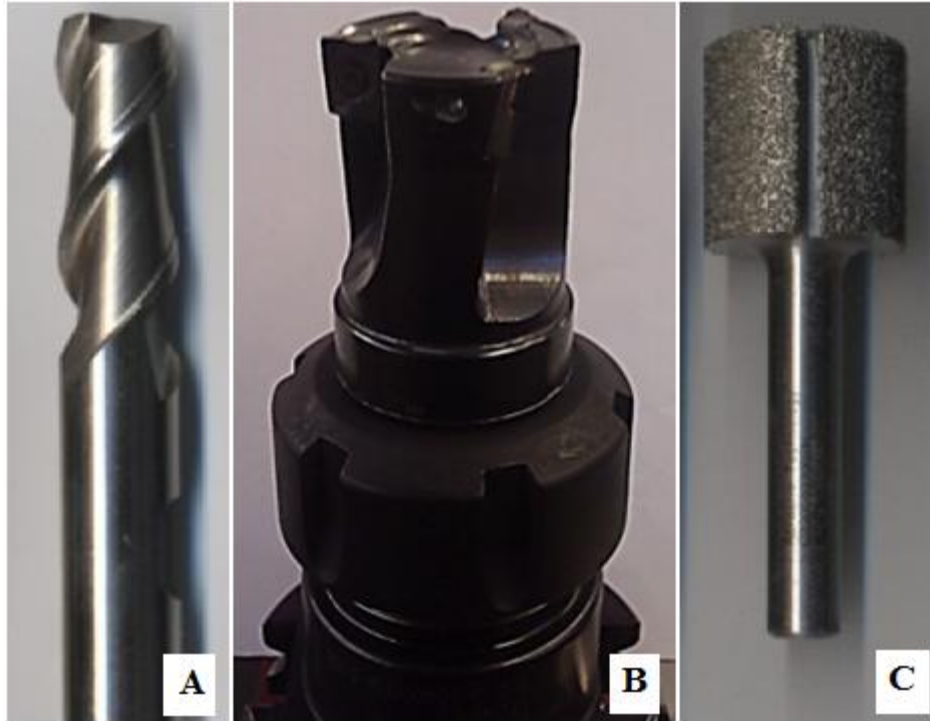


Figure 4-13: Cutting tools used during the feasibility experimental feasibility investigation: a.) 2 flute HSS endmill, b.) 3 flute PCD inserted endmill, c.) diamond abrasive cutter

Obtaining cutting velocities in the upper range of the material's manufacturer's suggested values would require tooling with a diameter greater than 25 mm given the RPM limitation of the machining system employed. The selected dynamometer system was only capable of holding tooling with a maximum shank size of 15.88 mm. Further complicating the issue, PCD tooling is not readily available in cutting diameters of the required size. Therefore, indexable tooling using PCD tipped inserts was selected. These inserts have a limited depth of cut of 3.18 mm. PCD cutting edges are brazed onto a carbide substrate. The insert holder was manufactured by Sandvik Coromant®, part number: RA390-032M32 – 11M. The tool body's shank was then machined down to 15.88 mm so that it could be held by the dynamometer collect system.

The second primary cutting tool type was diamond abrasive based tools. Two diameters were selected: 15.88 mm and 25.40 mm. Cutting tools of this type are most often used for machining composites, ceramics, and natural rock materials as well as concrete and are often

referred to as *diamond abrasive routers*. Unlike HSS and PCD, diamond abrasive type cutting tools do not use defined cutting edge geometry. Cutting edges are randomly oriented facets of granular abrasive particles bonded to a tool's shank.

4.5.3 Sample Preparation

Samples were cut from parent material blocks using a high pressure abrasive water jet. Sample sizes varied from 127x127x75 mm to 152x203x102 mm, Figure 4-14. Sample blocks were then bonded to a steel platen using a high strength epoxy. Platens served two purposes. The primary need was a low profile, reliable method of holding the samples. A low profile was an important consideration due to space constraints within the machine and dust enclosure used during the study. The second purpose was to overcome the difficulty found during securing the weak materials during machining. Materials often fracture if clamped. Platens were cleaned and sandblasted before each new sample was bonded. The platen and bonded sample was then bolted to an adapter plate mounted to the table of the milling machine.



Figure 4-14: CB1100 Sample Blocks.

Samples were then face milled using a cutter identical to the one utilized during the preceding test to ensure constant axial depths of cut would result during testing and no

irregularities would be induced by using a different tool to face the material. The sample and enclosure were then cleared of dust using compressed air.

4.5.4 Cutting Force Measurement

Samples were bonded to a clean platen, using high strength epoxy, and allowed to cure for a minimum of 24 hours. Samples were bolted to the adapter plate inside of the dust enclosure. The DynoWare software, data acquisition train, and spindle were then started and allowed to run through a *warm up* cycle to heat the bearings and lubrication system. The dynamometer was zeroed using the Type 5223 signal conditioning box. The dynamometer must be zeroed while the spindle is stationary but rotating at speed, otherwise subsequent measurements may be inaccurate. Each cutting test consisted of at least 2-3 passes through the sample. Cutting forces were recorded for each pass. Multiple data points could thus be rapidly collected with a single test program. An illustrated example of the cutting force measurement approach is given in Figure 4-15. Once the program was complete, the process was repeated and the program modified for the next set of cutting conditions. These tests were performed in the following three stages:

- a. Variation of depth of cut
- b. Variation of feed rate
- c. Variation of cutting speed

A test matrix of the range of cutting conditions selected is given in Table 4-4. Speeds of 5000, 5500 and 6000rpm were selected to stay within a close margin of the manufacture suggested cutting velocities. Axial depth of cut was varied from 3.18mm up to the maximum achievable depth of the tool being tested in increments of 3.18mm. Radial depth of cut was held

constant at 11.11mm for all cutters. A single radial depth of cut selected to reduce the number of required tests during the feasibility investigation.

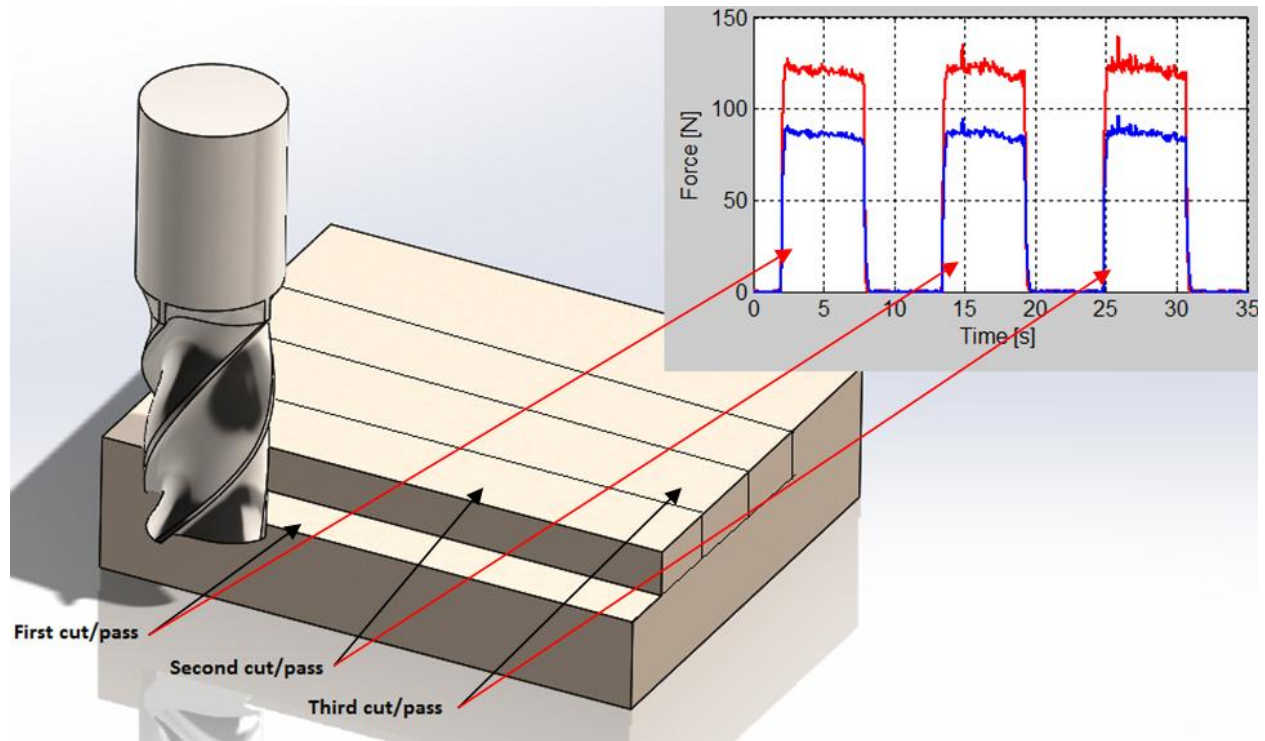


Figure 4-15: Illustrated test sample and tool path for cutting force measurement program

Table 4-4: Cutting condition test matrix

	Speeds [rpm]:	Feeds [m/min]:	Axial Depth of Cut [mm]:	Radial Depth of Cut [mm]:
Minimum	5000	0.254	3.18	11.11
Maximum	6000	10.16	25.40	11.11
Typical Increment	500	0.254	3.18	n/a

4.5.5 Tool Wear Measurement

The tool wear study was the final portion of the machining study performed that involved the machining and force measurement system. Tool wear studies were performed using HSS tooling in order to illustrate the tool wear growth. Identical samples to those used during the force study were bonded to platens and mounted in the milling machine as described previously.

The spindle was started and allowed to run through a *warm up* period to allow the milling machine to reach operational temperature. The dust enclosure was then sealed and the dust evacuation system started. The dynamometer was re-zeroed before the test was initiated. The CNC program used during the cutting test was retained for the tool wear study as well. However, in between each test cut, the program was paused and the tool was removed and cleaned in order to photograph and document the progression of the damage. In the case of diamond abrasive cutting tools, only light compressed air was used to clean the cutting tool in order to retain and document the clogging of material on the tool. The tool was then replaced in the milling machine and the program continued. The process was repeated for a total of 7 test cuts.

4.5.6 Surface Topography Studies

The surface profilometry measurements were carried out using a MahrSurf® XR20 table top surface profilometer, shown in Figure 4-16. Large sample blocks of 127 x 75 x 457 mm were cut using an abrasive water jet. Test surfaces were machined using a range of cutting conditions for each tool. After each cut, the surface was cleaned and labeled. Once all cuts were complete the block was cleaned using compressed air to force any embedded dust on the surface off. The surfaces were then investigated for any irregularities or damage. If a defect was found it was marked and noted. Each machined surface was tested in two separate locations labeled as location A and B. Where location A is the located toward the entrance side of the cut and B was later in the cut. Each location was tested using 4 separate traverses in the following sequence: In-feed direction, transverse to feed, 45 degree, and negative forty five degrees. A cutoff length of 0.80 mm was used with a total traverse length of 5.60 mm.



Figure 4-16: MahrSurf XR20 Surface Profilometer

4.5.7 Optical and Scanning Electron Microscopy Examination

Following surface profilometry, optical and scanning electron microscopy examinations of all three materials were performed. The optical study was carried out using a Micro-Vu Sol optical measurement system. Samples were wet sanded using 1200 grit sandpaper. Once samples were sanded they were dried using isopropyl alcohol and compressed air. A second phase of the optical examination portion of the study was then performed utilizing a stereo microscope in order to utilize a lower magnification due to the large size of the surface features found in the Cfoam. Samples were then mounted and sputter coated with gold for 90 seconds in preparation for the subsequent SEM studies.

4.6 Experimental Optimization Study

The following sections will describe the equipment and methodology used during the optimization study portion of the research. The experimental optimization stage will include a more in-depth study of the cutting forces over the range of parameters identified during the feasibility investigation. The methods used to analyze results from the cutting force, surface topography and surface integrity experiments are also provided.

4.6.1 Machining System

Machining tests were conducted using the same Haas TM1p vertical milling machine used during the feasibility investigations. However, a Kistler type 9257b three component plate dynamometer was used. The experimental setup is shown in Figure 4-17. The 9257b dynamometer was mounted into a Kurt machine vise located in the center of the milling table. Sample platens were loaded onto the dynamometer and secured with a fastener on either end. A Kistler 5070A signal conditioning box was used to amplify the dynamometer signal and send the output to the data acquisition system which was based on a PCI data acquisition card and Kistler DynoWare software.

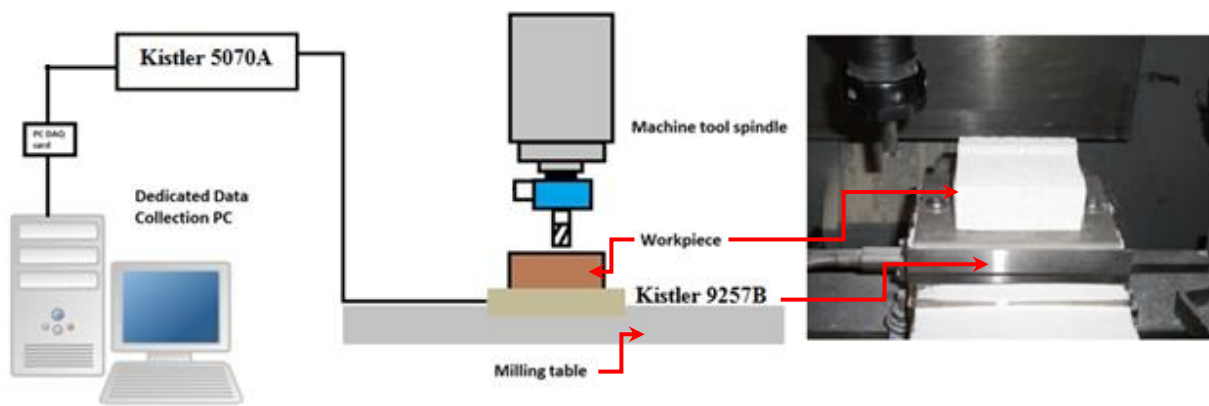


Figure 4-17: Schematic layout of cutting force measurement system.

4.6.2 Surface topography

Surface profilometry was conducted in order to determine the generated surface topography and quality. Samples of each material were machined using diamond abrasive and PCD cutting tools. Surface roughness profiles were recorded from the CB1100 machined sample surfaces using a MahrSurf® XR20 surface profilometer with a probe stylus tip radius of 2 μ m and a cut-off length of 0.8 mm as per ANSI standards. The traverse length was 5.6 mm. Surface

profilometry was not possible for Cfoam or AAC due to likely damage of the measurement probe which would result.

4.6.3 Microscopy

Several optical techniques and apparatus were used during this research. Scanning electron microscopy studies were carried out on a DEI Sirion scanning electron microscope equipped with an Oxford Energy Dispersion Spectrometer (EDS) system, Figure 4-18a. Optical microscopy studies were performed using one or more of the following systems. For low magnification large focal depth images a Micro-Vu Sol toolmakers microscope, shown in Figure 4-18b, was used. To capture low and medium magnification images when a large viewing area was required a Nikon SMZ1000 stereo microscope shown in Figure 4-18d was used. High magnification optical images were captured using a Nikon Eclipse LV150 microscope shown in Figure 4-18c. Both Nikon microscopes also employed the NIS-Elements software package for image capture and adjustment.

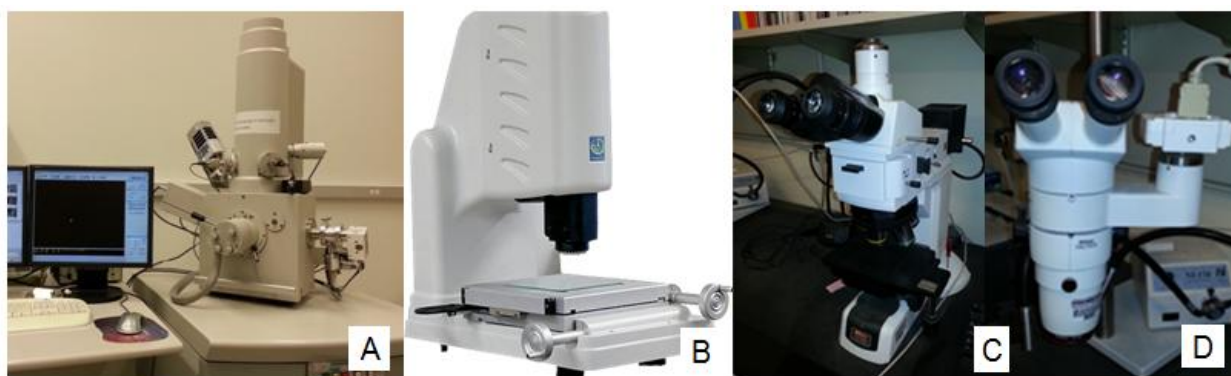


Figure 4-18: A) Sirion SEM and Oxford EDS system B) Micro-Vu® Sol microscope C) Nikon Eclipse LV150 D) Nikon SMZ1000.

4.6.4 Mechanical Testing

Mechanical testing involved a four-point bend experiment carried out on an Instron 5585h series floor model testing system, Figure 4-19. A custom built adjustable four-point bend fixture was also used. The support span was set to 80.0 mm with a loading span of 40.0 mm. The test was performed under displacement control at a rate of 0.5 mm/min.

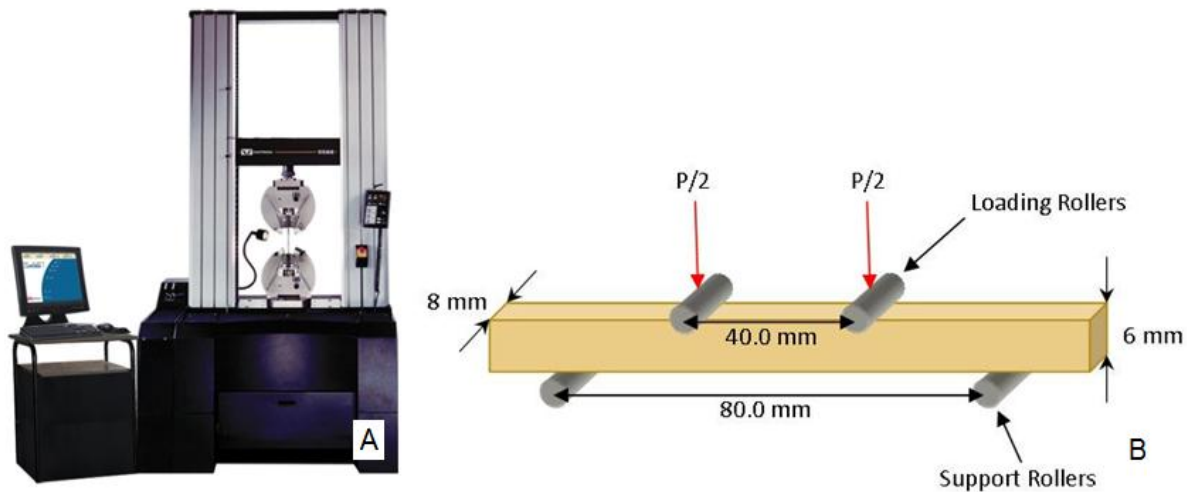


Figure 4-19: (a) Instron 5585h testing machine and (b) Four-point bend test fixture and sample schematic.

4.6.5 Optimization Study Procedure

Procedures and samples used during the optimization study stage of the research differ from those used in the feasibility study. The procedure used during the optimization study stage of the research is presented in the following sections including those used during the mechanical testing of machined surface integrity which was not conducted during the feasibility investigation. Design of experiments and experimental test matrixes are presented. Further, the methods of analysis for each experiment are also described.

4.6.5.1 Cutting Force Study

Specimens used during the cutting force study were cut from parent blocks of CB1100 using a bandsaw. The samples measured approximately 100(l) x 75(w) x 50(h) mm. Samples were then bonded to mounting plates using Crystalbond® 509. The sample and plate were then bolted directly to the dynamometer using two fasteners. In order to ensure a uniform axial depth of cut for all subsequent cuts performed, the sample was then face machined across the whole surface. Similarly the front surface was peripherally milled to ensure a constant radial depth of cut across the entire path. Care was taken to ensure that no damage would be induced that could affect the results or cutting forces of subsequent cuts. Once the specimen was mounted and squared, the first test cuts could be performed. The data acquisition system was then powered on and software initiated. The appropriate data and measurement ranges were selected. If the spindle had been idle for a long period of time a warm up program was then run. The spindle was then brought to the desired RPM and the data acquisition system was zeroed. The test was then carried out. A program was written to cut a single path at the defined cutting speed and feed then pause allowing the data acquisition system to be reset and data files renamed. The program would then repeat two more times, indexing the defined radial depth over each path. A distance of 6.0 mm or more was left on toward the rear of the sample in order ensure that any thin section breakouts were avoided that could cause a loss of useful data. Once the radial step-over began to near the rear edge, the surface was again face machined and the axial depth of cut was reset off of the new surface. This process continued until the sample did not have enough material remaining to continue machining. The sample was the replaced and the process repeated until all cutting tests had been conducted.

Table 4-5: Cutting force experimental test matrix

Factor	Levels	Units
Speed (A)	4000, 5000, 6000	RPM
Feed (B)	2.54, 5.08, 10.16	m/min
Axial Depth of Cut (C)	3.18, 6.35	mm
Radial Depth of Cut (D)	3.18, 6.35	mm

The experimental test matrix is given in Table 4-5. Following a full factorial DOE, four factors were selected: speed, feed, axial depth of cut, and radial depth of cut. Three levels of speed and feed were employed. Speeds of 4000, 5000, and 6000 rpm were selected. Feeds of 2.54, 5.08, and 10.16 m/min were also selected. Axial and radial depths of cut were varied in two levels: 3.18 and 6.35 mm. Two responses were selected: tangential cutting force (F_t) and radial cutting force (F_r). Three repeats of each combination of cutting condition were performed leading to a total of 108 cuts for the experiment.

4.6.5.2 Surface Topography and Quality

Surface topography samples were prepared similarly to the cutting force samples by first cutting the block from the larger as received parent block using a bandsaw. Samples were then bonded to the same mounting platens used during the cutting force experiments by applying Crystalbond® 509. Samples were machined in levels starting from the top down. The lighter cuts were performed first. High cutting force cuts were restricted to the bottom of the sample and performed last. This minimized the effect of the damage the larger cutting forces induced on the machining and surface quality of cut subsequent cuts. The sample machined and studied during the surface topography study is shown in Figure 4-20.

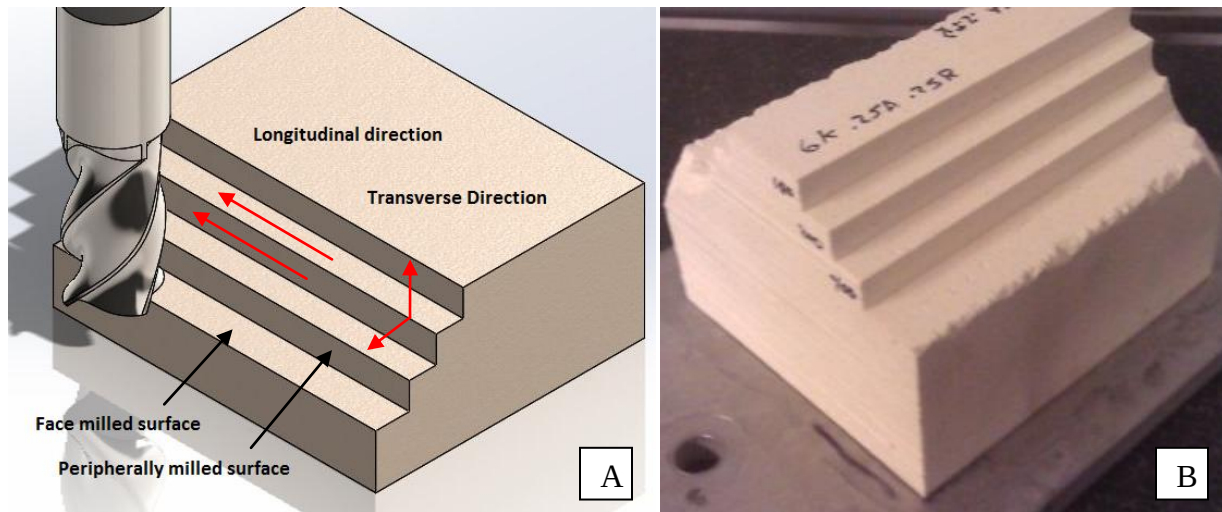


Figure 4-20: (a) Schematic of surface topography sample and measurement directions (b) Image of CB1100 surface topography sample.

Each step in the sample shown above was machined using different cutting conditions. Speeds of 4000, 5000, and 6000 RPM were selected. Feed rates of 2.54, 5.04, and 10.16 m/min were utilized at each speed. Radial and axial depths of cut were held constant at 6.35mm each. The test matrix is given in Table 4-6.

Table 4-6: Surface topography experimental test matrix.

Factor	Levels	Units
Speed	4000, 5000, 6000	RPM
Feed	2.54, 5.08, 10.16	m/min
Axial Depth of Cut	6.35	mm
Radial Depth of Cut	6.35	mm
Measurement Location	Entry, Center, Exit	n/a

Once the sample was machined it was removed from the milling machine, cleaned using compressed air and placed on the MahrSurf® XR20 surface profilometer. The surface profilometer was recalibrated following each removal and re-installation of the probe. Once calibration was complete the test settings were entered into the measurement system. The probe was then set at the desired starting location and balanced. The trace was then performed and process repeated for all locations and directions.

A total of 18 machined surfaces were studied: 9 peripherally milled and 9 subsequently face milled. Surface roughness measurements in both longitudinal and transverse directions were taken at three different locations, Table 4-6. A total count of 108 surface roughness profiles was obtained. Average surface roughness, R_a ; maximum peak-to-valley height, R_t ; root mean square roughness, R_q ; and ten point average surface roughness, R_z were recorded and given designations according to the naming convention in Table 4-7. Table 4-7 lists the measured surface roughness parameters, their relative surface, and direction along with their assigned designations. Each of listed parameters in Table 4-7 has three separate locations associated with them for a total of 48 recorded values at each level of Speed/Feed.

Table 4-7: Measure surface roughness parameters and designations.

Parameter	Direction	Surface	Designation
Ra	Longitudinal	Peripherally milled	Ra Edge Long
Ra	Longitudinal	Face milled	Ra Face Long
Ra	Transverse	Peripherally milled	Ra Edge Trans
Ra	Transverse	Face milled	Ra Face Trans
Rq	Longitudinal	Peripherally milled	Rq Edge Long
Rq	Longitudinal	Face milled	Rq Face Long
Rq	Transverse	Peripherally milled	Rq Edge Trans
Rq	Transverse	Face milled	Rq Face Trans
Rz	Longitudinal	Peripherally milled	Rz Edge Long
Rz	Longitudinal	Face milled	Rz Face Long
Rz	Transverse	Peripherally milled	Rz Edge Trans
Rz	Transverse	Face milled	Rz Face Trans
Rt	Longitudinal	Peripherally milled	Rt Edge Long
Rt	Longitudinal	Face milled	Rt Face Long
Rt	Transverse	Peripherally milled	Rt Edge Trans
Rt	Transverse	Face milled	Rt Face Trans

Following surface profilometry the sample was studied using optical and SEM microscopy in order to identify and characterize the damage induced by machining on both macro and micro scales. Documented damage induced will later be correlated with the results of the surface integrity and mechanical testing evaluation.

4.6.5.3 Mechanical Testing/Surface Integrity

In order to determine the effects of machining induced damage on CB1100 ceramic a four point bend test utilizing machined samples to determine any change in residual flexural strength was performed. Based upon the cutting forces and the resulting surface quality, two different sets of machining conditions, one which represented the highest cutting forces/low quality and one representing the lowest cutting forces/high quality were selected in order to machine the specimens. These conditions represent a best and worst case scenario to exemplify any possible affects which may be induces during machining. Fourteen samples were machined at 6000 RPM and 2.54 m/min (low cutting force). Additionally, 14 samples were machined at 4000 RPM and 10.16 m/min (high cutting force), for a total of 28 specimens. These specimens were all machined to ASTM standard C1161. Specimens were machined to the following dimensions: 90.0 (l) x 8.0(w) x 6.0(h) mm. Samples were rough to oversized dimensions using a band saw. Oversized samples were then mounted in a custom modular mounting fixture built to facilitate machining. Care was taken during mounting to ensure no fracture, gouging, or damage was induced by the fixture that may affect the results of the experiment. The samples were then individually machined down to the required dimensions and tolerances. All surfaces of the specimens were machined using a peripheral milling. Samples were individually dimensioned in order to ensure conformity to the tolerances defined by ASTM C1161. Once samples were dimensioned and labeled, testing began.

Four point bend experiments were carried out in accordance with ASTM C1161. Support and loading spans were set to 80.0 and 40.0 mm, respectively. Once the spans were verified, specimens were loaded onto the support rollers. The loading rollers were then lowered until contact with the specimen was established. The load cell and displacements were the balanced

and zeroed. The specimen was then progressively loaded at a displacement rate of 0.5 mm/min until fracture occurred. Once the specimen failed, the data was saved and the fractured specimen pieces were paired and stored for later analysis.

4.6.5.4 Analysis of Cutting Forces

The first step in the cutting force analysis involved the transformation from the recorded Cartesian force components of F_x and F_y to tangential and radial forces F_t and F_r . The cutting tool selected throughout the experiment was a 12.70mm diameter 0° helix carbide end mill. The 0° helix facilitated the calculation of tangential and radial cutting forces. Transformation from F_x , F_y to F_t and F_r is dependent upon the cutter orientation angle, a 0° helix ensures that all of the cutting edge is at the same orientation angle. The total cutter engagement for each condition was calculated based upon the employed cutting parameters. This engagement was then used to determine the time period of the engagement. This periodic time function was then plotted along with the active cutting force.

In order to determine phase shift of the orientation angle relative to the cutting force, the periodic engagement plot was shifted in order to line up with the periodic nature of the active cutting force. This is assumed to give a cutter orientation which is correlated with the cutting forces within an acceptable degree of accuracy ($\pm 2^\circ$). From this correlated orientation F_t and F_r can be found using the transformation matrix given here:

$$\begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix} = \begin{bmatrix} \sin \phi & -\cos \phi & 0 \\ \cos \phi & \sin \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} F_t \\ F_r \\ F_{ax} \end{Bmatrix} \quad \text{Eq. (4.1)}$$

The maximum cutting force of five test cuts was determined and averaged for both F_t and F_r . The average value was used during the empirical modeling stage of the study using Design

Expert 8® software. Average peak cutting force also aided the analytical modeling stage of testing in determining cutting coefficients.

Following the determination of the average peak tangential and radial cutting forces an ANOVA was performed. A full quadratic model was assumed. Factorial and factorial interaction contributions were studied and non-influential terms were eliminated from the model. Non-influential terms were determined through the study of the p-values and F-values found using the Design Expert® 8 software package. The F-value is a test for comparing the model variance with the residual variance, or error, and is found by dividing model mean square by the residual mean square. The closer this ratio is to one the less likely the factor under question significant to the model. The greater the F-value is, the greater the probability that the factor has a significant influence of the response of the model. The p-value is the probability of obtaining the observed F-value if the null hypothesis is true (factor has no influence). If the probability is high the null hypothesis may be true. If the probability is low, the null hypothesis is rejected. As a general rule if the p-value is less than 0.05 the null hypothesis is rejected and the probability that the factor is influential on the response is high.

4.6.5.5 Analysis of Surface Roughness and Topography

The results of the surface roughness study were analyzed in much the same manner as the cutting forces. ANOVA analysis was performed using Design Expert 8 in order to model the surface roughness values of R_a , R_t , R_z and R_q . To begin, a full quadratic model was assumed. Factorial and factorial interactions were studied and non-influential terms were eliminated from the model. As in the cutting force analysis the non-influential terms were identified by the reported p-values and F-values.

Values obtained from surface profilometry were also normalized according to the cutting parameters used during machining based upon chipload. Chipload is defined as the maximum chip thickness of the cut, per tooth and normally expressed in units of mm/tooth. Chipload is a convenient factor to normalize these values due to the fact that it is directly related to cutting forces and the size and distribution of tool marks; both of which directly affect surface topography.

4.6.5.6 Analysis of Surface Integrity

The results of the surface integrity study were analyzed through studying the maximum flexural stress obtained during the four point bend tests. These flexural strengths were correlated with the surface roughness values obtained during the surface roughness study. This allowed the determination of the existence of a correlation between induced surface topography or damage and the residual flexural strength of the material. Furthermore, a Weibull analysis was performed in order to determine changes in the probability of failure due to changes in machining conditions. For the Weibull analysis the lowest possible failure stress was assumed to be zero. Therefore, the three parameter form of the Weibull distribution for fracture strength has the following form:

$$P(\sigma) = 1 - \exp \left[- \left(\frac{\sigma}{\sigma_0} \right)^m \right] \quad \text{Eq. (4.2)}$$

Where,

$P(\sigma)$ = probability of failure
 σ = observed fracture strength
 σ_0 = characteristic strength
 m = Weibull modulus

Using a double logarithmic transformation equation Eq. (4.2) can be linearized into the following form:

$$\ln\left(\frac{1}{1 - P(\sigma)}\right) = m \ln \sigma - m \ln \sigma_0 \quad \text{Eq. (4.3)}$$

Observed failure strengths are first ordered from lowest to highest and assigned an index, n , from $1 - N$ where N is the total number of samples. The probability of failure $P(\sigma)$ is determined from the ordered data using equation Eq. (4.4):

$$P(\sigma) = \frac{n}{N + 1} \quad \text{Eq. (4.4)}$$

The two Weibull parameters of m and σ_0 can then be determined by performing a linear regression on the plot of $P(\sigma)$ vs. $\ln(\sigma)$. The slope of the fitted line represents the modulus, m . The characteristic strength, σ_0 , can be determined from the intercept and equation Eq. (4.5).

$$\sigma_0 = \exp\left[-\left(\frac{\text{intercept}}{m}\right)\right] \quad \text{Eq. (4.5)}$$

From the calculated Weibull parameters the true probability of failure versus strength can now be plotted using Equation Eq. (4.2).

Chapter 5: Feasibility Study

A preliminary investigation of the end milling process in: Cfoam, AAC, and CB1100 was conducted. Each material offers a unique set of properties and challenges to machining. In this chapter, varying process parameters were used in conducting feasibility experiments. The purpose of the feasibility study was to provide insight into the cutting forces and other measured parameters which would be further, and more rigorously, investigated during the subsequent experimental optimization stage. Experiments included: cutting force measurement, surface profilometry and tool wear. Results are presented and discussed in the following sections. In addition, experimental observations of defects and challenges encountered during machining are given in the ‘Comments on Machinability’ section.

5.1 Machining Tests

Cutting force experiments were performed using a Haas TM1p vertical milling machine equipped with a Kistler Instruments® type 9123c rotating dynamometer. Cutting force measurements of tangential and radial cutting forces, F_t and F_r , were recorded as well as the machined surface topography and cutting edge wear. Details and specifications of equipment including the milling machine, cutting tools, dynamometer, fixtures, and procedures used during the feasibility study are described in Chapter 4. Because the purpose of the feasibility study was only to provide an initial investigation into the machining behavior of the materials, a full design of experiment was not conducted. Cutting tests were conducted in three stages, depth of cut variation stage, speed variation stage, and feed variation stage. During each stage, one machining parameter was varied while all others were held constant. This approach provided insight to each parameters influence on cutting forces without the use of a full design of experiment. The direct influence of changes made to one parameter was immediately visible in

the results. Surface quality was measured by machining test samples with varied combinations of cutting conditions. Surface trace profiles were measured in several locations in differing orientations. The procedures used for the analysis of the cutting forces and surface roughness are described in Chapter 4.

5.2 Results

Cutting forces, surface quality and tool wear results obtained during the feasibility study are presented in the following sections. Cutting force results are divided by candidate tooling material and the cutting tool used. Cutting force measurements of all three experiments: feed variation, speed variation and depth of cut variation are presented. Influences on cutting forces caused by variation in individual cutting parameters will be discussed in the Discussion section of the chapter.

5.2.1 Cutting Forces of CB1100 Using Diamond Abrasive Cutting Tools

The cutting conditions selected for studies conducted in CB1100 using diamond abrasive cutting tools are listed below in Table 5-1. Table 5-1 lists the conditions used for all three cutting force experiments combined. Cutting speeds of 6000, 5500 and 5000 RPM were chosen. Feed rate was varied from 0.51m/min to 2.03m/min. Radial depth of cut was held at 15.88mm. Axial depth of cut was varied from 3.18 – 25.40mm.

Table 5-1: Cutting conditions for studies using diamond abrasive type cutting tools.

Speed [rpm]:	Feed [m/min]:	Axial Depth of Cut [mm]	Radial Depth of Cut [mm]:
6000	0.51	12.70	15.88
6000	0.76	12.70	15.88
5000	0.76	12.70	15.88
5500	0.76	12.70	15.88
6000	0.76	12.70	15.88
6000	1.02	12.70	15.88
5000	1.02	12.70	15.88
5500	1.02	12.70	15.88
6000	1.02	12.70	15.88
5000	1.27	12.70	15.88
5500	1.27	12.70	15.88
6000	1.27	12.70	15.88
6000	1.27	3.18	15.88
6000	1.27	6.35	15.88
6000	1.27	9.53	15.88
6000	1.27	15.88	15.88
6000	1.27	19.05	15.88
6000	1.27	22.23	15.88
6000	1.27	25.40	15.88
6000	1.27	12.70	15.88
6000	1.52	12.70	15.88
6000	1.78	12.70	15.88
6000	2.03	12.70	15.88

Cutting force plots obtained while varying the depth of cut using diamond abrasive cutting tools in CB1100 are shown in Figure 5-1. During this experiment, depth of cut was varied from 3.18mm to 25.40mm at a speed of 6000RPM and a feed rate of 1.27m/min. Depths of cut in the radial directions were held constant at 15.88mm. Tangential cutting force was found to range from 10 N at a depth of cut of 3.18mm up to 90 N at a depth of cut of 25.40mm increasing linearly over the range of selected conditions. Radial cutting force ranged from 2N at a depth of cut of 3.18mm to 120N at a depth of cut of 22.23mm. Radial cutting force increased rapidly above 19.05mm and exceeded the tangential cutting force. Radial cutting force at an

axial depth of cut of 25.40mm decreased compared to forces measured at a 22.23mm depth of cut. Tangential cutting force between 22.23mm and 25.40mm depths of cut remained nearly constant at approximately 85-90N while radial force decreased from 120N to 110N. The rapid increase in the radial cutting force above 19.05mm is likely due to poor material evacuation of the dust produced during machining. Cutting forces across the samples were not constant due to chipping and fracture which was observed near the entry and/or exit of the cuts causing drops and spikes in cutting force. Further, cutting forces varied from one end of the sample to the other in both linear and non-linear fashions. Changes in density or mechanical properties across the sample are the suspected cause.

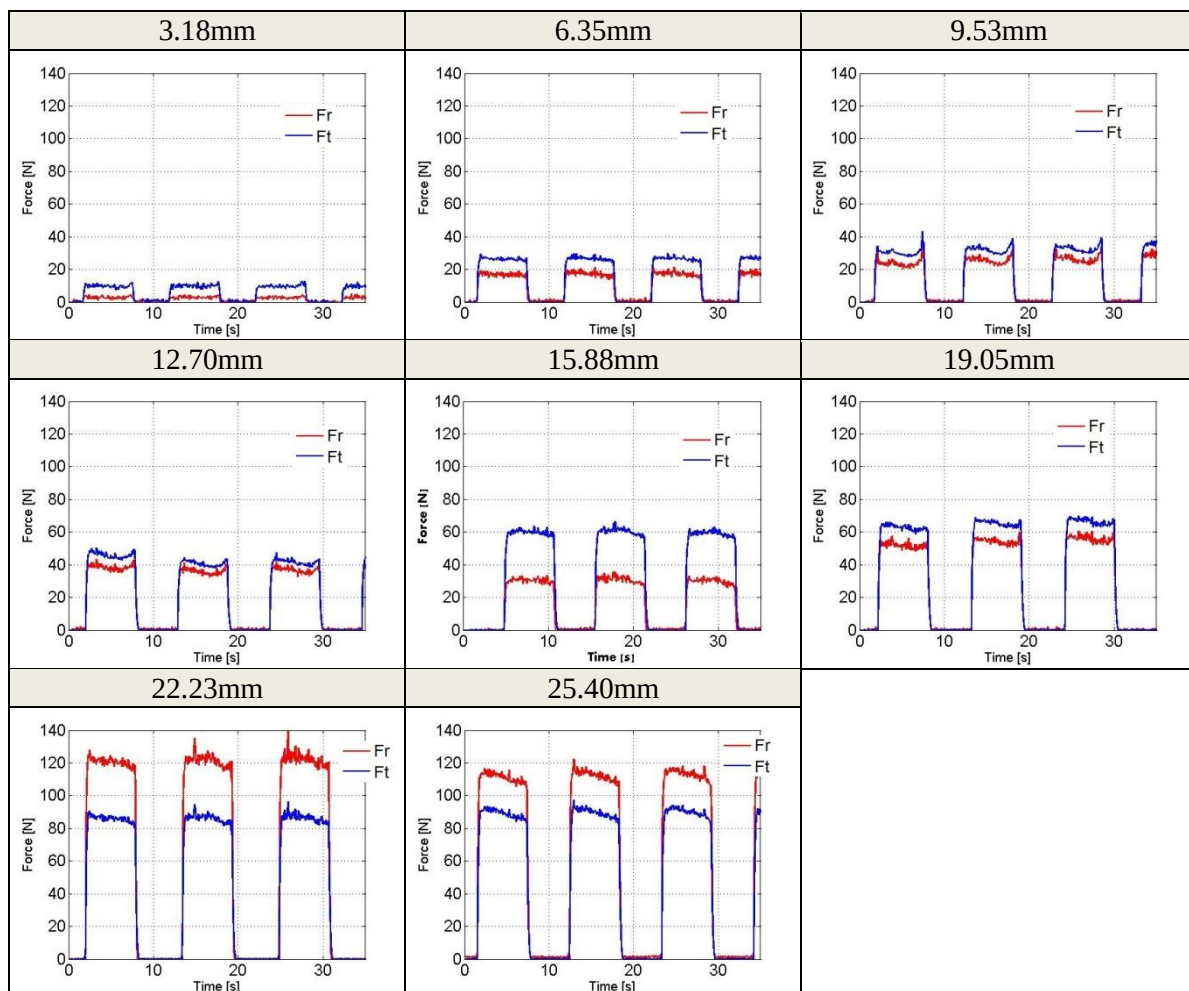


Figure 5-1: Cb1100 cutting force plots for different depths of cut using diamond abrasive cutting tool (15.88mm, 40grit) at a speed:6000rpm, feed 1.27m/min, 15.88mm RDOC.

Cutting forces measured while varying the feed rate in CB1100 using diamond abrasive cutting tools are given in Figure 5-2. Feed rate was varied from 0.51 – 2.03 m/min. Axial and radial depths of cut were held constant at 12.70mm and 15.88mm respectively. Feed rate was increased starting from 0.51 m/min by increments of 0.254 m/min until forces began inducing fracturing of the sample. This occurred at feed rates above 2.03 m/min. Tangential cutting forces ranged from 25.0 – 400 N while radial forces ranged from 10.0 – 350 N.

As the feed rate was increased from 0.51m/min, the ratio of F_r to F_t increased. Radial cutting force exceeds tangential force for feed rates at or above 1.016m/min. However, at a feed rate 2.03m/min the relationship reverses and tangential cutting force exceeds radial cutting force. The ratio of F_r to F_t is approximately constant for feed rates between 1.27 – 1.78 m/min. A sharp increase in both tangential and radial cutting forces was observed when the feed rate was increased from 1.27m/min to 1.52m/min. Both F_t and F_r approximately doubled in magnitude at a feed rate of 1.52m/min compared to 1.27m/min. As in previous tests, chipping and fracture was observed at the entry of the cut during some tests. This is evident in the cutting forces measured during the first test cut at 2.03 m/min, and is shown in the first profile in the lower left of Figure 5-18.

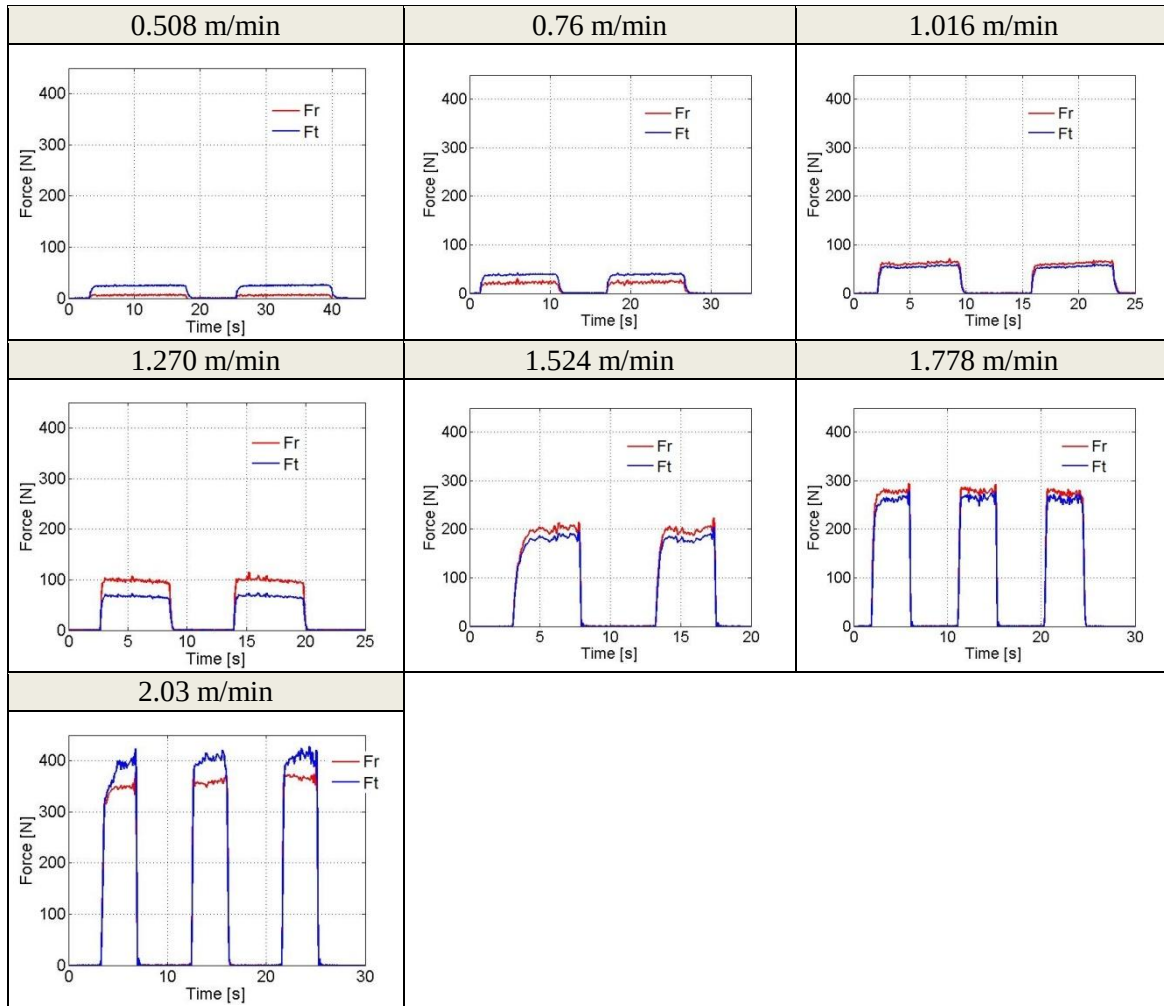


Figure 5-2: Cutting force plots for different feed rates using diamond abrasive cutting tool in CB1100 (15.88mm dia 40grit) [speed:6000 RPM, 12.70mm ADOC, 15.88mm RDOC].

Cutting forces obtained by varying cutting speed are plotted in Figure 5-3. Speeds of 5000, 5500, and 6000 RPM were chosen. Three levels of feed rate were used during this experiment: 1.27, 1.016, 0.76 m/min. Depths of cut in the radial and axial directions were held constant at 12.70 and 15.88 mm respectively. A total of nine combinations of speed and feed were utilized. Figure 5-3 shows, as feed rate increases and RPM decreases, cutting forces climb rapidly. However, no consistent relationship between F_t and F_r is discernible. Radial cutting force appears higher than tangential force in some cases and equal or lower in others. Buildup of dust on the cutting tool was observed and is the likely cause of the inconsistent radial forces.

The first two plots of Figure 5-3 show an unusual dip which consistently appears near the center of the sample. No fracture or chipping was observed during these tests. No visual indications or discrepancies in the machined surface were found either. And no changes to the setup or machining system had occurred. Therefore, it is believed that a section of reduced strength near the center of the sample was encountered during the tests. It is proposed that this region is a manufacturing defect in the sample resulting from incomplete mixing or imbalance in the local composition. This phenomenon will be further explored in the discussion section of this chapter.

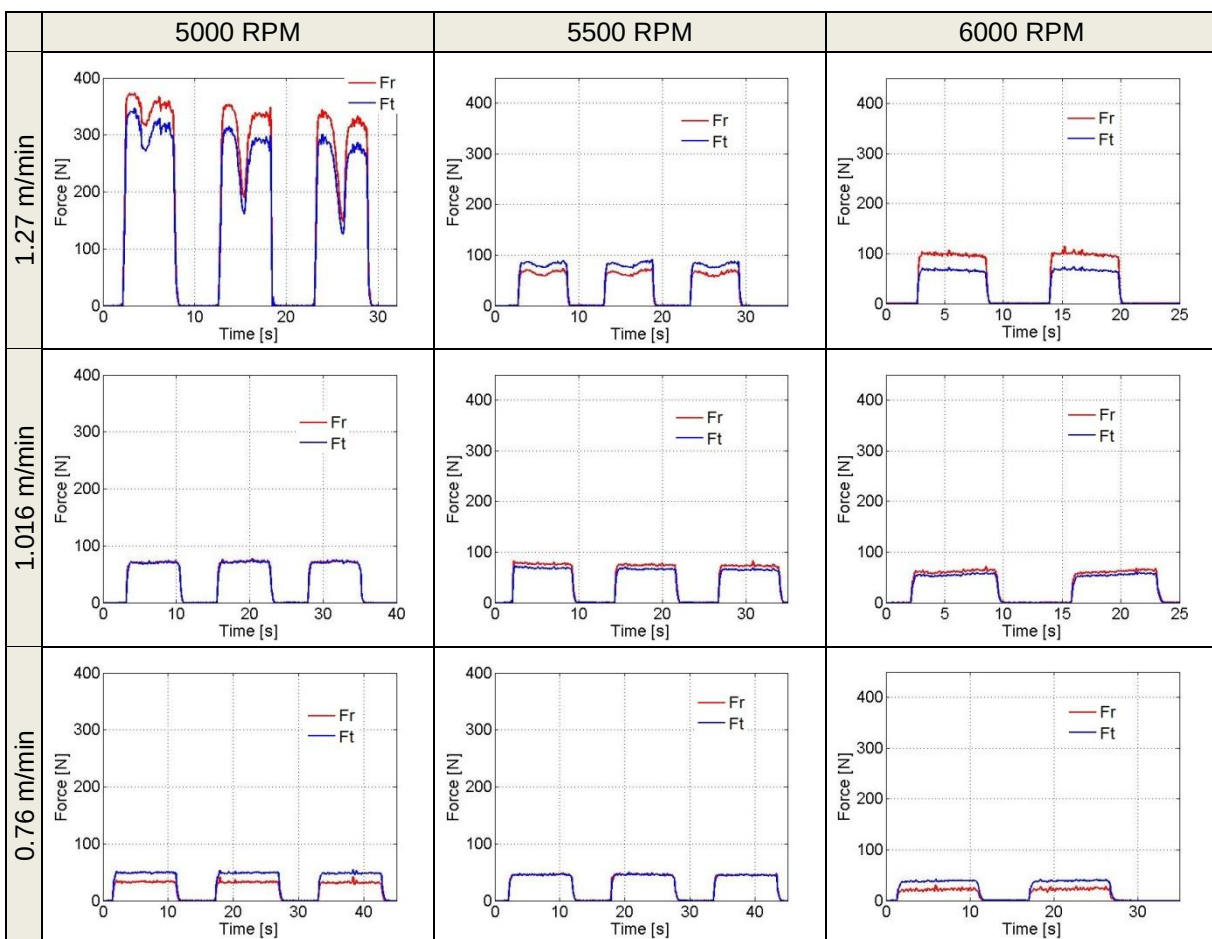


Figure 5-3: CB1100 cutting force plots of diamond abrasive tool (15.88mm diameter, 40grit) at 12.70mm ADOC, and 15.88mm RDOC arranged according to feed and speed.

5.2.2 Cutting Forces of CB1100 using PCD Cutting Tools

Fewer cutting parameters were selected for the studies using PCD cutting tools than those conducted using diamond abrasive type cutting tools. Three levels of feed rate were selected: 2.54, 5.08, 10.16 m/min. The maximum depth of cut of the PCD cutting tool was 3.18mm. Due to the low axial depth of cut, only the maximum radial depth of cut was selected in order to ensure the cutting forces were high enough to produce a reliable measurement. Therefore, depths of cut in the axial and radial directions were held constant at 3.18 and 31.75 mm respectively. Feed rates selected for the PCD cutting tool were much higher than those of the diamond abrasive cutting tool. The low axial depth of cut offered by the PCD tipped inserts require high feed rates in order to achieve high material removal rates.

Cutting forces in the tangential and radial directions are plotted in Figure 5-4, for all three feed rates. Cutting forces in CB1100 using PCD cutting tools are low in magnitude ranging from 10 – 35 N. High consistency exists cut to cut in shape and magnitude. Force profiles are also more defined than those produced using diamond abrasive tooling. Further, the relationship between tangential and radial cutting force is consistent for the range of parameters selected.

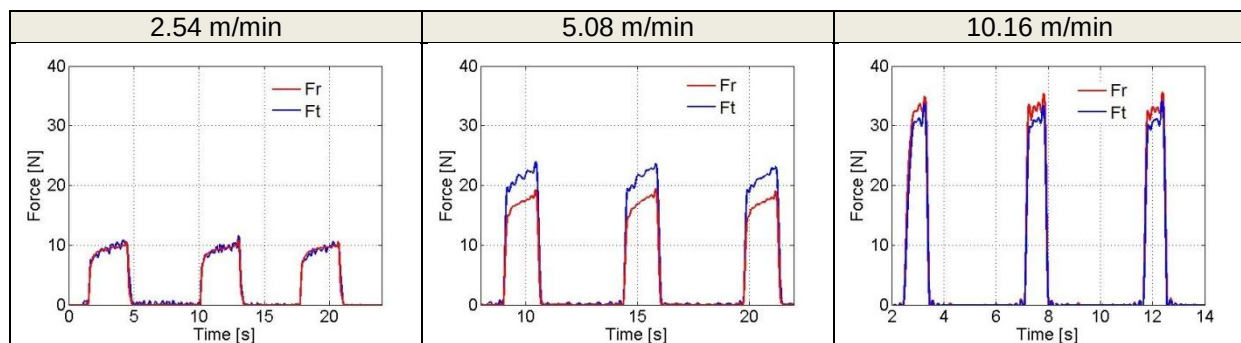


Figure 5-4: CB1100 Tangential and radial cutting force plots of PCD tooling at different feed rates [speed: 6000rpm, 3.18mm ADOC].

5.2.3 Cutting Forces of AAC using Diamond Abrasive Cutting Tools

Cutting speed was not varied during experiments in AAC. Clogging of the cutting tool caused severe damage to the workpiece at RPMs lower than 6000 RPM. Dust particles bonded to the cutting tool producing forces larger than the material sample was capable of sustaining resulting in fracturing. Thus, speeds below 6000 RPM were deemed unfeasible. In addition, axial depths of cut greater than 12.70mm produced fracturing and damage to the workpiece as well. Therefore, axial depth of cut was limited to a maximum of 12.70mm. Cutting conditions chosen for studies in AAC using diamond abrasive cutting tools are given in Table 5-2. Feed rate was varied from 1.27m/min to 5.08m/min. Three levels of axial depth of cut were chosen: 3.18mm, 6.35mm, and 12.70mm. Radial depth of cut was held constant at 15.88mm.

Table 5-2: AAC Feed Variation Study Parameter Set Using Diamond Abrasive Tooling.

Speed [RPM]:	Feed [m/min]:	Axial Depth of Cut [mm]	Radial Depth of Cut [mm]:
6000	1.270	12.70	15.88
	2.54	12.70	
	1.270	6.35	
	2.54	6.35	
	3.81	6.35	
	5.08	6.35	
	1.270	3.18	
	2.54	3.18	
	3.81	3.18	
	5.08	3.18	

Average radial cutting forces found during the feed variation study ranged from approximately 25.0 to 200 N. Tangential cutting forces varied from 15.0 -110N. Cutting force plots obtained using diamond abrasive cutting tools are shown in Figure 5-5 arranged according to feed rate and axial depth of cut.

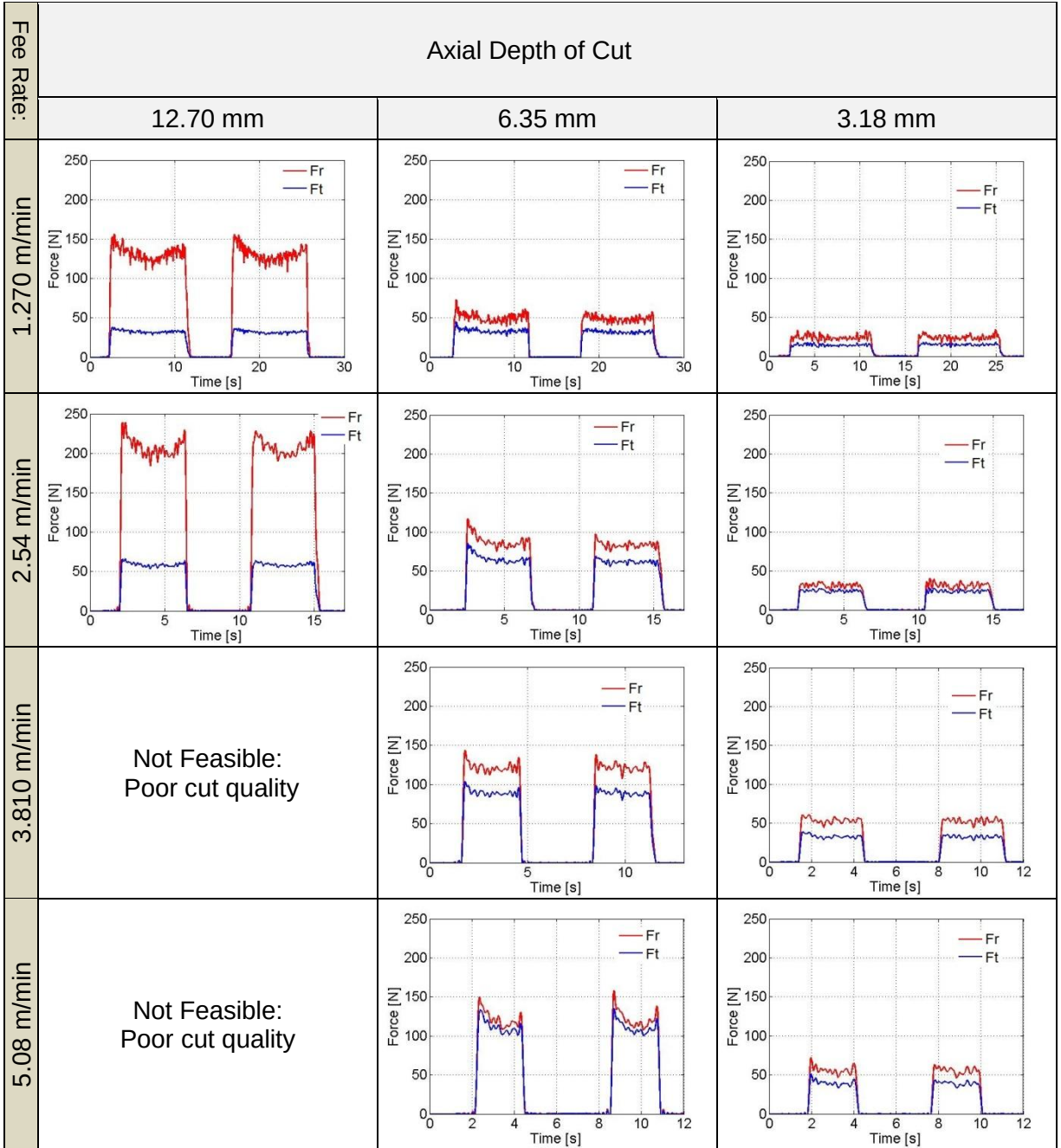


Figure 5-5: Diamond abrasive cutting forces arranged according to axial depth of cut and feed rate.

Radial cutting force was consistently higher than tangential cutting force throughout the experiments. At 12.70mm of axial depth of cut the ratio of radial to tangential cutting force was approximately 4:1. In addition, radial cutting force increased at a more rapid rate than tangential cutting force when feed rate or axial depth of cut was increased. As the axial depth of cut grew, the rate at which radial cutting forces increased with respect to feed rate accelerated. At an axial

depth of cut of 3.18mm, radial cutting force increased from approximately 25 N at a feed rate of 1.27m/min to 60 N when feed rate was increased to 5.08m/min. At an axial depth of cut of 12.70mm, radial cutting force increased from 140N to 220N when feed rate was increased from 1.27m/min to only 2.54m/min. The increased sensitivity of radial cutting forces at higher axial depths of cut is believed to be due to poor material evacuation of the dust created during machining. Further, it was observed that the fine dust particles had a tendency to adhere to the cutting tool and fill the crevasses between abrasive particles.

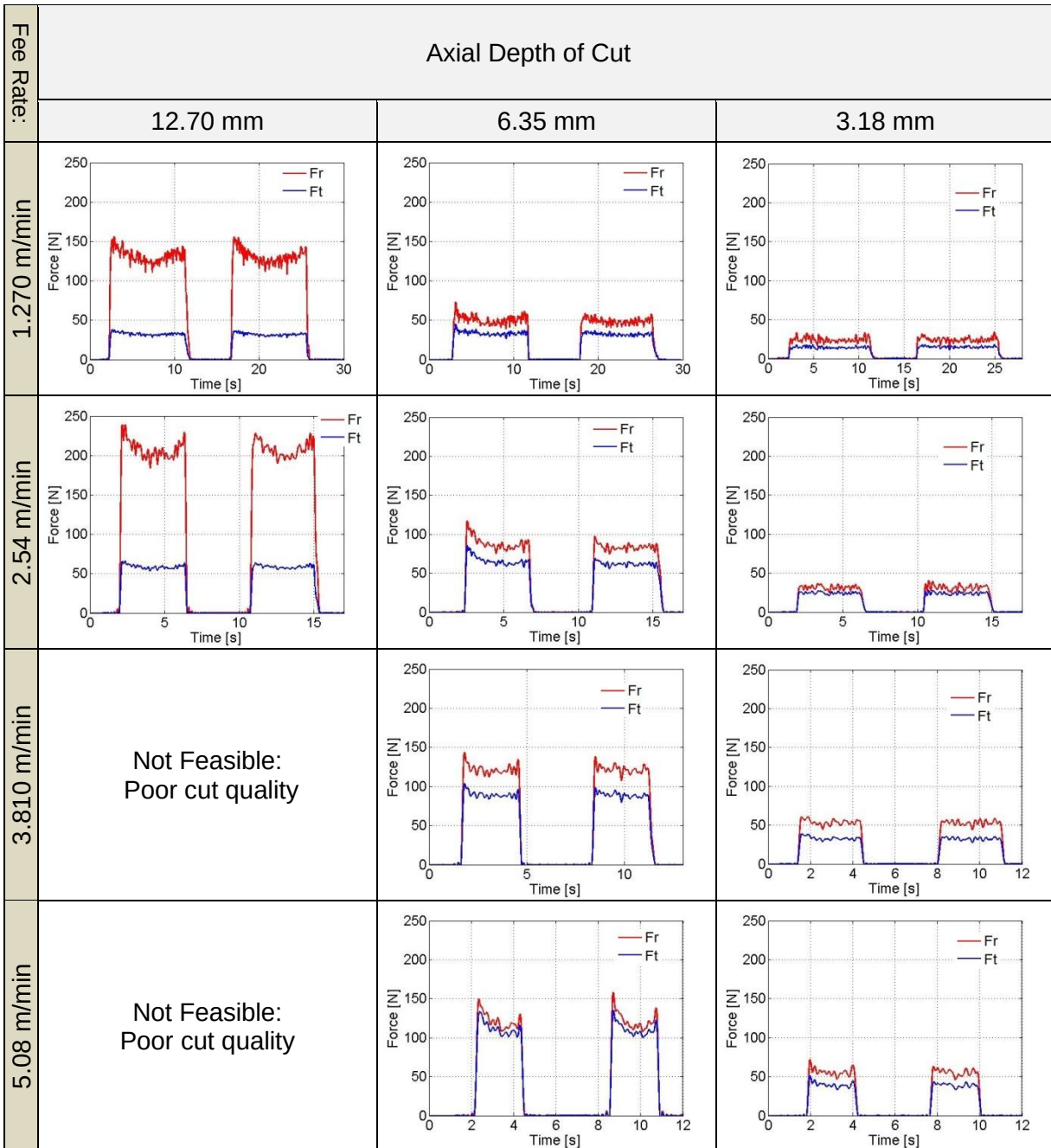


Figure 5-6: Cutting force plots of AAC machined at various feed rates and axial depths of cut using diamond abrasive cutting tool at 6000 RPM and 15.88mm RDOC.

5.2.4 Cutting Forces of AAC using PCD Cutting Tools

Cutting parameters selected for the study of PCD cutting force in AAC were limited due to the low axial depth of cut achievable by the inserted type PCD cutting tool. Four levels of feed rate were selected: 2.54, 5.08, 7.62 and 10.16 m/min. Depths of cut in the axial and radial directions were held constant at 3.18 and 31.75 mm respectively. Cutting speed was held constant at 6000rpm. Plots of the cutting forces obtained using PCD cutting tools in AAC during the feed rate variation study are given in Figure 5-7. Measured cutting forces produced by PCD tools are low in magnitude, ranging from 1.0 – 3.5 N. At a feed rate of 2.54m/min, tangential and radial cutting forces were approximately equal with a 10-15% reduced radial force. At a feed rate of 7.62 m/min radial force was approximately 20% higher than tangential cutting force. However, only at feed rates of 2.54 and 7.62 m/min, was tangential force present. As shown in Figure 5-7, at feed rates of 5.08m/min and 10.16 m/min, radial cutting forces were not distinct or identifiable. The cause of the inconsistency in radial forces during the test is unknown. Further investigation during the experimental optimization stage of the research is needed in order to explore the unexplained behavior using a more robust design of experiment.

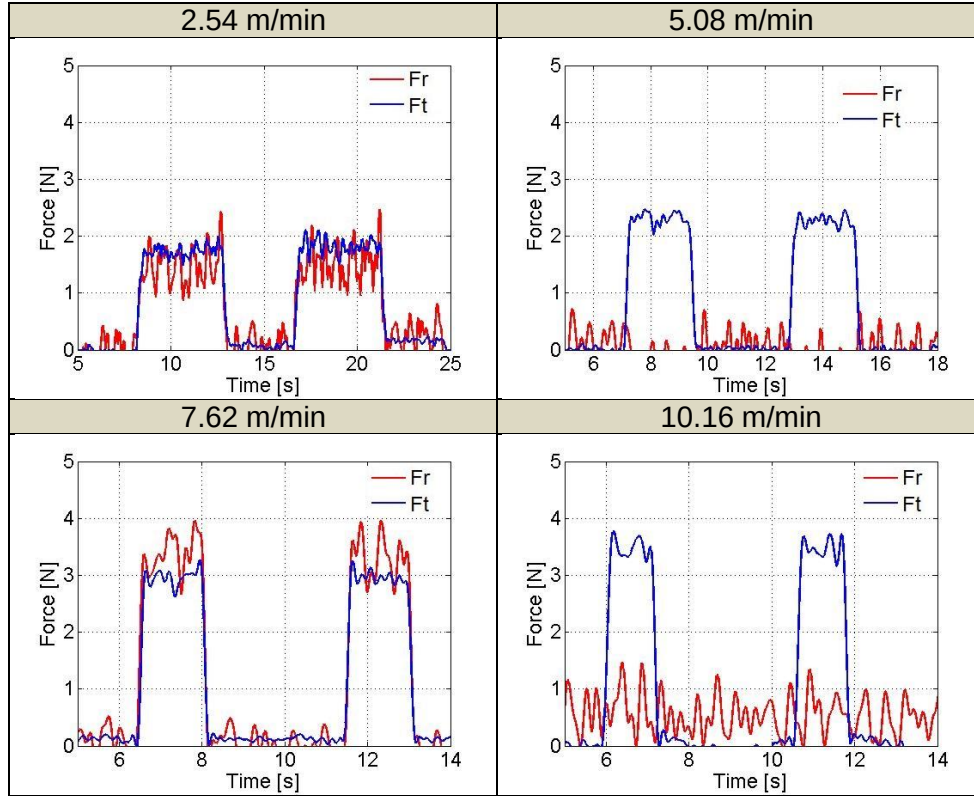


Figure 5-7: Cutting force plots of AAC machined at various feed rates using PCD cutting tool at 6000 RPM and 31.75mm RDOC and 3.18mm ADOC.

5.2.5 Cutting Forces of Cfoam using Diamond Abrasive Cutting Tools

Cutting parameters chosen for the cutting force study in Cfoam using diamond abrasive type cutting tools were limited due to the low strength of the material and low sensitivity of the force measurement system. High feed rates were required in order to produce sufficient force to yield reliable measurement. Feed rates of: 2.54, 5.08, 7.62, and 10.16 m/min were selected. Axial depth of cut was held at the maximum level of 25.40 mm for the same reason. Radial depth of cut was held constant at 15.88 mm. Cutting force plots obtained by machining Cfoam using the diamond abrasive cutting tool are given in Figure 5-8. Average cutting force ranged from approximately 4 – 40 N. Peak cutting force magnitudes were varied within each test feed rates of 5.08 and 10.16m/min showed the largest variation with average peak tangential cutting forces varying by 12-25%. Unlike the studies conducted in AAC or CB1100 cutting forces in the

tangential direction were consistently higher than those in the radial direction. Furthermore, the relationship between tangential and radial forces was consistent throughout the study. No buildup or bonding of dust to the cutting tool was observed. This supports the belief that the radial force inconsistencies found in AAC and CB1100 while using diamond abrasive type tools is more likely due to the material buildup on the cutting tool than a material dependent behavior.

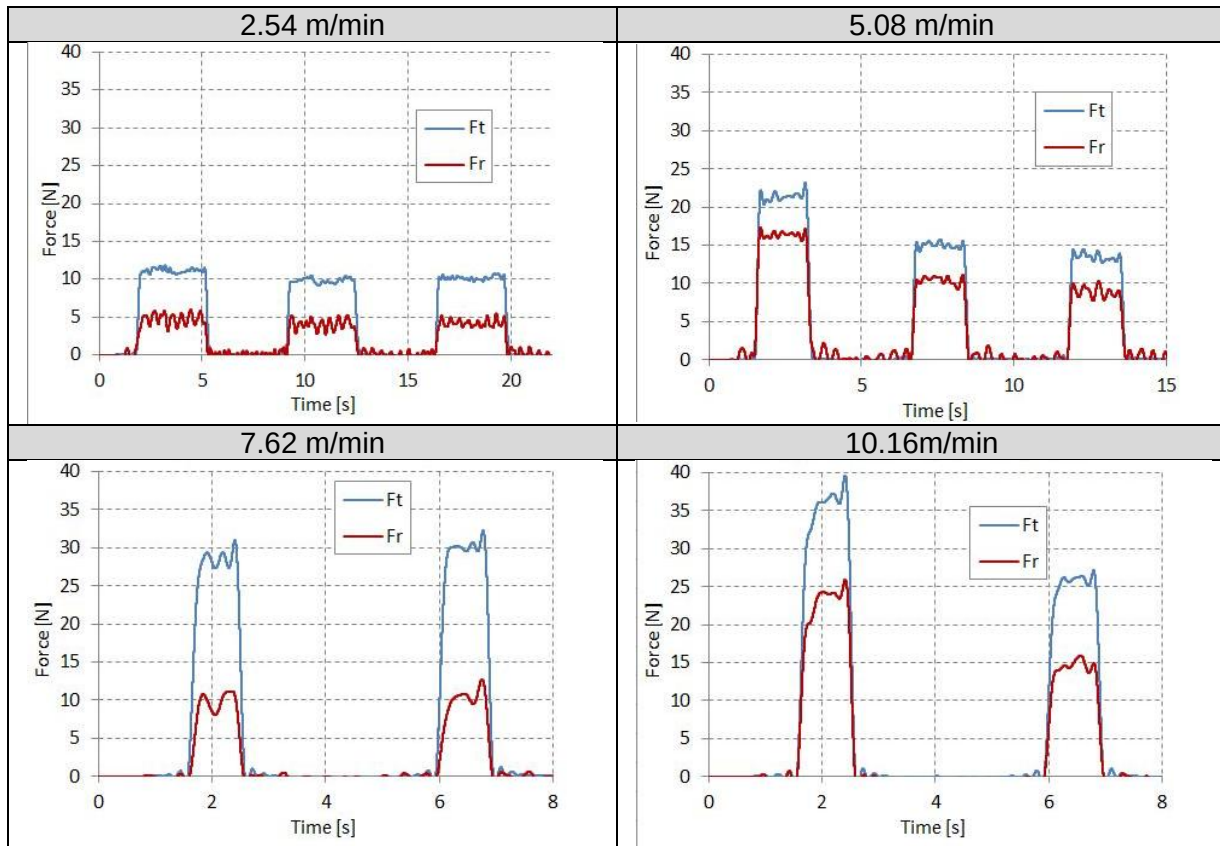


Figure 5-8: Cutting force plots of Cfoam machined at various feed rates using diamond abrasive cutting tool at 6000 RPM, 25.40mm ADOC and 15.88mm RDOC.

5.2.6 Cutting forces of Cfoam Using PCD Cutting Tools

Due to the low strength of Cfoam and the limited axial depth of cut of the PCD cutting tool, only the maximum feed rate, 10.16m/min, yielded high enough forces for reliable measurement. Axial and radial depths of cut were 3.18mm and 31.75mm, respectively. The speed chosen for the test was 6000rpm. The tangential and radial cutting forces are plotted below in Figure 5-9. Measured cutting forces were noisy and random in magnitude. Peak magnitude of cutting forces from profile to profile varied significantly between the three tests. Tangential cutting force ranged from approximately 2.5 – 7.5 N. Radial cutting force is not distinct for the first or last profiles but is estimated to be approximately 1.5-2 N. Contrarily, the second test cut profile, shown in the center of the plot, shows significant radial force. The increase in radial force in the second test cut profile is the result of the presence of bonding material used to bond subsequent blocks of material which was unexpectedly encounter during the test. However, the results of this test were not discarded in order to illustrate a challenge which would be encountered during the machining of these materials when used for composite tooling. Although the magnitude of the force was still low the relative increase is significant, particularly in the radial direction, which increased approximately 1000%. When machining a substrate for a composite tool, a sudden and unexpected increase in cutting forces during machining could cause significant damage to the workpiece incurring additional costs.

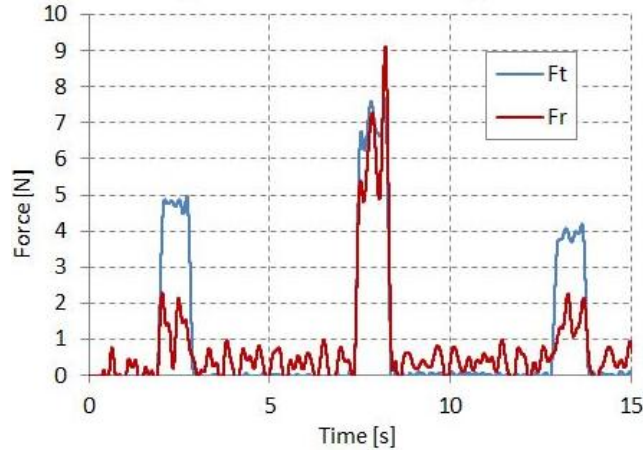


Figure 5-9: Tangential and radial cutting force of Cfoam using PCD cutting tool at 6000 RPM, 10.16 m/min, 3.18mm ADOC, and 31.75mm RDOC.

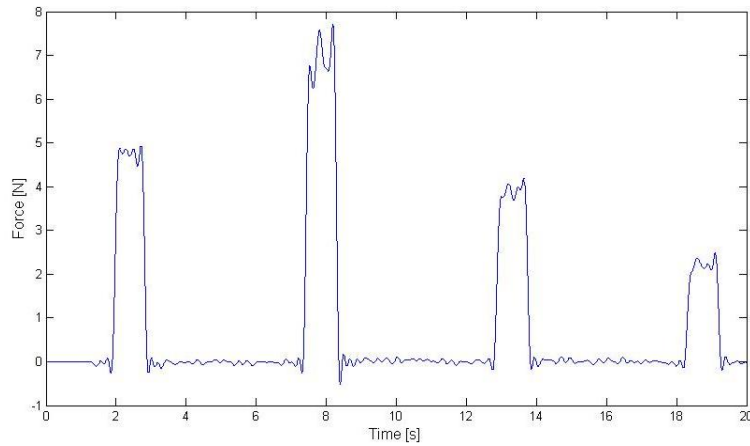


Figure 5-10: Tangential cutting forces obtained using PCD tooling in Cfoam at 6000 RPM, 10.16 m/min feed rate, and 3.18mm axial depth of cut.

5.2.7 Surface Quality of Machined CB1100

In the following section, typical results of the surface roughness study are presented. As mentioned previously, surface profilometry of AAC and Cfoam was not conducted during the feasibility study due to risk of damage to the probe. Therefore, the focus of the surface quality portion of the study will be CB1100. The complete data set, including measurements of R_z , R_y and complete profiles are available in Appendix C. Figure 5-11 shows two surface profiles taken from CB1100 corresponding to the surface profiles shown in Figure 5-12. Minimal variation in roughness was found across each surface. Further, minimal variation in surface roughness was

measured when comparing the surfaces created using *roughing* parameters and typical *finishing* parameters. Only minute differences in the surface quality obtained using the lowest chipload level, shown in Figure 5-12a, and the heaviest chipload level shown in Figure 5-12b were found using PCD.

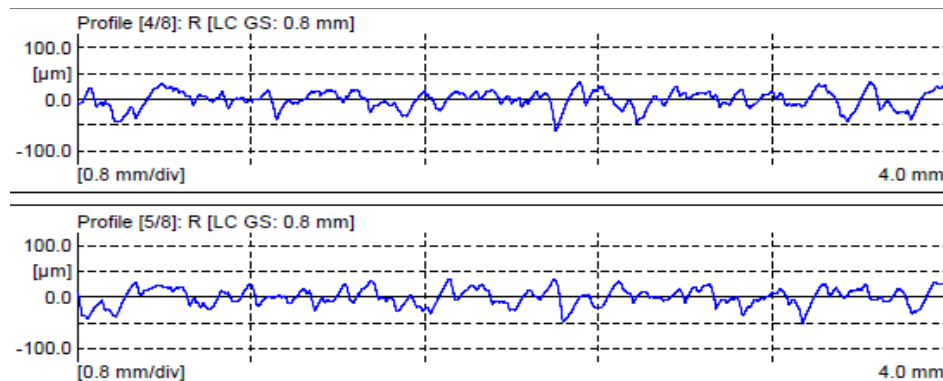


Figure 5-11: Typical surface profiles obtained from CB1100.

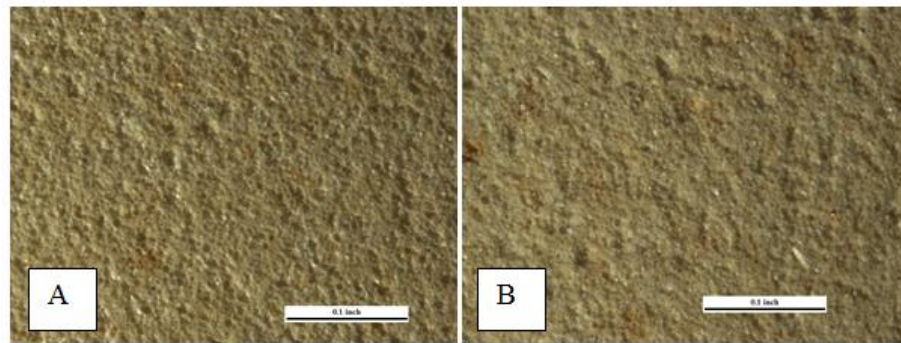


Figure 5-12: (a) CB1100 6000rpm/ 0.254 m/min /PCD and (b) 5000rpm/10.16 m/min / PCD.

Table 5-3 and Table 5-4 list the surface roughness measurements in terms of Average Roughness (R_a) in units of micrometers for diamond abrasive and PCD cutting tools, respectively. Measurements R_{a1} – R_{a8} correspond to measurements in the feed direction, transverse to feed, 45 degrees, and -45 degrees, in that order.

Table 5-3: Diamond Abrasive Surface Roughness Measurements for CB1100.

Speed [RPM]	Feed [m/min]	Velocity [m/min]	Chipload [mm/rev]	MRR [m ³ /min]	Ra1 [μm]	Ra2 [μm]	Ra3 [μm]	Ra4 [μm]	Ra5 [μm]	Ra6 [μm]	Ra7 [μm]	Ra8 [μm]
5000	1.27	399	0.25	9.86E-03	15.27	17.75	12.97	15.22	14.13	11.11	14.75	11.96
5000	2.54	399	0.51	1.04E-02	16.18	14.69	17.71	12.94	13.56	13.57	16.58	14.53
5000	3.81	399	0.76	1.12E-02	17.32	18.78	16.19	14.53	16.53	15.47	17.28	16.53
6000	2.54	479	0.42	8.73E-03	13.50	11.82	13.23	16.90	14.99	18.35	17.55	18.97
6000	5.08	479	0.85	1.12E-02	17.32	15.06	15.27	18.58	12.88	15.55	15.37	19.08

Table 5-4: PCD Tool Surface Roughness for CB1100.

Speed [RPM]	Feed [m/min]	Velocity [m/min]	Chipload [mm/tooth]	MRR [m ³ /min]	R _{a1} [μm]	R _{a2} [μm]	R _{a3} [μm]	R _{a4} [μm]	R _{a5} [μm]	R _{a6} [μm]	R _{a7} [μm]	R _{a8} [μm]
5000	2.54	498	0.18	2.24E-04	13.94	14.62	14.71	15.64	10.89	14.56	12.78	12.34
5000	5.08	498	0.33	4.48E-04	11.69	13.34	13.25	15.08	14.27	14.61	15.23	12.46
5000	7.62	498	0.51	6.72E-04	12.54	12.33	13.42	14.51	13.76	13.78	14.32	16.09
5000	10.16	498	0.69	8.96E-04	15.75	13.21	13.17	13.74	14.30	14.62	12.83	16.15
6000	0.25	598	0.03	2.24E-05	12.97	12.22	14.29	13.17	13.28	12.76	14.57	12.31
6000	0.51	598	0.03	4.48E-05	11.88	12.11	13.49	11.78	15.38	11.44	15.31	12.24
6000	0.76	598	0.05	6.72E-05	14.68	13.93	13.16	14.38	13.98	15.09	14.60	15.62
6000	1.02	598	0.05	8.96E-05	11.46	12.88	15.82	13.90	14.81	12.74	15.12	12.74
6000	1.27	598	0.08	1.12E-04	10.82	11.98	14.60	13.16	16.66	11.98	12.33	14.50
6000	1.52	598	0.08	1.34E-04	12.42	11.34	13.63	16.82	14.87	14.77	15.23	13.67
6000	1.78	598	0.10	1.57E-04	14.56	11.88	16.35	15.62	15.06	14.29	12.13	11.79
6000	2.03	598	0.10	1.79E-04	14.12	12.13	12.38	12.20	17.32	14.01	14.60	14.30
6000	2.29	598	0.13	2.02E-04	12.48	12.38	13.07	13.29	13.75	14.95	15.05	13.58
6000	2.54	598	0.15	2.24E-04	14.21	10.77	13.82	14.53	16.35	11.91	10.99	15.60
6000	2.79	598	0.15	2.46E-04	12.70	12.20	16.02	11.50	12.37	14.57	13.10	13.67
6000	3.05	598	0.18	2.69E-04	11.87	12.33	16.15	14.59	16.42	11.89	14.00	14.36
6000	3.30	598	0.18	2.91E-04	12.61	18.61	12.92	10.29	14.99	13.33	14.77	17.29
6000	3.56	598	0.20	3.14E-04	15.00	16.21	13.94	14.28	13.63	14.23	11.97	13.05
6000	3.81	598	0.20	3.36E-04	14.80	15.62	11.41	14.76	13.37	15.08	12.11	16.10
6000	4.06	598	0.23	3.58E-04	13.73	10.02	14.39	14.62	14.24	11.48	12.61	16.41
6000	4.32	598	0.23	3.81E-04	13.55	14.94	16.32	16.39	16.84	15.25	14.27	12.46
6000	4.83	598	0.28	4.26E-04	14.42	12.35	15.86	12.20	14.65	12.89	13.60	14.70
6000	5.08	598	0.28	4.48E-04	13.50	14.91	12.76	14.95	12.40	14.32	15.68	12.96
6000	6.35	598	0.36	5.60E-04	13.94	13.39	16.07	13.84	14.94	14.17	12.36	14.30
6000	7.62	598	0.43	6.72E-04	13.46	13.17	11.69	14.15	14.09	15.95	14.65	12.37
6000	8.89	1077	0.48	1.41E-03	15.95	13.58	13.59	16.17	19.28	15.30	13.65	11.62
6000	10.16	1555	0.56	2.33E-03	15.96	10.77	10.16	14.50	13.57	13.58	12.24	13.11

5.2.8 Cutting Edge Wear from Machining Cfoam

Tool wear for PCD and diamond abrasive tooling in both CB1100 and AAC were found to be minimal and can be considered negligible. However, Cfoam was found to be extremely abrasive and cause a significant and measurable amount of tool wear. Therefore, Cfoam will be the focus of the tool wear portion of this study. As discussed earlier, cutting forces in the Cfoam are nearly negligible. However, the resulting tool wear is extremely high due to the highly abrasive nature of the material. For an essential comparison to gain perspective to PCD and diamond abrasive tooling, studies involving high speed steel cutting tools were performed. . Figure 5-13 illustrates the increase in tangential cutting force experienced during a single cutting test. Each peak represents a traverse length of approximately 127 mm. A steep linear increase in the tangential cutting force is clearly visible and is due to the loss of cutting tool geometry.

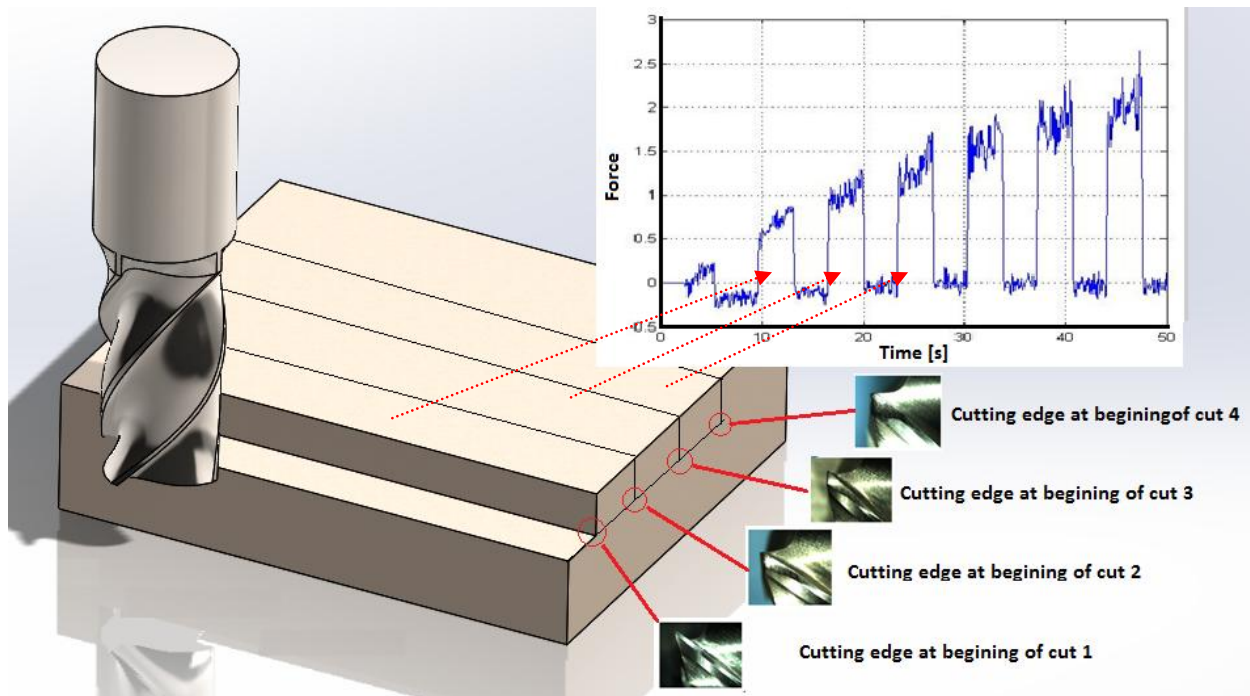


Figure 5-13: Tangential cutting force vs. time in Cfoam using HSS endmill at 6000 RPM and 10.16 m/min.

High speed steel cutting tools were found to exhibit a near total loss of geometry after only approximately 98 cm³ of material removal, a total cutting time of less than 60.0 seconds. Clearly

illustrated in Figure 5-14, tangential cutting forces are on the order of less than 2.22 N while the rapid progression of tool wear is visually illustrated by the progressive snapshots taken during the experiment.

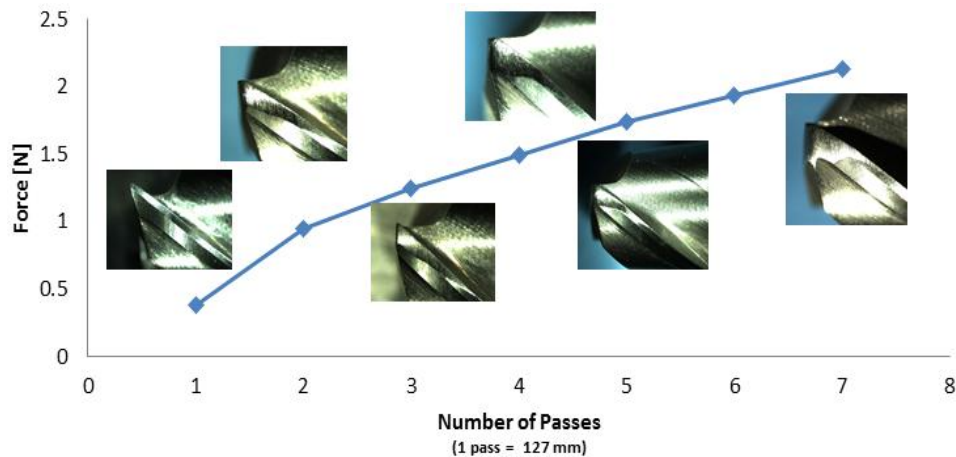


Figure 5-14: Tangential cutting force vs. traverse length in Cfoam using HSS with tool wear snapshots.

Figure 5-15 illustrates the dramatic loss of geometry in HSS cutting tools in Cfoam. After three passes, the tool wear progressed beyond the first land of the flute and had already progressed into the secondary face of the tool. The wear is shown above in Figure 5-15, along with reference datum highlighted in red. Edge definition of the bottom facets of the tool is also nearly completely eroded.

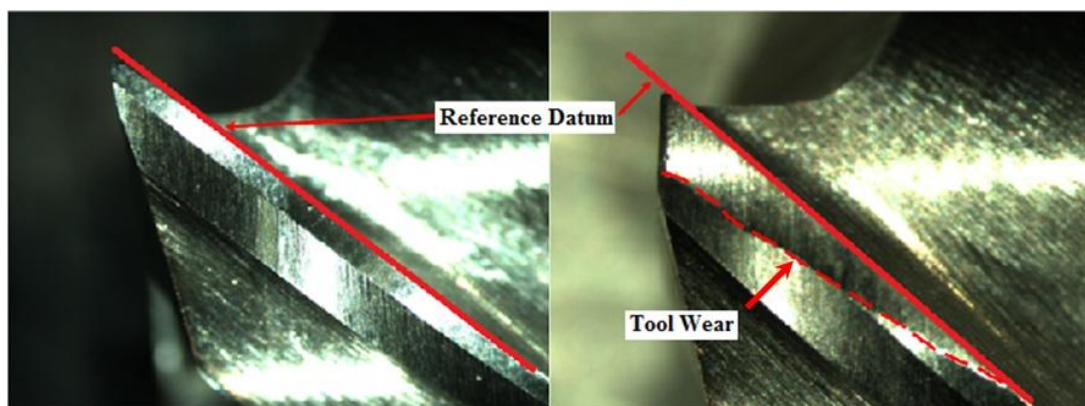


Figure 5-15: HSS endmill before and after 0.38 m of linear traverse while machining Cfoam.

Figure 5-16 illustrates the cutting edge wear resulting from machining Cfoam using PCD cutting tools. Edge wear was measured to be 0.08mm after a cumulative 90 seconds of

machining time. PCD cutting tools are known to initially lose the extremely sharp edges they often possess from the maker soon after machining is initiated. After the edge has lost its initial sharpness the rate of wear levels out. From this point on, the tool provides a long tool life. However, the amount of wear observed in Cfoam was still unexpected given the low cutting forces and short duration of time it took place in. The tool wear mechanism in PCD was found to be erosive in nature. Grains or crystals of the cutting edge were dislodged leaving wear grooves, visible in Figure 5-16.

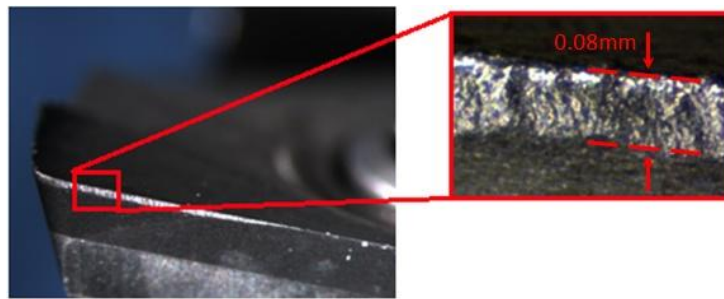


Figure 5-16: PCD cutting edge wear from machining Cfoam.

Little to no wear was found while using diamond abrasive type cutting tools in any of the three candidate tooling materials. Since the diamond abrasive particles are bonded to the substrate using a metallic plating method, the metallic coating covering the outer surfaces of the many cutting edges was lost. However, retention of the diamond particles was not hindered, Figure 5-17. No dislodged or lost particles could be identified.

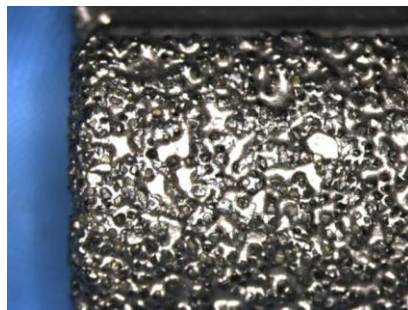


Figure 5-17: Diamond abrasive cutting tool after machining Cfoam.

The abrasive nature of Cfoam makes machining impractical using traditional tooling materials despite the low cutting forces. The only tool capable of sustained machining in Cfoam was found to be the diamond abrasive based cutting tools. PCD cutting tools showed 0.08 mm of flank wear after testing. PCD and diamond abrasive tooling both use diamond based media for the cutting edges. However, diamond abrasive tooling was found to exhibit no measureable wear. Diamond abrasive tools have countless random cutting edges while the PCD tooling used here has only three cutting edges. Thus, work done on the cutter by the material is spread over a larger total surface area. Therefore, the wear at any one point is reduced as the number of cutting edges increases.

5.3 Discussion

The results obtained during the feasibility investigation portion of the research which has been presented will be discussed in the following sections. The influence of variations in machining conditions on measured cutting forces in the three materials will be examined. In addition, the differences between the measured cutting forces differing types of cutting tools and materials will be weighed. Further, the relationships between material removal rate and cutting force are considered. Trends and variation in surface topography with respect to cutting conditions are explored and discussed. Finally, notable challenges in the machining of the candidate materials which were discovered or encountered during the study are presented in the ‘Comments on Machinability’ section.

5.3.1 Cutting Forces

Cutting forces measured in the three candidate tooling materials were random in shape and magnitude. The randomness is a combination of the inherent porosity, changes in material homogeneity, and process induced damage. Behavior of the cutting forces at the entry and exit of the cut was often unpredictable. As the cutting tool entered or exited the workpiece, chipping and fracture intermittently occurred causing spikes or drops in cutting forces. An example of a drop in cutting force due to fracture at the entry of a cut in CB1100 is shown in Figure 5-18. Discontinuities in cutting force were observed in all materials and increased in frequency and severity with increased forces. Therefore, when analyzing the general trends of the cutting forces, the initial and final regions of the data were disregarded. Average forces were then determined and trends with respect to changes in cutting conditions were plotted.

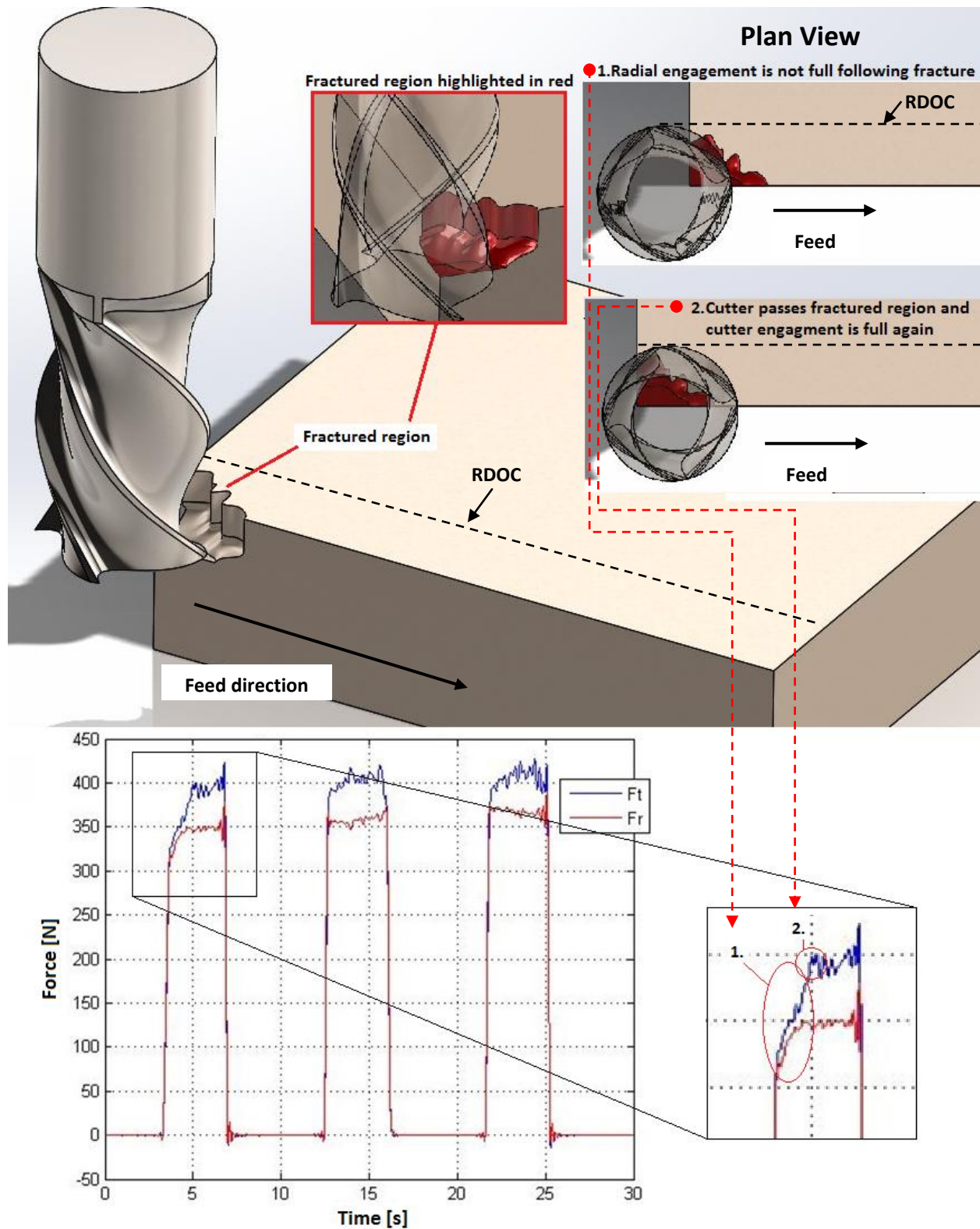


Figure 5-18: Cutting force decrease involving fracture at entry of cut in CB1100.

During testing it was apparent that relationships between tangential and radial cutting forces were inconsistent. Cutting forces shown in Figure 5-19 were obtained by machining AAC using a 15.88mm diamond abrasive cutting tool at the following cutting conditions: 6000 RPM, 12.70mm ADOC, 15.88mm RDOC, and feed rates of 0.5 m/min and 2.54 m/min. Radial cutting forces were found to be significantly higher than tangential cutting forces. The large magnitude of cutting forces in the radial direction often caused fracturing and significant damage to the workpiece. The large radial forces were the result of fine dust produced during machining which bonded to the cutting tool.

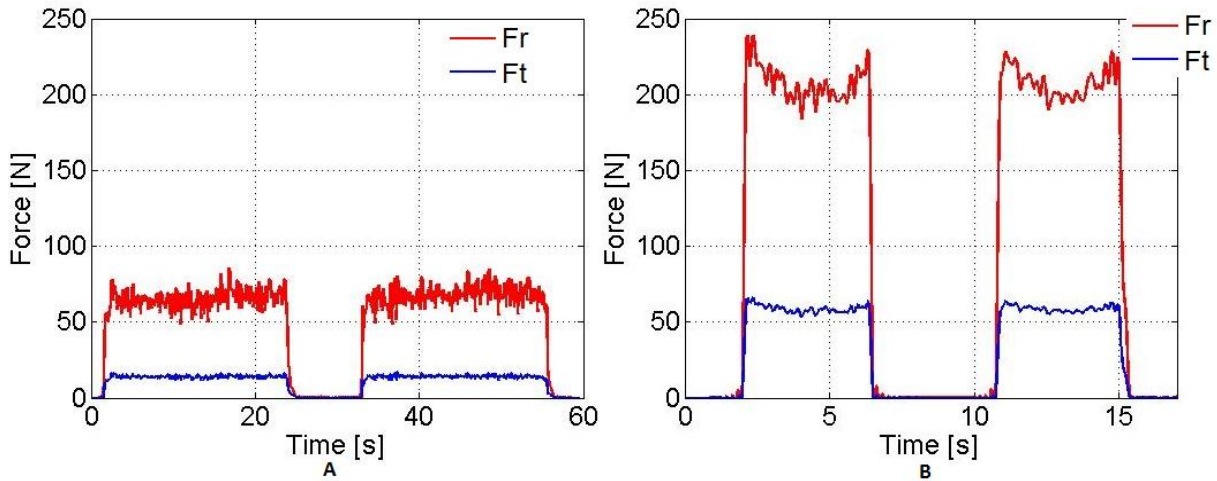


Figure 5-19: Tangential and radial cutting force profiles obtained using 15.88mm diamond abrasive cutting tool in AAC at: 6000 RPM, 12.70mm ADOC, 15.88 RDOC, and feed rate of: (a) 0.51 m/min, and (b) 2.54 m/min.

In metals, changes in axial depth of cut would yield an equal effect on both tangential and radial cutting force in most cases. However, similar dependencies of cutting force in the tangential and radial directions were not observed during the studies conducted. As shown in Figure 5-20, radial cutting forces were found to have higher dependency on axial depth of cut than tangential cutting forces. While tangential cutting force has increased approximately 100%, radial cutting force has jumped approximately 400% between the two plots. Again, this is likely due to poor material evacuation, a problem which increases as axial depth of cut grows.

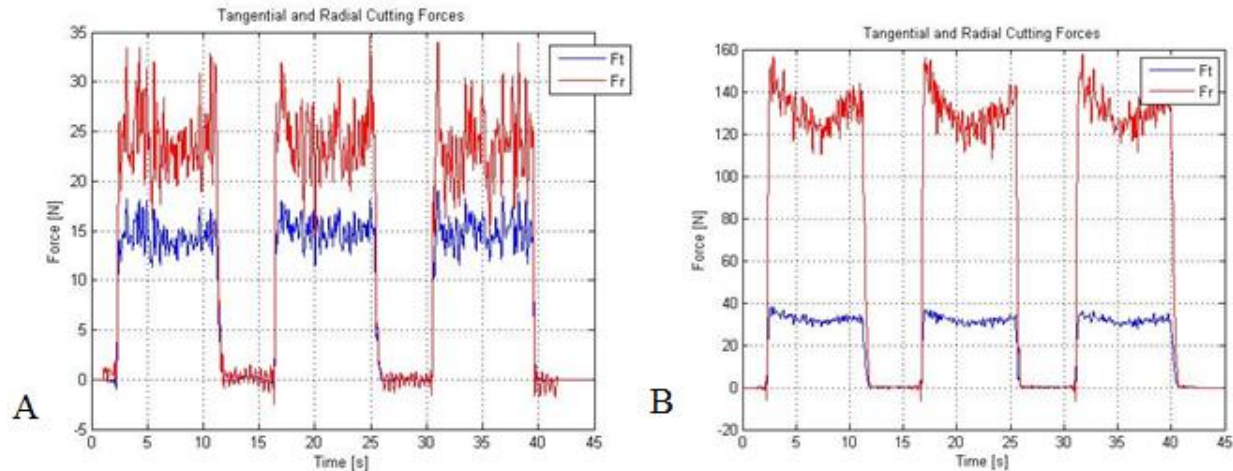


Figure 5-20: AAC tangential and radial cutting force obtained using diamond abrasive tooling at (a.) 3.18 mm and (b.) 12.70 mm depths of cut.

5.3.2 Material Removal Rate and Cutting Force

Removing the maximum amount of material, while maintaining the lowest feasible cutting forces, is desirable when rough machining. However, the cutting conditions selected effect the magnitude of the cutting forces. Thus, simply selecting the parameters which achieve the maximum material removal is not always feasible. When machining metals, the maximum allowable axial depth of cut should always be selected. However, relationships between cutting forces and cutting conditions in the materials studied here frequently do not coincide with those observed in metals. Therefore, an investigation into the trends in cutting force with respect material removal rate was performed.

The initial and final region of cutting time, when radial engagement is not constant, was neglected; the remaining tangential and radial cutting forces were then averaged and recorded. To further simplify and expedite analysis, average cutting forces in the tangential and radial directions are combined using a vector summation in order to determine the resultant active cutting force. Active cutting force vs. material removal rate is shown below in Figure 5-21. Results obtained by varying the depth of cut, feed rate, and speed are plotted together.

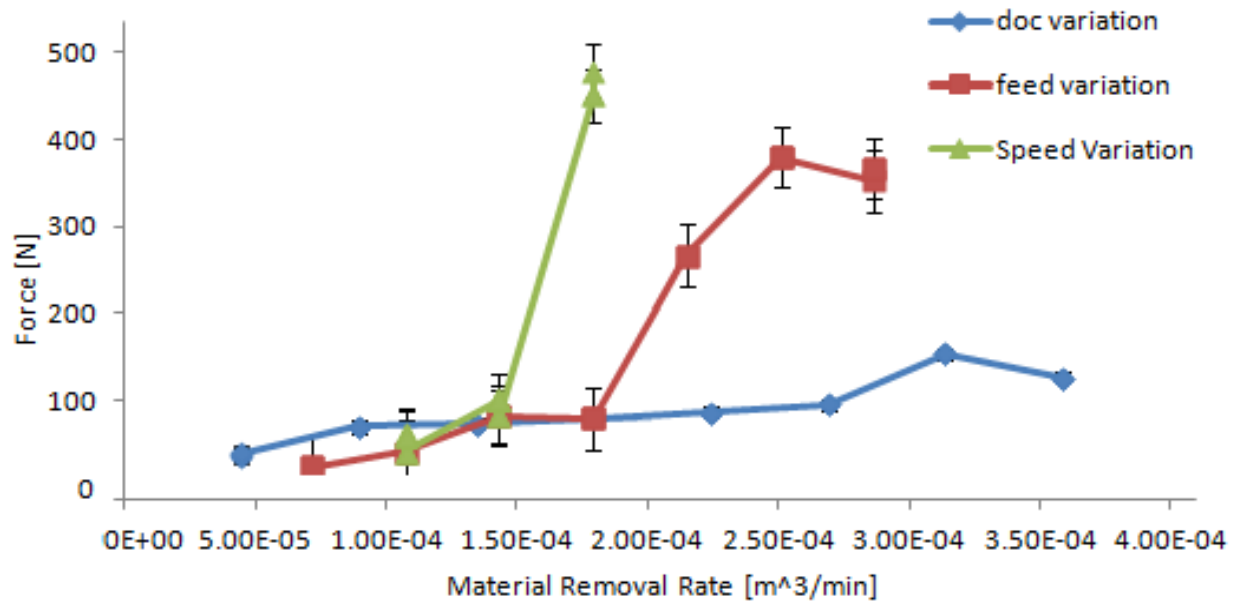


Figure 5-21: Combined cutting force vs. MRR for diamond abrasive tooling in CB1100.

Increasing feed rate will rapidly increase cutting forces while only marginally increasing material removal rate. However, if the feed rate is increased beyond a certain threshold, cutting forces decrease. It is postulated that the increase in radial cutting forces at this level increase the rate of damage propagation ahead of the tool thereby decreasing the overall cutting forces by reducing the tangential cutting force. Figure 5-21 suggests that maximum feasible axial depth of cut should always be used during rough machining. Doing so will yield the maximum MRR while maintaining low cutting forces and prolonging tool life. Axial depth of cut is only limited by the amount of edge loss and damage which can be tolerated.

The active cutting force using PCD the cutting tool is plotted vs. MRR in Figure 5-22. The maximum combined cutting force using PCD was 45.4 N, at an approximate MRR of 900 cm³/min. The active cutting force when using diamond abrasive tooling at the same MRR was only 22.0 N. Therefore, diamond abrasive type cutting tools will yield approximately twice the MRR at half the force when compared to PCD type cutting tools.

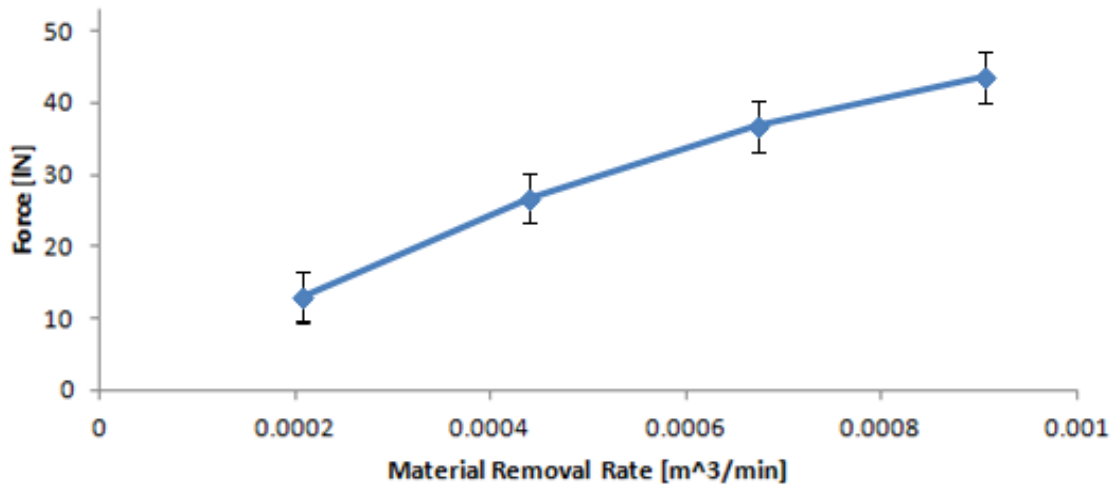


Figure 5-22: Combined cutting force vs. MRR for PCD cutting tool in CB1100.

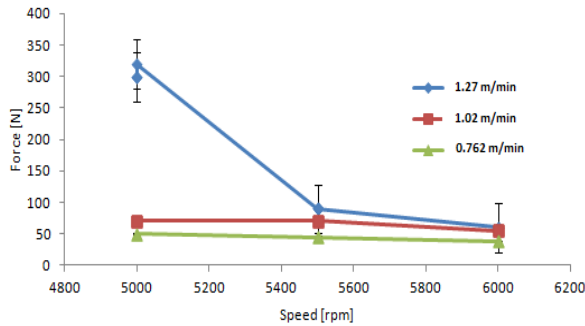
5.3.3 Effects of Cutting Conditions on Cutting Force

The influence of any one cutting parameter, such as speed, not only influences the cutting forces directly but also through a combination of interactions with other parameters. For this portion of the research only an investigatory approach is required. A general understanding of the relative influence of the significant factors is sufficient in selecting an envelope of parameters appropriate for optimization in later stages of research. An understanding of the general trends and the degree of complexity in the cutting force evolution will aid in defining the design of experiment which will be conducted in the experimental optimization stage of the research.

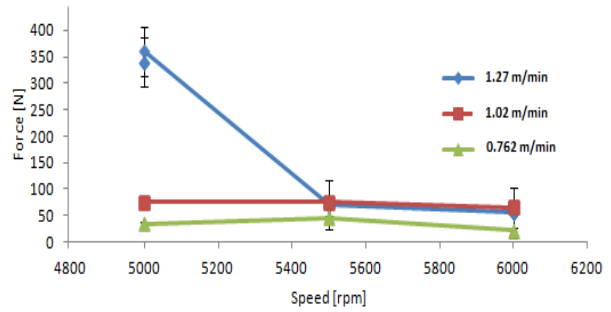
5.3.3.1 CB1100

Measured cutting forces in CB1100 were tabulated and plotted in order to investigate trends and the influence of feed rate and cutting speed. Cutting force vs. speed at three different feed rates utilizing diamond abrasive tooling is shown in Figure 5-23 for CB1100. From Figure 5-23a and Figure 5-23b, the same dependence on cutting speed can be seen for tangential and radial cutting forces. A similar dependence between tangential and radial cutting forces on feed

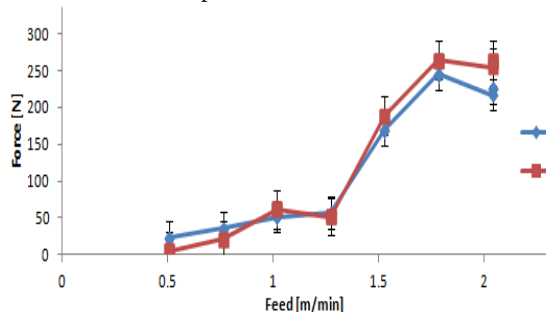
and depth of cut is also found and shown in Figure 5-23c Figure 5-23d. Figure 5-23d illustrates the linear influence of depth of cut on tangential and radial cutting forces. A slightly higher sloped region is shown for low depths of cut. A possible explanation is that this is due to the larger amount of scatter in low cutting force measurements.



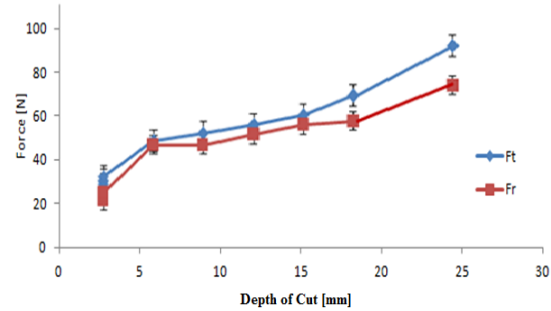
a.) Diamond abrasive tooling tangential cutting force vs. speed in CB1100



b.) Diamond abrasive tooling radial cutting force vs. speed in CB1100



c.) Diamond abrasive tooling radial and tangential cutting force vs. feed rate in CB1100



d.) Diamond abrasive tooling radial and tangential cutting force vs. depth of cut in CB1100

Figure 5-23: Diamond abrasive tooling tangential force trends in CB1100.

PCD cutting tools also showed a similar dependence on feed for tangential and radial cutting forces, shown in Figure 5-24. For all cutting tools and parameters it is found that tangential and radial cutting forces exhibit similar dependencies and behavior. Further, the magnitudes of the cutting forces in the tangential and radial directions are similar in nearly all cases.

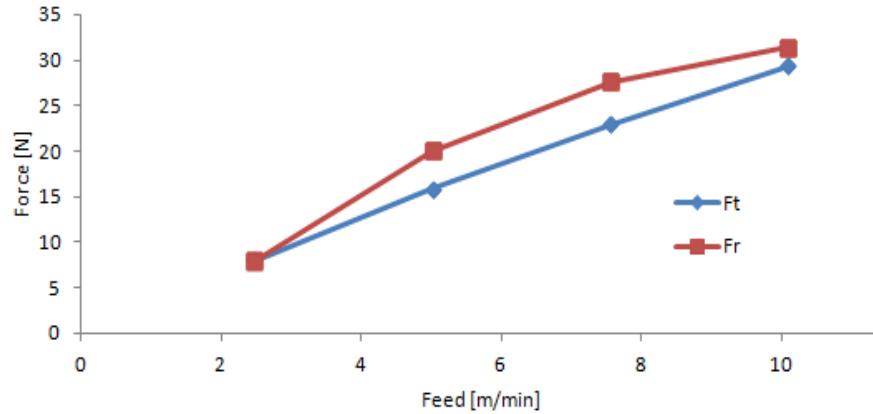


Figure 5-24: PCD Tooling Radial and Tangential Force vs. Feed Rate in CB1100.

From the machining tests conducted in CB1100 using diamond abrasive cutting tools, a chipload threshold was found, below which minimal cutting forces are produced. Testing shows that this minimal chipload level occurs at a feed rate of 1.27 m/min at 5500 RPM, which corresponds to a chipload of 0.23 mm/rev. This leads to the following finding with respect to machining CB1100 with diamond abrasive type tools: *There exists a threshold chipload level of 0.23 mm/rev below which, cutting forces remain minimal and slowly increase linearly with greater chipload. Above this threshold level, cutting forces rapidly increase.*

Feed rates for the PCD cutting tool were varied from 2.54 – 10.16 mm/min. A shallow linear increase in cutting force was observed for PCD tooling. This behavior leads to suggest that PCD based tooling should utilize the maximum feed rate possible. For diamond abrasive tooling, it is suggested that increased material evacuation be investigated. However, due to the high depth of cut that diamond abrasive tooling is capable of supporting the maximum material removal rates surpass that of the PCD tooling investigated regardless of this problem.

5.3.3.2 AAC

Cutting forces in AAC measured using PCD cutting tools were too low to ensure reliable data. Therefore, the cutting force study for AAC was based upon diamond abrasive type tooling. The measured tangential and radial cutting forces were tabulated and plotted in order to illustrate the effects of different feed rates. The influence of feed rate on radial cutting force is shown in Figure 5-25. A linear relationship is evident between feed rate and cutting force. The influences of feed rate at three different axial depths of cut are shown. As depth of cut increases, the dependence on feed rate (slope) increases as well. This indicates an interaction effect between feed rate and depth of cut for radial cutting force.

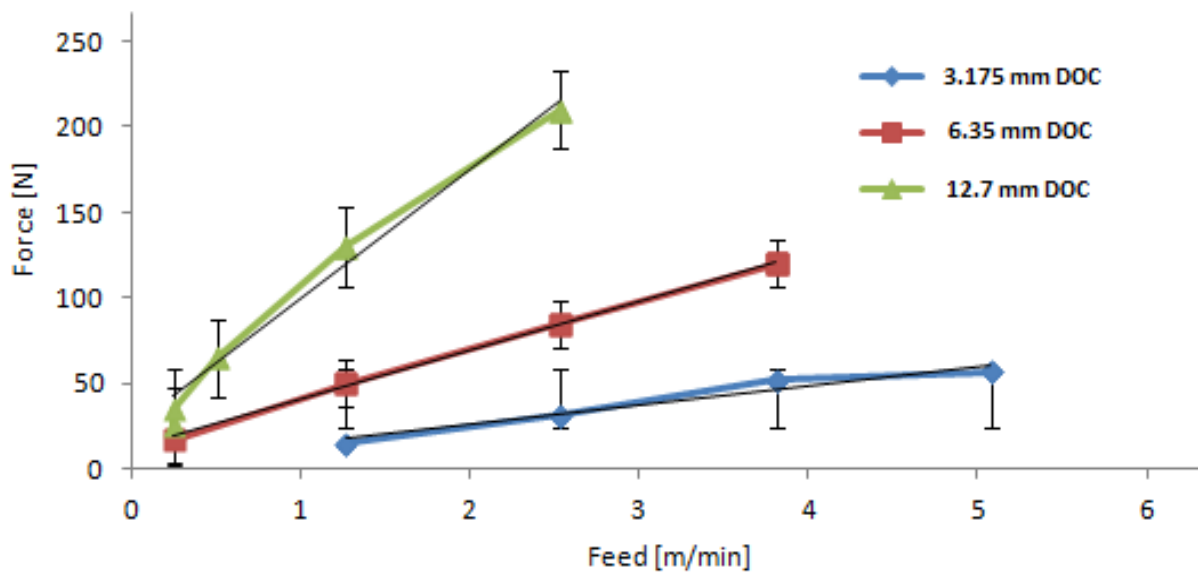


Figure 5-25: Radial cutting force vs. feed rate for 3.18, 6.35, and 12.70 mm axial depths of cut using diamond abrasive tooling in AAC.

Unlike the radial cutting force, tangential cutting forces did not show an increasing dependency on feed rate at higher depths of cut, Figure 5-26. It was found that the tangential cutting forces measured at 6.35 mm and 12.70 mm depths of cut were equal and showed the same dependence on feed rate. No interaction effect between the depth of cut and feed rate was evident at this level. However, at lower depths of cut an interaction effect is visible. When axial

depth of cut is increased from 3.18mm to 6.35mm the slope of cutting forces increases. This behavior is indicative of a higher order interaction effect between depth of cut and feed rate in the tangential direction than radial.

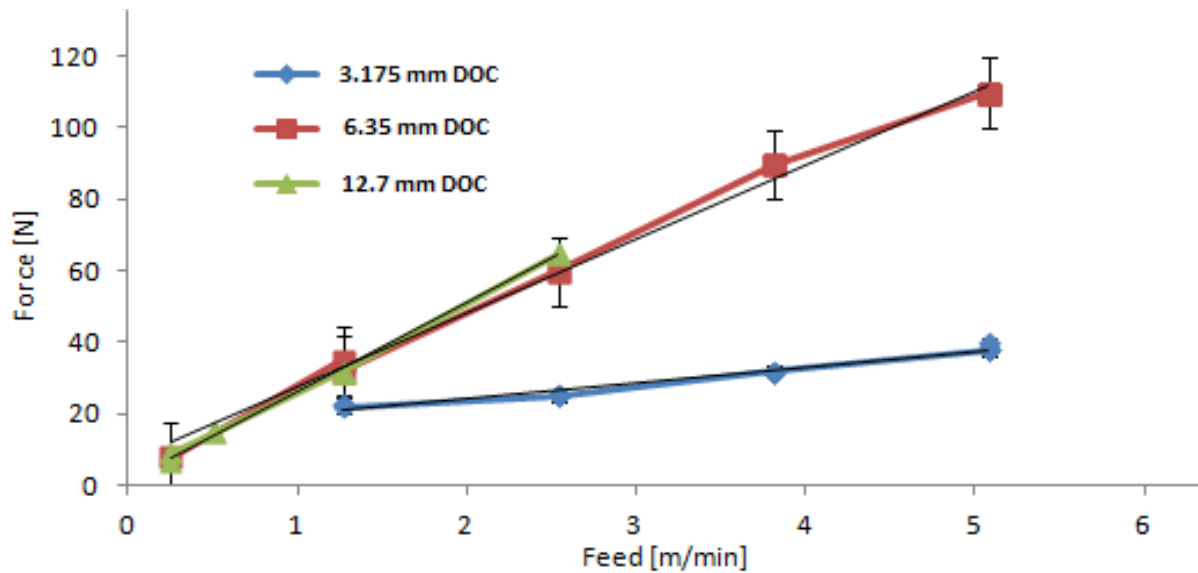


Figure 5-26: Tangential cutting force vs. feed rate for 3.18, 6.35, and 12.70 mm axial depths of cut using diamond abrasive tooling in AAC.

Observed increases in radial cutting force sensitivity to feed rate when employing increased depth of cut is a result of poor material evacuation. Radial forces increase in order to maintain contact with the material. Tangential forces increase as radial pressure and frictional forces increase. However, tangential force will only increase until the pressure exerted on the material in the tangential direction reaches the strength of the material. When this occurs, the tool is essentially forced through the material with the material fracturing/crushing as a function of the thrust force and friction.

5.3.3.3 Cfoam

As in AAC, PCD cutting tools failed to produce cutting forces high enough in magnitude to yield reliable measurements in Cfoam. Background noise of the dynamometer was on the same order as the cutting forces. This was largely due to the limited depth of cut possible with the available tooling. With diamond abrasive tooling the *minimum* depth of cut was also limited. For axial depths of cut below 12.70 mm the cutting forces were of similar magnitude to the background noise of the system and could not be reliably measured. The tangential and radial cutting forces vs. feed rate are shown below in Figure 5-27 and Figure 5-28. Variation in the cutting forces resulted in a high average standard deviation. This is partially due to the variation in the pore geometry and distribution. Variation in measurement of the cutting forces due to the low nominal magnitude and the presence of background noise contributed to high standard deviation as well. Depth of cut had a linear effect on cutting force. The sensitivity, or slope, is low and with large amounts of scatter in the data. Although a positive relationship would be expected, the scatter in the data does not allow the exclusion of a nearly flat, or non-relationship.

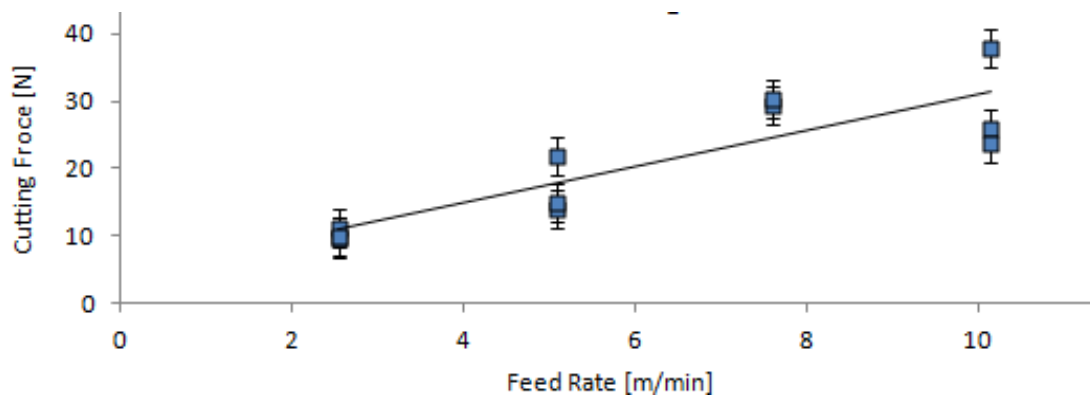


Figure 5-27: Tangential cutting force vs. feed rate obtained using 12.70 mm depth of cut using diamond abrasive tooling in Cfoam.

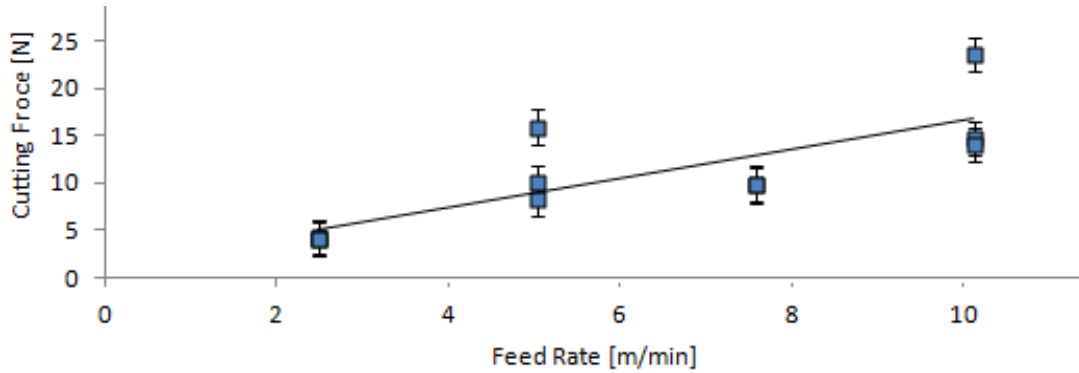


Figure 5-28: Radial cutting force vs. feed rate obtained using 12.70 mm depth of cut using diamond abrasive tooling in Cfoam.

5.3.4 Effects of Cutting Tool Type on Cutting Forces

Cutting forces depend upon cutting edge geometry. Different types and geometries of cutting tools produce different cutting forces and behavior as shown in Figure 5-29. Selected cutting force plots typical of those produced by each type of cutting tool at 6000 RPM and 10.16 m/min. Plots presented here were recorded while machining Cfoam. Fluted tools produce low radial cutting forces in comparison to the tangential direction. Diamond abrasive cutting tools exhibit more distinct radial cutting forces and higher cutting force magnitudes in both the tangential and radial directions when compared to fluted tools.

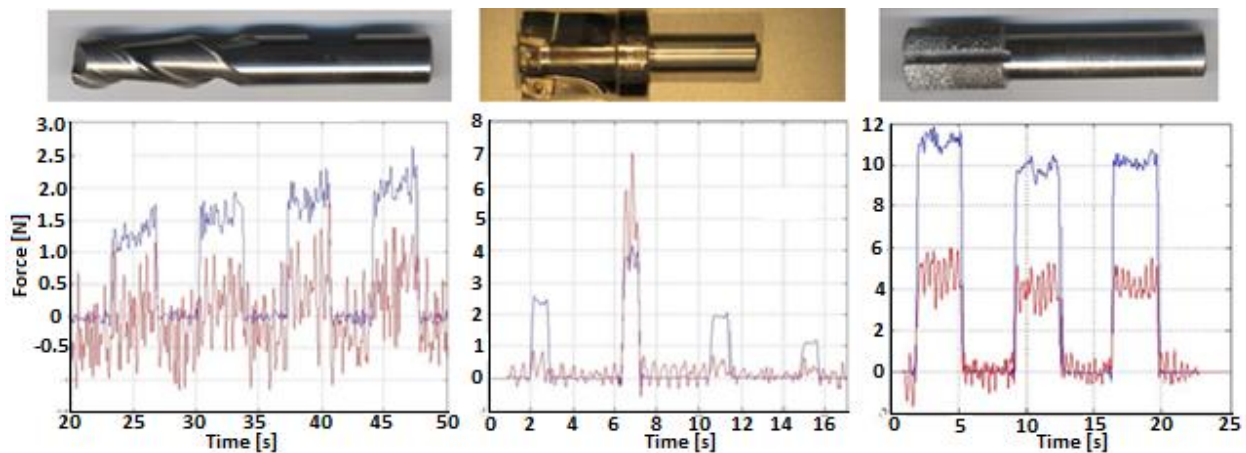


Figure 5-29: Comparison of typical cutting forces of each type of cutting tool studied in Cfoam at 6000 RPM and 10.16 m/min.

5.3.5 Surface Quality

The surface roughness of the machined surfaces in AAC and Cfoam was dominated by the pits and holes inherent to the material. Surface roughness measurement of AAC and Cfoam was not possible with current equipment available. Pores were too large for the standard 2.0 μm radius tip probe. Further, the 1.50 mm ball tipped probe smoothed the surface to an erroneously low value, making it seem as though the Cfoam and CB1100 had similar surface roughness values. Figure 5-30 and Figure 5-31 plot the measured average surface roughness values in all directions against feed rate and chipload respectively for CB1100. Roughness is nearly constant when plotted against feed rate, Figure 5-30. However, the band of roughness values plotted by chipload show more consistently higher roughness values in all directions as chipload increases. Both plots show a maximum roughness threshold of approximately 18.0 μm , roughly the low range of the pore radius in CB1100, 20 μm .

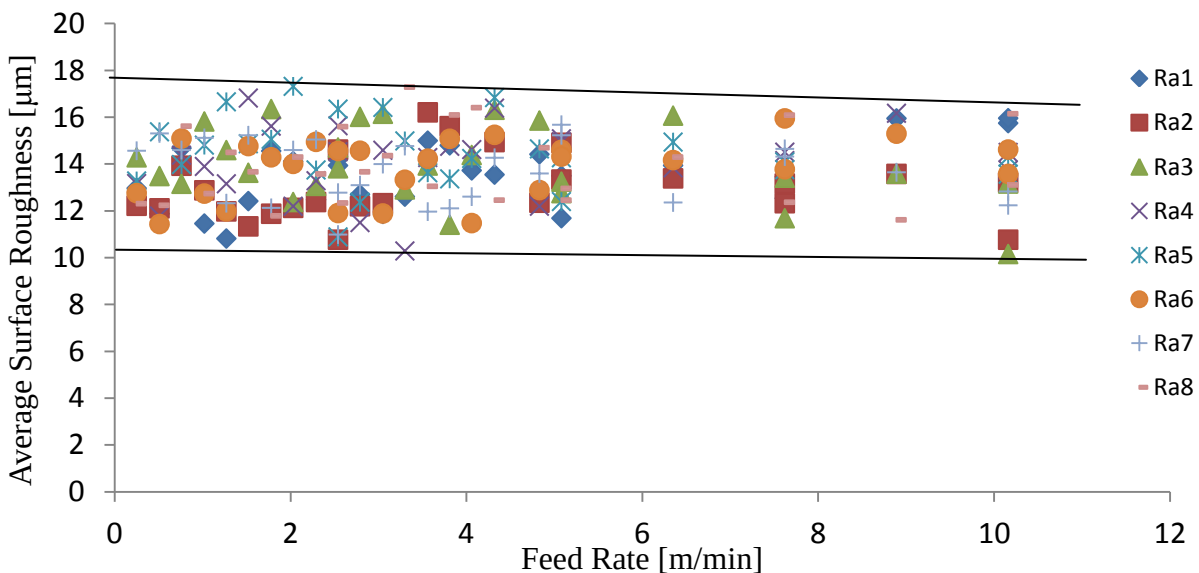


Figure 5-30: Average surface roughness vs. feed rate in CB1100 for PCD cutting tool.

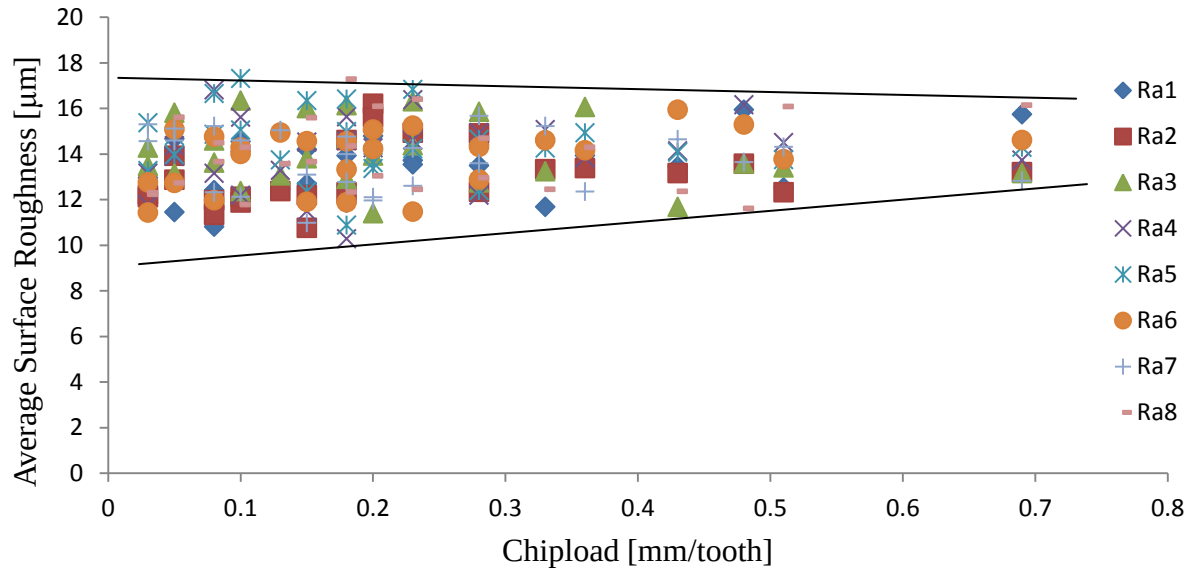


Figure 5-31: Average surface roughness vs. chipload in CB1100 for PCD cutting tool.

An SEM image of a machined sample of CB1100 is shown below in, Figure 5-32 in which small circular pores are visible. The majority of pores range in size from 0.04 - 0.15 mm in diameter. Pores are relatively large in comparison to the theoretical size of the feed marks which normally dominate surface roughness; explaining why cutting conditions are not as influential on the surface roughness as expected.

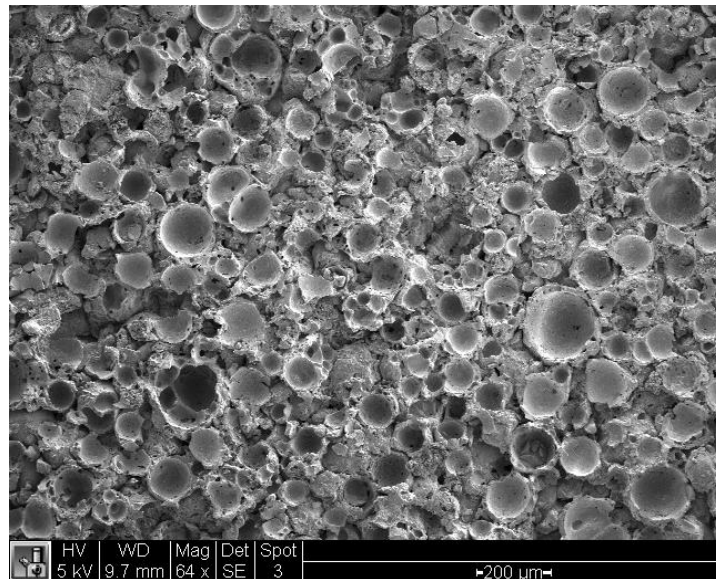


Figure 5-32: SEM image of CB1100 machined at 4000RPM and 10.16 m/min.

5.3.6 Comments on Machinability

These following sections will discuss three experimental observations noted during testing that were determined to be of significant importance to the machinability of the materials. The maximum feed rate used during cutting force measurement of CB1100 with the diamond abrasive tooling was 2.0 m/min. At feed rates beyond this level material evacuation became problematic leading to clogging or buildup of powder on the surface of the tool. Clogging was most problematic on the bottom surface of the tool as shown in Figure 5-33.

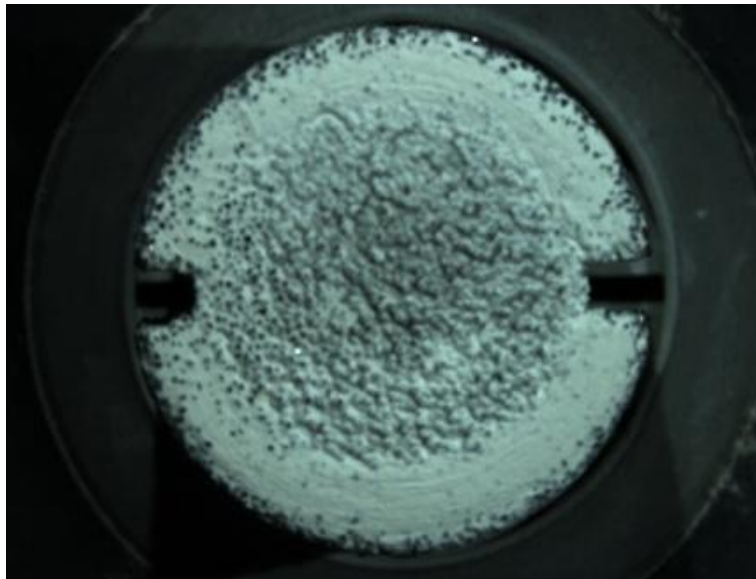


Figure 5-33: CB1100 powder buildup on tool face.

Buildup of material was also particularly problematic for the 25.40 mm diameter diamond abrasive tool used to create the surface roughness test surfaces. The larger diameter tool was less efficient at material evacuation than the smaller diameter tool tested. Thus limiting the feed rates used during both the force measurement portion of the study as well as the surface roughness portion. Figure 5-34 illustrates the damaging effect of this buildup on the workpiece.

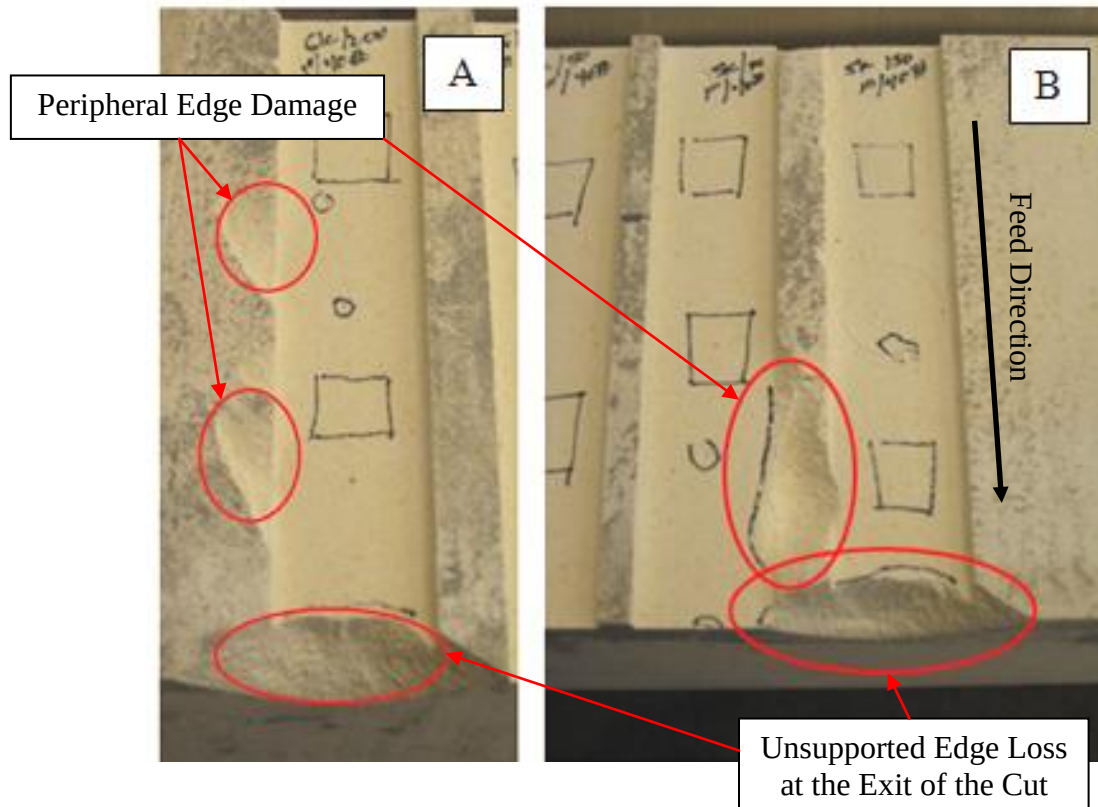


Figure 5-34: Surface roughness sample showing damage occurring while machining CB1100 using a 40# diamond abrasive tool at 6000rpm, 25.40mm RDOC and (a) 5.08 m/min (b) 3.81 m/min.

Large sections of edge damage in these figures are the result of high radial cutting forces. Peripheral damage is the result of the tool deflecting heavily due to poor material evacuation at higher feed rates. Unsupported edge loss occurred as the tool neared the edge of the sample. As the tool nears the exit of the cut the sample fractures when the remaining thickness of the sample is incapable of supporting the forces. Unsupported edge loss was the most severe of the observed damage. A schematic diagram of the types of macro-scale damage observed during testing is shown in Figure 5-35.

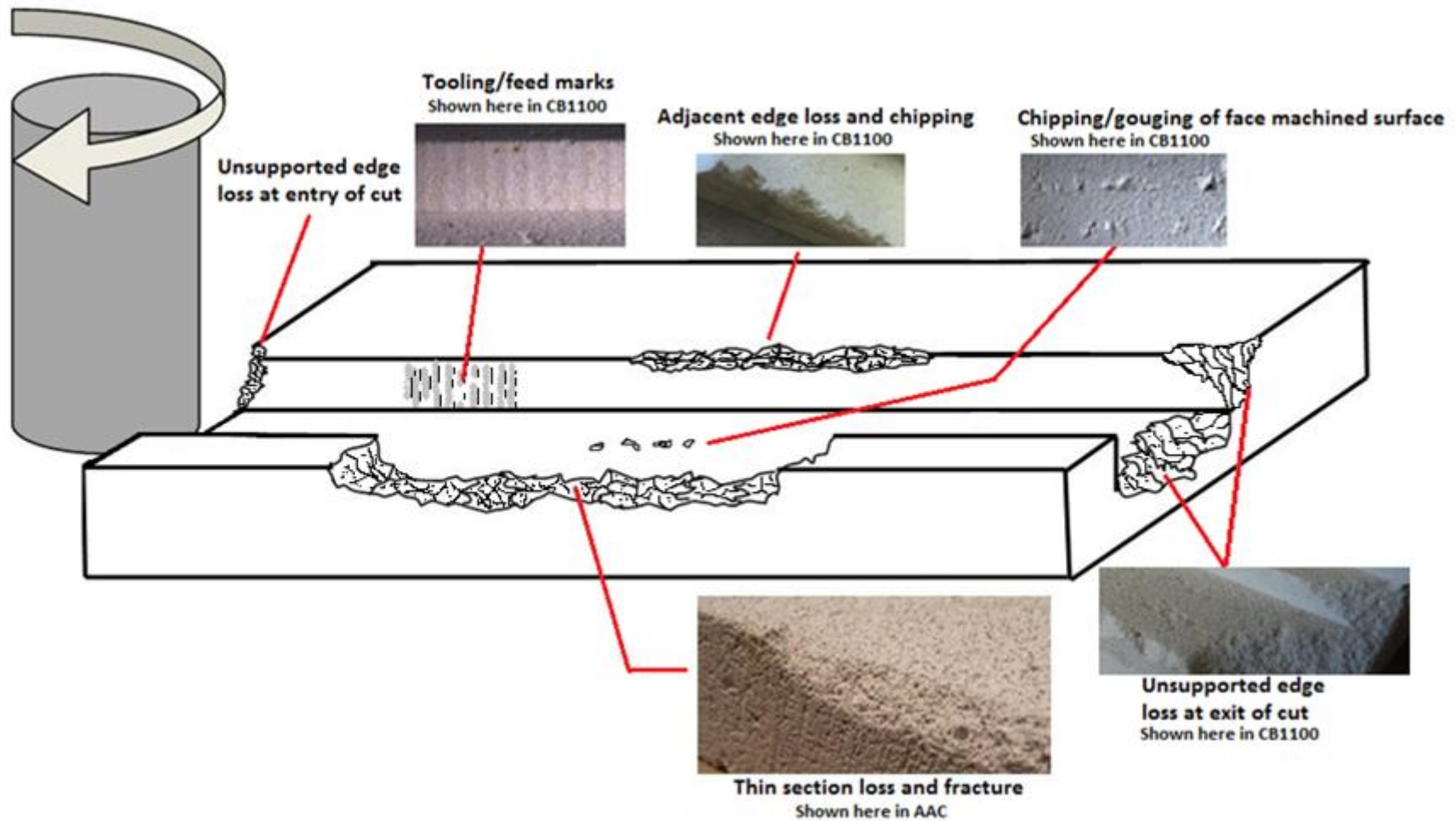


Figure 5-35: Schematic diagram of types of observed damage.

Although upon initial inspections CB1100 appeared to be a predominately homogeneous material, significant sized sections of lower strength material were found. These lower strength sections were found to have largely reduced cutting forces in both tangential and radial respects. Significant decrease of cutting forces found to be in the center of the sample material block, which was observed for several test cuts as shown in Figure 5-36 and highlighted in Figure 5-35. Further study the sample following the cutting tests was not possible because the section had been machined away.

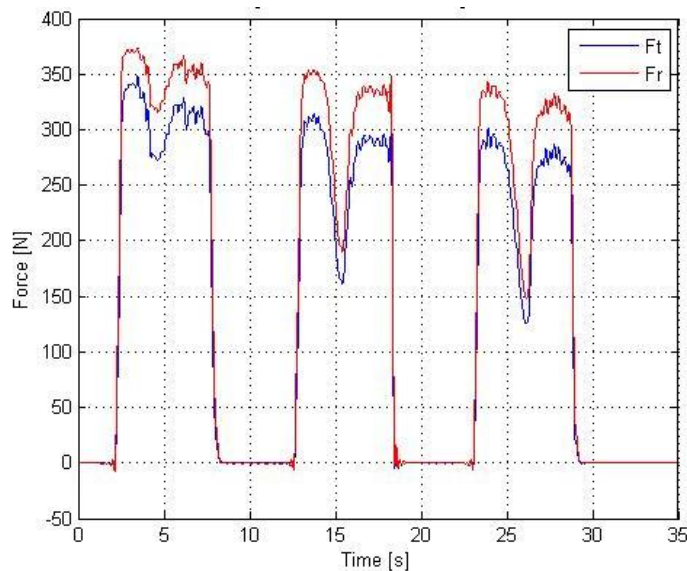


Figure 5-36: Cutting force curves illustrating heterogeneous sections of CB1100.

If the edges of the cutting force profiles are correlated to the edges of the sample the size of the region corresponds to an elliptical shaped section of approximately 75x50x13 mm. A region of this size with sub-standard properties can lead to a loss of the workpiece's ability to sustain its structural integrity. For example, if this section were near the exiting edge of the workpiece it may not be able to sustain the forces imposed by the cutting tool leading to a significant section of material loss. Heterogeneity could be due to poor manufacturing or quality

control standards. Heterogeneity can lead to a significant temperature and/or stress differential in the finished composite tool which may lead to distortion, cracking or even failure during use.

Figure 5-37 shows the tangential and radial cutting forces of four test cuts performed in Cfoam using a PCD cutting tool at 6000 RPM. In Figure 5-37b radial cutting forces are negligible for three of the four test cuts. The peak occurring at approximately 6 seconds is due to the cutting tool encountering the hardened bonding material used to bond blocks of Cfoam together. The bonding lines found in Cfoam are the result of the material used to join subsequent blocks of material together when larger workpieces are required. Bonding material causes two problems. First, material in these regions has significantly higher cutting forces than the surrounding Cfoam. Secondly, the hardened bonding material is brittle and commonly fails in large planar sections. These sections have a tendency to remove significant portions of the adjacent material. Should a heterogeneous section of material with reduced machinability be encountered, feeds and speeds must be decreased to compensate. If a section such as this be encountered unexpectedly during machining, damage to the cutting tool and workpiece may occur.

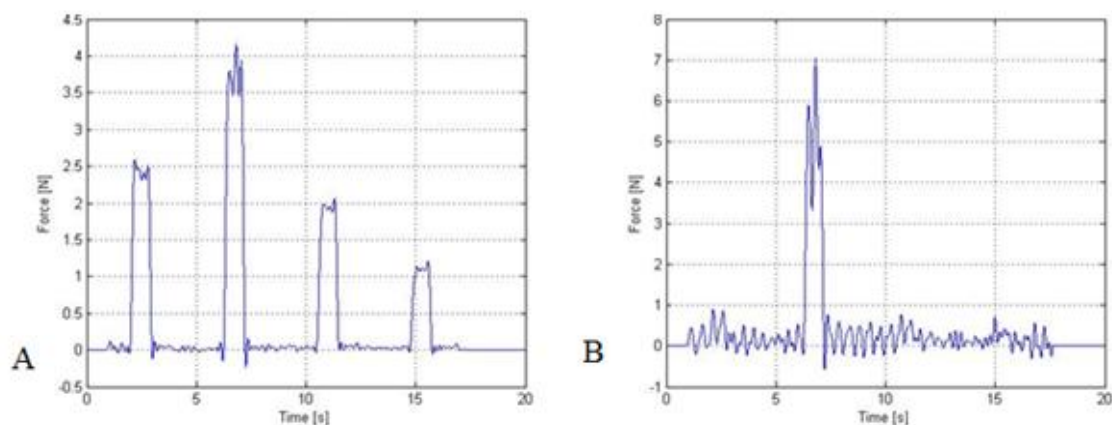


Figure 5-37: (a) Tangential and (b) radial cutting force in Cfoam using PCD cutting tool at 6000 RPM, 10.16 m/min, 3.18mm ADOC.

5.4 Summary and Conclusions

Machinability experiments have been conducted on three separate commercially available brittle porous materials as a feasibility investigation for the fabrication and use of these materials in aerospace composite tooling. Machinability was evaluated in terms of cutting force measurement, surface profilometry, and optical examination in order to determine the best feasible cutting conditions. Experiments investigating the cutting forces' profiles and behavior with respect to variation in the: speed, feed, depth of cut, cutting tool material and type were performed. Surface quality and the effects of machining conditions upon surface integrity were investigated using surface profilometry and optical examination. Tool wear resulting from the machining of these three materials was also studied. Based on this preliminary study, following conclusions and observations were made:

5.4.1 CB1100:

- When using diamond abrasive tooling, there exists a “threshold” chipload level of approximately 0.23 mm/rev below which, cutting forces are consistently linear and low. Beyond this chipload, cutting forces increase rapidly.
- Diamond abrasive tooling produced high material removal rates due to the large axial depths of cut that were achievable.
- The PCD tooling used, while capable of higher feeds than the diamond abrasive tooling, had a limited material removal rate due to the low axial depth of cut capabilities.
- Surface quality was found to be nearly independent of the machining conditions due to the presence of spherical pores inherent to the material.

- Pores range from 0.051 - 0.127 mm in diameter causing them to dominate surface integrity behavior.
- No significant or measurable tool wear was experienced while machining this material.

5.4.2 Cfoam

- Cfoam was found to be extremely free cutting, with very low cutting forces.
- Despite the low cutting forces, the extremely abrasive nature of this material lead to rapid cutting tool wear in HSS tooling.
- Measurable tool wear was also found while using PCD tooling.
- Little to no wear was found while using diamond abrasive cutting tools due to the fact that the abrasion was distributed over numerous cutting edges instead of concentrated on only 3. Therefore, diamond abrasive tooling is exclusively recommended for this material.
- Edge retention was found to be problematic at higher feeds and lower speeds due to the materials inability to support the higher loads. This decreased the achievable material removal rates.
- Surface quality of Cfoam was also dominated by the material's inherent surface features and found to remain nearly constant regardless of machining conditions.
- On a macro scale Cfoam itself is a homogeneous material. However, the adhesive used to bond adjacent blocks of Cfoam together creates heterogeneous regions within the part.

- This region has cutting forces many times greater than that of the Cfoam. This leads to a significant concern when machining at high feed rates. When encountered, these regions often fracture causing heavy damage to the workpiece.

5.4.3 AAC

- Autoclaved aerated concrete was found to have large radial forces at higher feeds. This is likely due to poor material evacuation. Powdered material from the machining of AAC would periodically build up on the tool by being compressed into the crevices between abrasive particles. This leads to a “built up edge” type effect in which radial forces drastically increase and cause excessive heating and possible failure of the tool and/or severe damage to the workpiece.
- This effect was also found to occur on the bottom face of the tool, again causing severe damage to the workpiece.
- This difficulty limited the maximum achievable material removal rate but was less significant at lower feed rates.
- No significant tool wear was observed while machining this material with any cutting tool.
- Surface finish was again dominated by macroscopic features inherent to the material’s surface. The low strength of this material lead to significant edge retention difficulties. Large sections of material near the tool’s exit were regularly lost due to the materials inability to support the loads.
- AAC was also noted to be significantly heterogeneous, containing regions of noticeably higher density and lower porosity.

5.4.4 Summary

The recommended parameters given in Table 5-5 are intended as conservative starting points and should be adjusted to suit the machining system employed.

Table 5-5: Recommended cutting parameters

Material	Tool Type	Recommended Speed [surf m/min]	Recommended Chipload [mm/rev]DA / [mm/tooth]PCD	Recommended Depth of Cut [mm]
CB1100	Diamond Abrasive	299	0.229	12.70 - 19.05
CB1100	PCD	597	0.406	3.18
Cfoam	Diamond Abrasive	299	1.270	12.70 - 25.40
AAC	Diamond Abrasive	299	0.076	12.70
AAC	PCD	597	0.406	3.18
Cfoam	PCD (not recommended)	597	0.406	3.18

As shown in Table 5-5, utilizing diamond abrasive cutting tools and Cfoam carbon foam yields the highest material removal rate. Cfoam is capable of the most rapid production of net geometric form for composite tooling substrates. In conclusion, the machinability of three commercially available materials: AAC, CB1100 and Cfoam have been investigated based upon cutting forces, surface topography, and tool wear for differing tool types. Effects of cutting conditions on each of the aforementioned parameters has been investigated and discussed. Finally the best feasible cutting conditions have been given as recommended conservative starting points for the machining of these three materials based upon cutting force, surface quality, and tool type. These recommendations and the ranges of measured responses will be used during the remainder of the research to design and guide further experimentation.

Chapter 6: Experimental optimization

The experimental optimization stage of the research was focused on modeling of the cutting forces and determination of the effects of machining induced damage on surface integrity. Empirical determination and modeling of the tangential and radial cutting force for each material was performed using a full factorial design of experiment. Machining induced damage was identified using SEM and optical examinations. Four point flexural tests were conducted in order to determine the effects of machining induced damage on residual flexural strength and surface integrity.

The results and discussion of the experimental optimization study are presented in the following sections. The chip formation of each material is presented followed by cutting forces, surface topography, machining induced damage, and finally surface integrity. The results of each study in each material are presented in separate subsections. A selection of typical results of each study is presented for all three materials. The full collection of the results is offered in Appendix D-G

6.1 Experimental equipment

Machining tests were conducted on the same Haas TM1p vertical milling machine used during the feasibility investigation. However, the primary cutting force measurement instrument during the optimization study was a Kistler Instruments 9257b three component plate dynamometer. The rotating dynamometer utilized during the feasibility investigation was not available during the experimental optimization stage of the research.

The cutting tool used throughout the research was a 12.70mm diameter 0° helix carbide cutter. A single cutter geometry and cutting tool material were selected for the experimental optimization stage of the research. A fluted tool was chosen in order to avoid the problematic

clogging of the tool observed during the feasibility investigation. The 9257b plate dynamometer had no cutter rotation angle or synchronization signal available. Therefore, a 0° helix cutter was chosen in order to simplify the calculation of tangential and radial cutting forces from Cartesian coordinate forces. Further, a 0° cutter would aid in distinguishing random and low magnitude cutting forces from the background noise of the measurement system. Carbide was selected as the cutting tool material primarily due to the lower cost compared to PCD. A carbide tool provided increased flute lengths at a fraction of the cost of an equivalent PCD cutting tool. In addition, carbide is a standard cutting tool material in the aerospace and composite industries.

6.2 Chip Formation

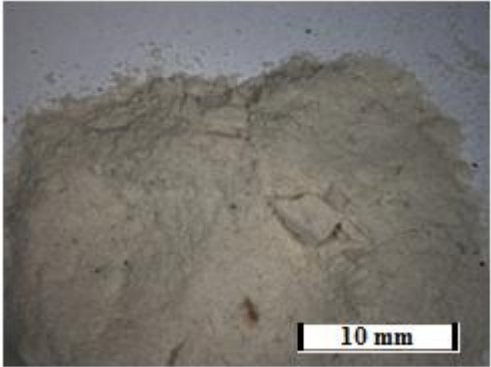
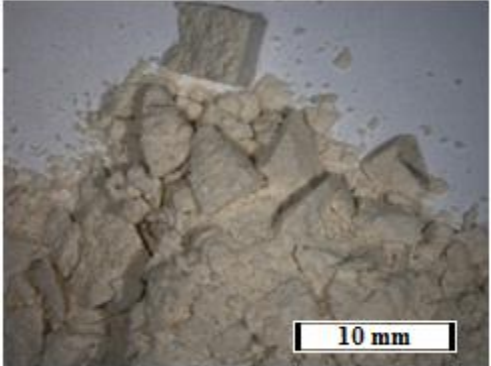
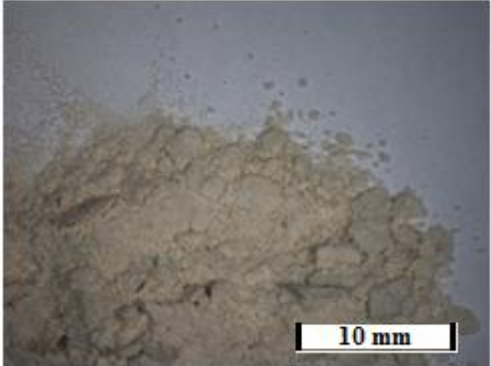
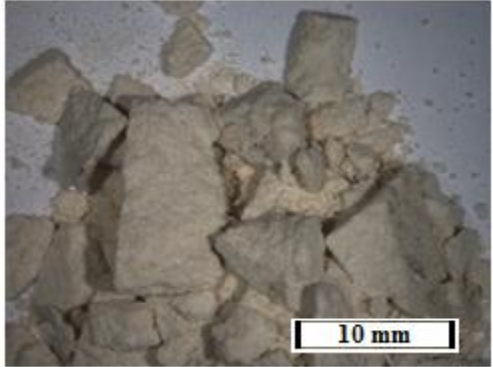
Chips and dust were collected during machining tests in order to study the size and form of the removed material. Both dust and larger sections of fractured material were collected and studied through optical examinations. Material was collected from all three materials over a range of cutting conditions in order to evaluate the influence of cutting conditions on the chip formation mechanism.

6.2.1 CB1100

The chip formation mechanism identified during the machining of CB1100 was found to be a combination of fracture/chipping and crushing. Larger sections of material were found to be removed in the form of chips of irregular shape due to the random nature of cracking and crack propagation. Material which is not fractured off in the form of a chip is likely crushed and removed in the form of a fine powder. The majority of material is removed in this manner. The mass of dust or powder created during machining outweighs the mass of the chips removed. However, as the cutting area and forces increases, the size of the chipped material and the ratio

of chips/dust increases as well. This can be seen in Table 6-1; as RPM increases and feed decreases, chip size decreases and dust volume increases. CB1100 was the only material to exhibit a change in the size fractured particles and or the ratio of chips/dust.

Table 6-1: Typical collected chips during machining CB1100

	4000 RPM	5000 RPM	6000 RPM
2.54 m/min			
5.08 m/min			
10.16 m/min			

6.2.2 AAC

Material removal in AAC during milling is primarily in the form of a fine powder with small fractured material interspersed. Large portions of removed material were only found when edge loss had occurred and large sections of material fracture away from the workpiece. However, these are not chips resulting from the primary material removal process and were not included in the examinations. A typical sample of the collected material is shown in Figure 6-1.



Figure 6-1: Typical dust collected while machining AAC

Chips resulting from the machining of the material were found. These chips were consistent in size and estimated to be approximately 1.0 mm across regardless of the cutting conditions. This suggests that their size is defined by the pore size and spacing. The majority of the particles shown in Figure 6-1 have an approximately size of 0.10 – 0.20 mm with intermittent larger particles of approximately 1.0mm. Fine powder is also present. The ratio of chips to dust per unit volume remained constant regardless of cutting conditions. With no change in the size of the chips or the ratio of chips/dust, it is believed that the chip formation mechanism is defined

by the pore size and spacing and is independent of machining conditions or cutting force within the conditions tested.

6.2.3 Cfoam

While machining Cfoam, material is removed in the form of a coarse powder which resembles loose abrasive aggregate particles. Large chips are not common, as shown in Figure 6-2. Large sections of material that are found are the result of edge loss or macro scale damage to the workpiece during machining. These sections are not chips resulting from cutting and were not included in the examinations.

The particle size of the removed material is estimated to be in the range from 0.05mm to 1.0 mm across their longest dimension. The variation in size is relatively large. However, it is consistent with respect to cutting conditions and showed no changes between cutting conditions. Because the material removal action is a form of controlled crushing and fracture, the particle size is controlled by the spacing of the pores and the size of the ligaments.

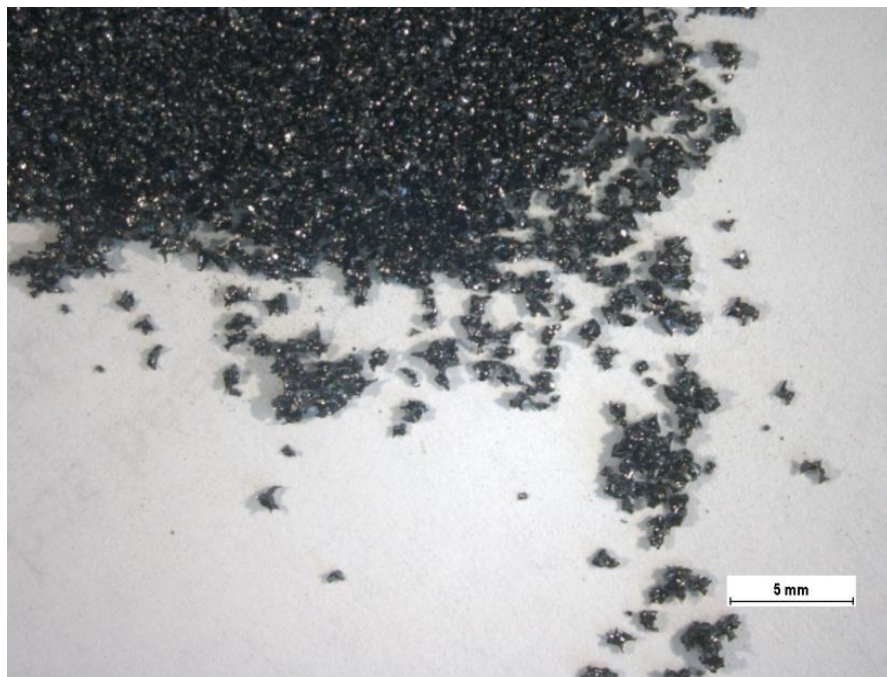


Figure 6-2: Typical dust collected while machining Cfoam

6.3 Cutting Forces

The cutting forces of the three tooling materials were tested according to a full factorial DOE using a Kistler Instruments plate dynamometer. The DOE for the experiments was described in Chapter 4 along with the force measurement system and methods. Following the experiments cutting forces were modeled empirically and analyzed through ANOVA. Selected results which are representative of the typical cutting forces for each material are presented in the following subsections. Results of the ANOVA and the empirical modeling of the cutting forces will be given in the discussion section of this chapter along with a comparison of the cutting forces of each material.

6.3.1 CB1100 Cutting Forces

With the highest density and smallest pore size, CB1100 is the strongest of the three materials. Cutting forces for CB1100 were therefore also the highest. Tangential and radial cutting forces were calculated from recorded Cartesian data according to the method described in Chapter 4. Plots illustrating the typical nature of tangential and radial cutting forces are shown below in Figure 6-3.

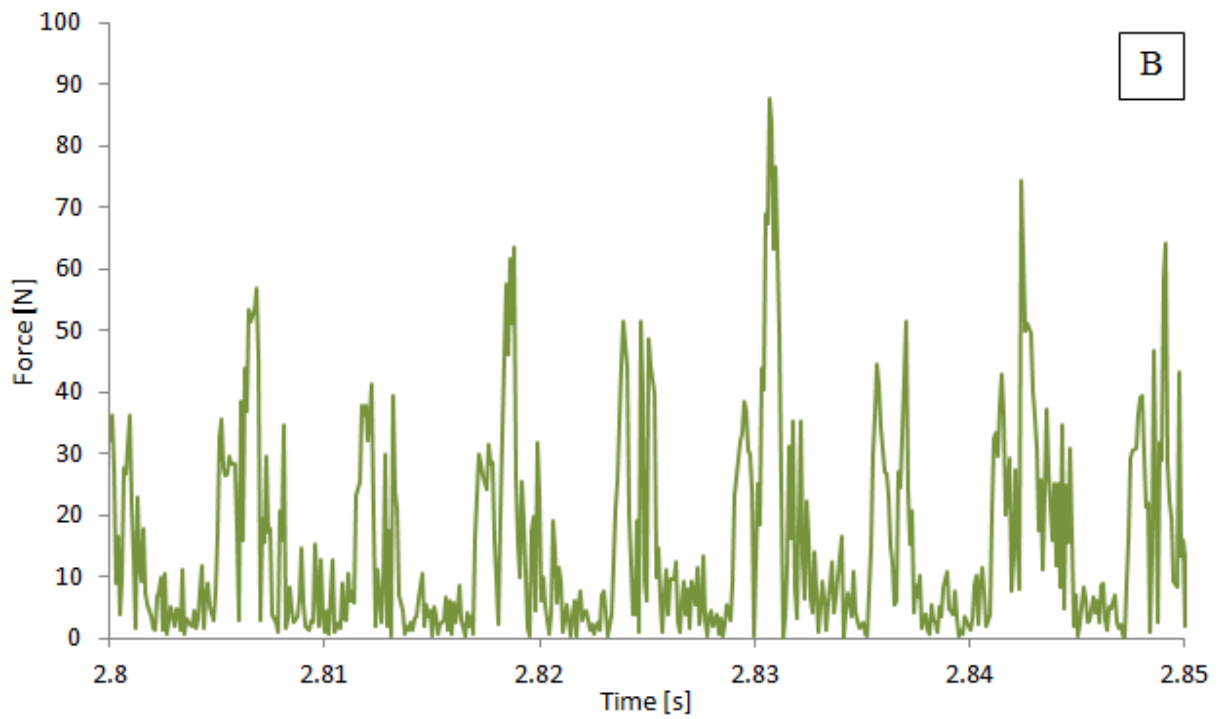
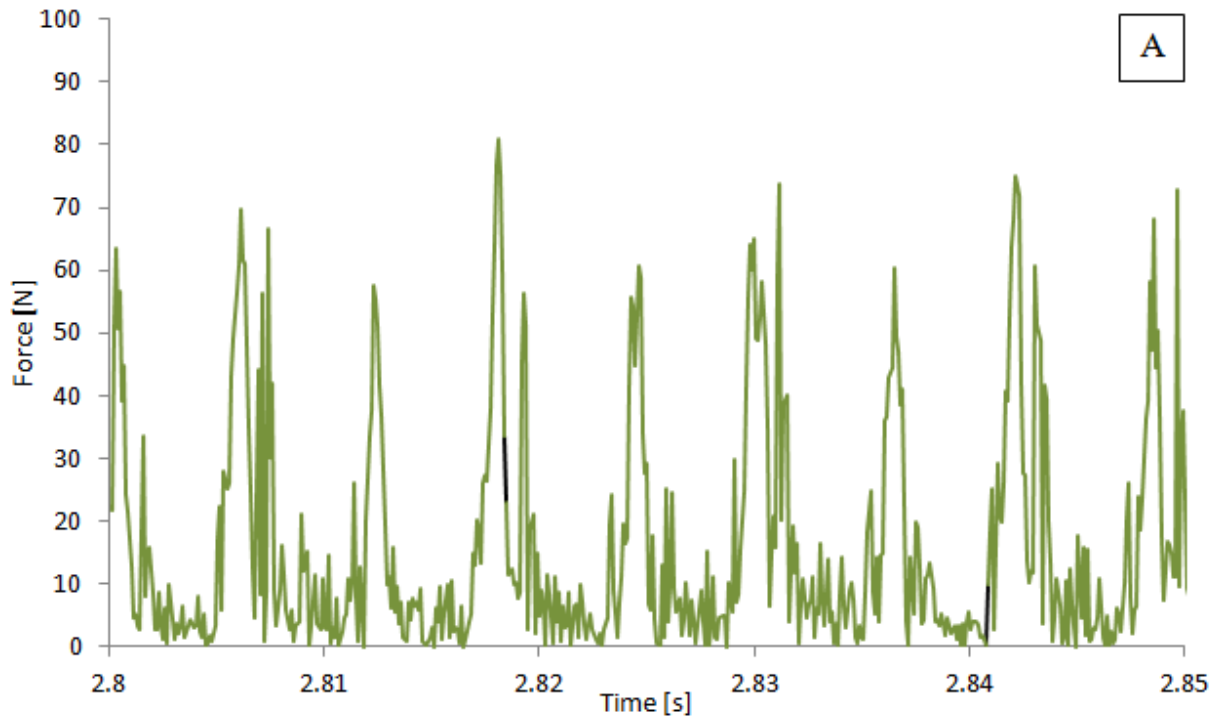


Figure 6-3: (a) Tangential and (b) radial cutting force in CB1100 using carbide tool at 6000 RPM, 5.08 m/min, 6.35mm ADOC, 6.35mm RDOC

Peak cutting forces ranged from 10 – 160 N. Peak cutting forces during heavy cutting conditions could vary as much as 40-50 N within the same test. For low cutting force conditions a variation of 100-200% in peak cutting force from one engagement to the next was common, even for the same tooth. Cutting force profiles were random in shape and magnitude, due to the random nature of the material's porosity. Mechanics of the process, dictated by the machining conditions, would predict the peak cutting force to occur just before the exit of the engagement. However, the peak cutting force magnitude and location occurred randomly. Despite the random nature of the cutting force profiles and magnitudes, the averaged measured peak cutting forces were found to behave predominantly linearly with respect to cutting parameters. The predominant influential factors affecting the peak cutting forces were found to be the feed rate and axial depth of cut.

6.3.2 AAC Cutting Forces

Typical tangential and radial cutting force plots are shown below in Figure 6-4. The peak tangential cutting forces were found to range from 10-70 N while the peak radial forces were found to range from 8 – 60 N. The radial cutting force was often nearly as high as the tangential cutting force and periodically higher. There was a large variation of cutting force within the same cutting conditions. Cutting forces were found to vary as much as 200% from one cutter engagement to the next, due to the random nature of the pores of the material. The randomness of the pore size and distribution is due to the variation imparted during manufacture. As discussed in Chapter 4, homogeneity is difficult to ensure due to the process used to manufacture the material.

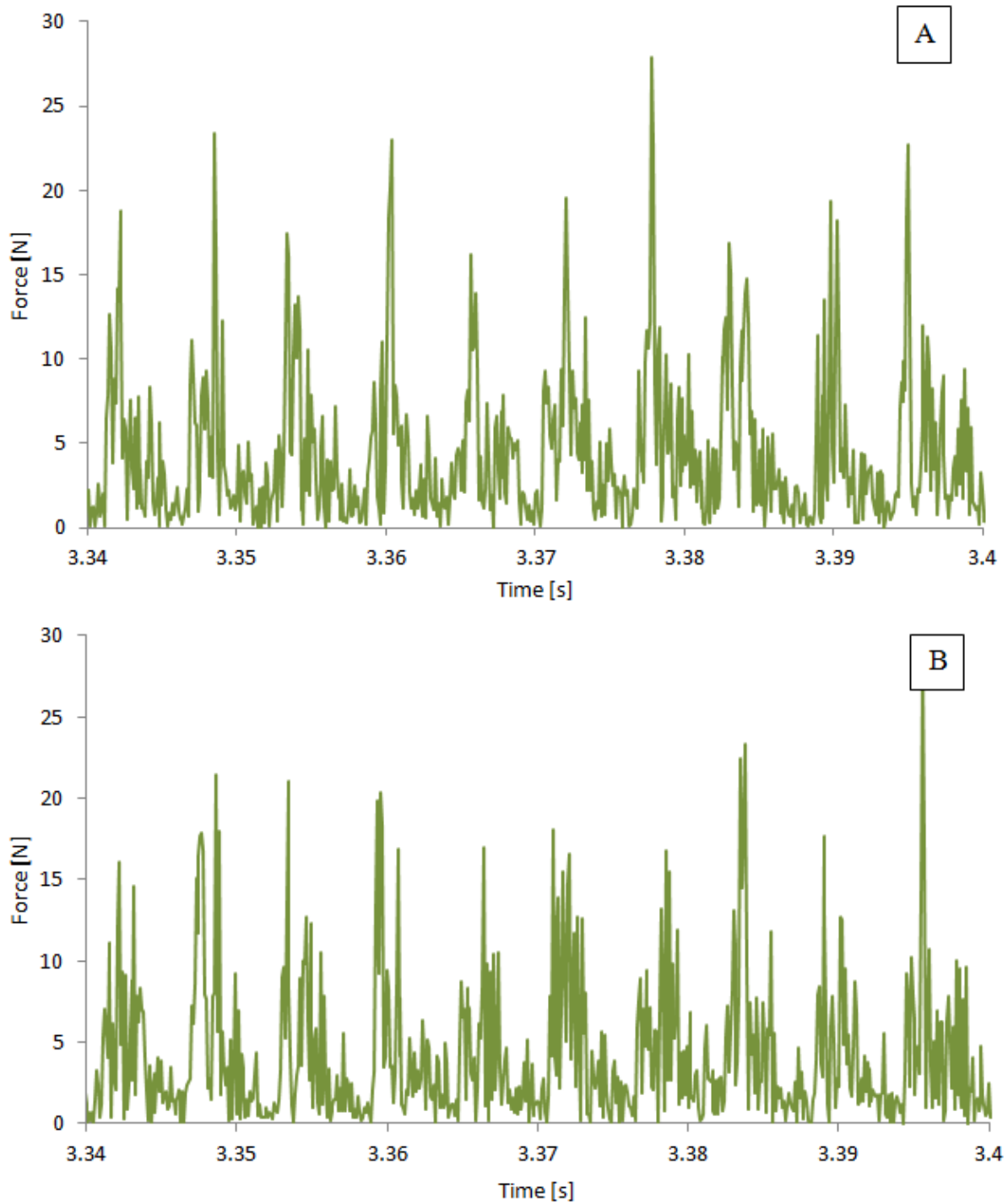


Figure 6-4: (a) Tangential and (b) radial cutting force in AAC using carbide cutting tool at 5000rpm, 2.54m/min, 6.35mm ADOC, 6.35mm RDOC

6.3.3 Cfoam Cutting Forces

The results of the cutting force study on Cfoam are presented here. Tangential and radial cutting forces were calculated from the recorded data according to the analysis discussed in the Cutting Force Analysis section. Typical tangential and radial cutting force plots are shown in Figure 6-5 for cutting conditions of 6000 RPM, 2.54 m/min, 6.35mm ADOC, and 6.35mm RDOC. The time period when the cutting edge is in contact with the material is referred to as the *engagement period*, and is plotted as a red square wave in Figure 6-5.

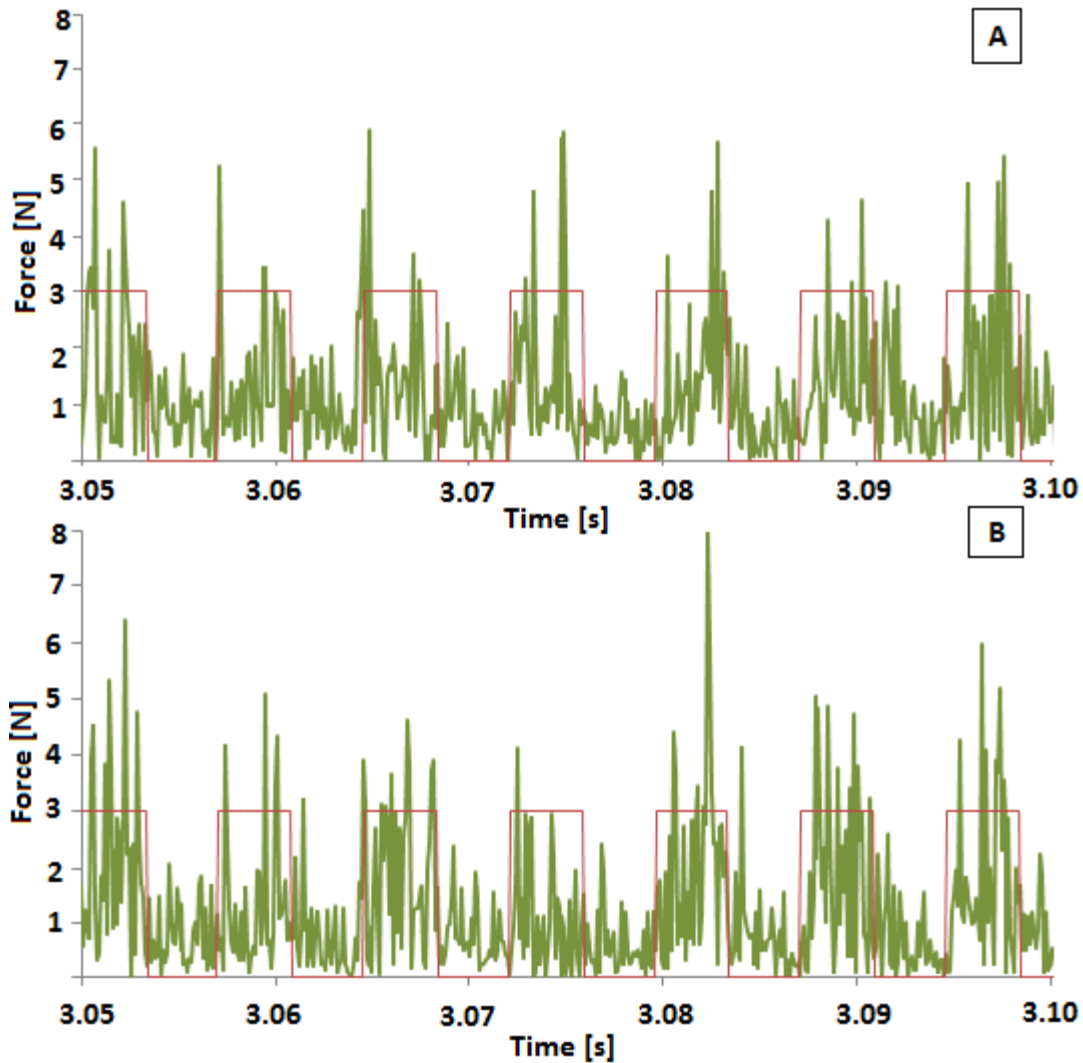


Figure 6-5: (a) Tangential and (b) radial cutting forces machining Cfoam at 6000RPM, 2.54m/min, 6.35 ADOC, and 6.35 RDOC.

The engagement period is plotted to help the reader visually distinguish the cutting forces from the background noise of the signal. The average peak cutting forces ranged from 5 – 50 N. Cutting force profiles in Cfoam exhibited the highest level of randomness and variation. Peak cutting forces varied as much 200% while using constant cutting conditions. Cfoam contains large pores, which are the most randomly shaped of the three tested materials. The low strength of the Cfoam resulted in low cutting forces which were often difficult to accurately measure.

6.4 Surface Topography and Machining Induced Damage

Machined surface topography and machining induced micro scale damage was evaluated using a combination of surface profilometry, scanning electron microscopy and optical microscopy. Two sets of machining parameters were used to create samples from each material. The two sets of cutting conditions were: 4000 RPM with a feed rate of 10.16 m/min and 6000 RPM with a feed rate of 2.54 m/min. These conditions represent the extremities of the cutting forces found during the cutting force experiments. Based on the results of the feasibility investigation, high cutting forces are assumed to induce equal or higher levels of damage than low cutting forces. Any changes in the amount of damage induced during machining should therefore be evident between the two sample sets. Results of the surface topography studies and examinations of machining induced damage are presented in the following sections.

6.4.1 CB1100 Machined Surface Topography

Figure 6-6 shows the surface morphology of the machined surfaces and their corresponding surface profiles. Scanning electron images of samples machined at high cutting force (4000 RPM and 10.16 m/min) and low cutting force (6000 RPM 2.54 m/min) are shown in Figure 6-6a. At low magnification, little difference in the surface topography is discernible with

the naked eye. However, surface profilometry was able to distinguish differences between the samples. Typical surface roughness profiles obtained during the surface quality study are shown in Figure 6-6b. Directional dependency of the surface roughness was found and is evident in Figure 6-6c. There is also a dependency upon type of cutting action which created the surface, i.e. peripheral or face milling.

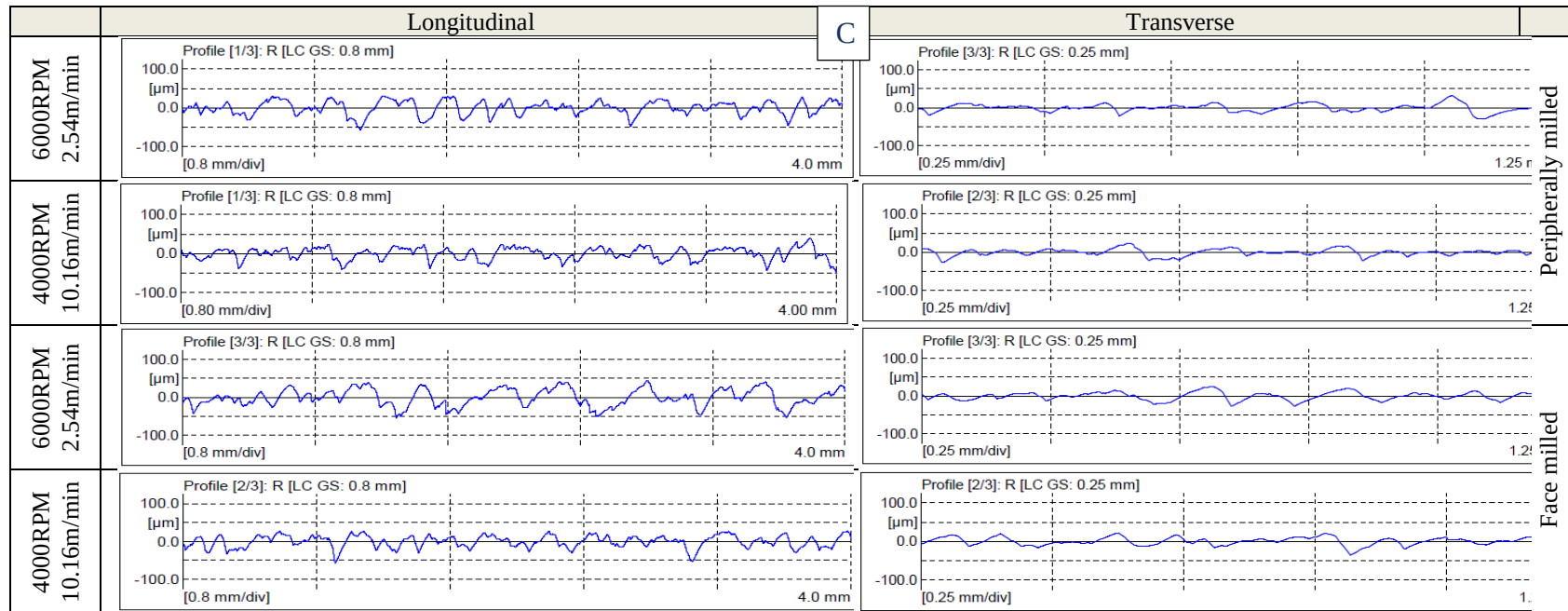
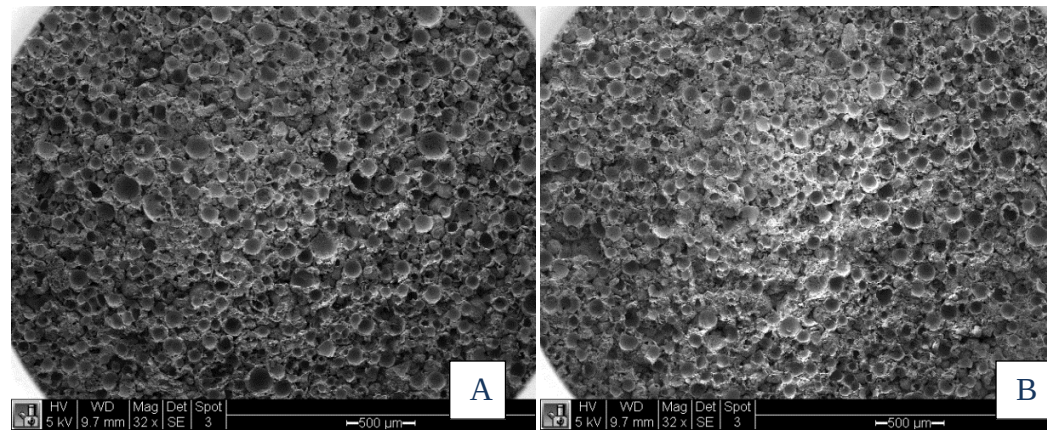


Figure 6-6: a.) SEM image of CB1100 surface machined at 4000 RPM and 10.16 m/min. b.) SEM image of CB1100 surface machined at 6000 RPM and 2.54 m/min c.) Typical peripherally and face milled surface profiles

A summary of the surface roughness values is tabulated results of the studies are shown in Table 6-2 and Table 6-3. Average surface roughness (R_a) values in the range 12 - 14 μm were found in the peripherally milled surface in the longitudinal direction. Values of R_a in the same direction on the face milled surface averaged between 14 - 18 μm . Average surface roughness in the transverse direction were in the range of 6 -9 μm , regardless of the cutting action. The lower roughness in the transverse direction suggests that grooves or marks left by the cutting tool were significant enough to influence the surface topography in the longitudinal directions of both peripherally and face milled surfaces.

Table 6-2: Average surface roughness parameters for peripherally milled surfaces(Measurements are in μm)

Speed	Feed [m/min]	Ra edge long	Rq edge long	Rz edge long	Rt edge long	Rq/Ra edge long	Ra edge trans	Rq edge trans	Rz edge trans	Rt edge trans	Rq/Ra edge trans
6000	2.54	12.33	15.50	65.83	94.87	1.26	6.10	7.87	30.18	41.80	1.29
6000	5.08	12.98	16.40	71.90	82.86	1.26	6.60	8.32	31.46	44.56	1.26
6000	10.16	13.45	17.76	81.15	117.17	1.32	7.80	10.48	41.16	60.87	1.34
5000	2.54	11.95	15.27	67.73	87.07	1.28	6.44	8.23	31.96	42.87	1.28
5000	5.08	13.83	18.24	76.59	112.14	1.32	7.74	10.09	37.89	60.12	1.30
5000	10.16	14.92	19.76	85.59	119.03	1.32	8.09	9.77	34.90	48.76	1.21
4000	2.54	11.61	15.11	65.95	94.77	1.30	7.65	9.50	34.85	50.88	1.24
4000	5.08	13.40	16.56	69.63	92.15	1.24	7.89	9.63	34.52	49.30	1.22
4000	10.16	14.08	17.39	71.88	93.31	1.24	8.14	10.39	37.58	53.48	1.28

Table 6-3: Average surface roughness parameters for Face milled surfaces (Measurements in μm)

Speed	Feed [m/min]	Ra face long	Rq face long	Rz face long	Rt face long	Rq/Ra face long	Ra face trans	Rq face trans	Rz face trans	Rt face trans	Rq/Ra Face trans
6000	2.54	13.97	17.23	73.69	97.58	1.23	7.95	10.07	35.61	56.98	1.27
6000	5.08	13.61	17.16	72.66	98.48	1.26	6.43	8.11	32.64	41.70	1.26
6000	10.16	15.28	18.93	81.74	101.97	1.24	7.39	8.86	31.69	44.23	1.20
5000	2.54	12.51	15.71	65.97	90.50	1.26	6.34	7.90	29.65	41.51	1.25
5000	5.08	15.48	19.29	79.33	101.60	1.25	7.55	9.85	35.91	58.09	1.30
5000	10.16	17.92	22.83	92.03	131.48	1.27	8.11	10.10	35.18	51.73	1.25
4000	2.54	13.26	16.63	69.33	97.67	1.25	7.10	9.04	33.76	51.45	1.27
4000	5.08	16.60	20.71	87.81	109.64	1.25	9.01	11.26	40.79	59.18	1.25
4000	10.16	17.74	21.96	89.28	113.28	1.24	8.53	10.60	38.27	55.42	1.24

6.4.2 Cfoam Machined Surface Topography

Surface quality was measured in terms of surface roughness and surface defects. Surface roughness profiles were recorded from the machined surface using a MahrSurf XR20 surface profilometer with a probe stylus radius of $2\mu\text{m}$ and a cut-off length of 0.8 mm as per ANSI standard, in an attempt to quantify the surface quality. Because of possible damage to the surface profilometer probe, only the surface roughness of the bend samples was recorded. Previous observations from the preliminary study had shown that little variation in surface topography is discernible in even the most extreme cutting conditions. The surface roughness profiles were characterized by evaluating the average surface roughness, R_a ; maximum peak-to-valley height, R_t ; root mean square roughness, R_q ; and ten point average surface roughness, R_z . Defects were further examined using both optical and Scanning electron microscopy. Typical surface traces recorded for both longitudinal and transverse directions, with respect to the feed direction, are shown below in Figure 6-7.

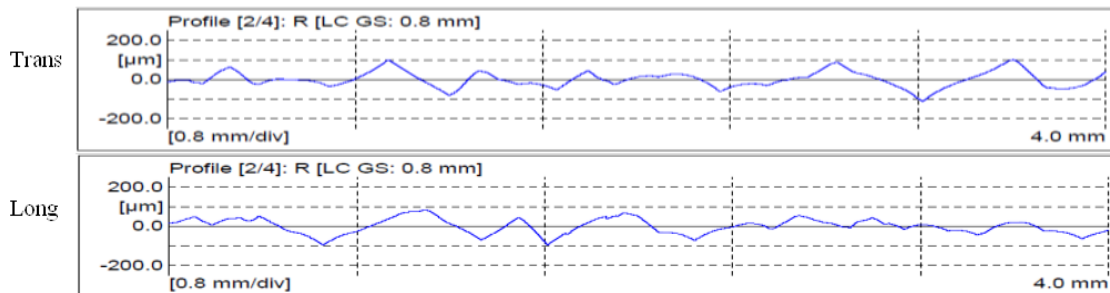


Figure 6-7: Typical surface roughness profile in transvers and longitudinal directions.

6.4.3 Machining Induced Damage in CB1100

Macro scale induced damage was observed to primarily be a combination of two forms: unsupported edge loss and chipping/gouging of the face machined surface as shown in Figure 6-8. Unsupported edge loss is the result of thin or unsupported sections of material fracturing

under load of the cutting forces. The greater the magnitude of the cutting forces, the greater the severity and extent of unsupported edge losses. The most common occurrence is at the edge of the material where the cutter exits. Unsupported edge loss occurs at nearly all exiting edges. Edge loss typically occurs on either the edge normal to the feed direction or the edge perpendicular to the feed direction, where the cutter exits the material as shown in Figure 6-8a. Chipping of the face machined surfaces occurs at the center of the cutter and is likely due to the passage of chips underneath the tool. Chipping or gouging of the face machined surface is not only visibly evident on the material surface, as shown in Figure 6-8b, but also is clearly evident in the cutting forces as well. Peaks in the cutting forces are sharp and often exceed the cutting force magnitude. They are random in occurrence but occur preferentially in between cutter engagement periods as shown in Figure 6-8c. The occurrences between the cutter engagements are likely due to the fact that the cutting edges are oriented perpendicular to the feed direction at this point. At this orientation, chips are more likely to become entrapped at the center of the tool and forced underneath as observed.

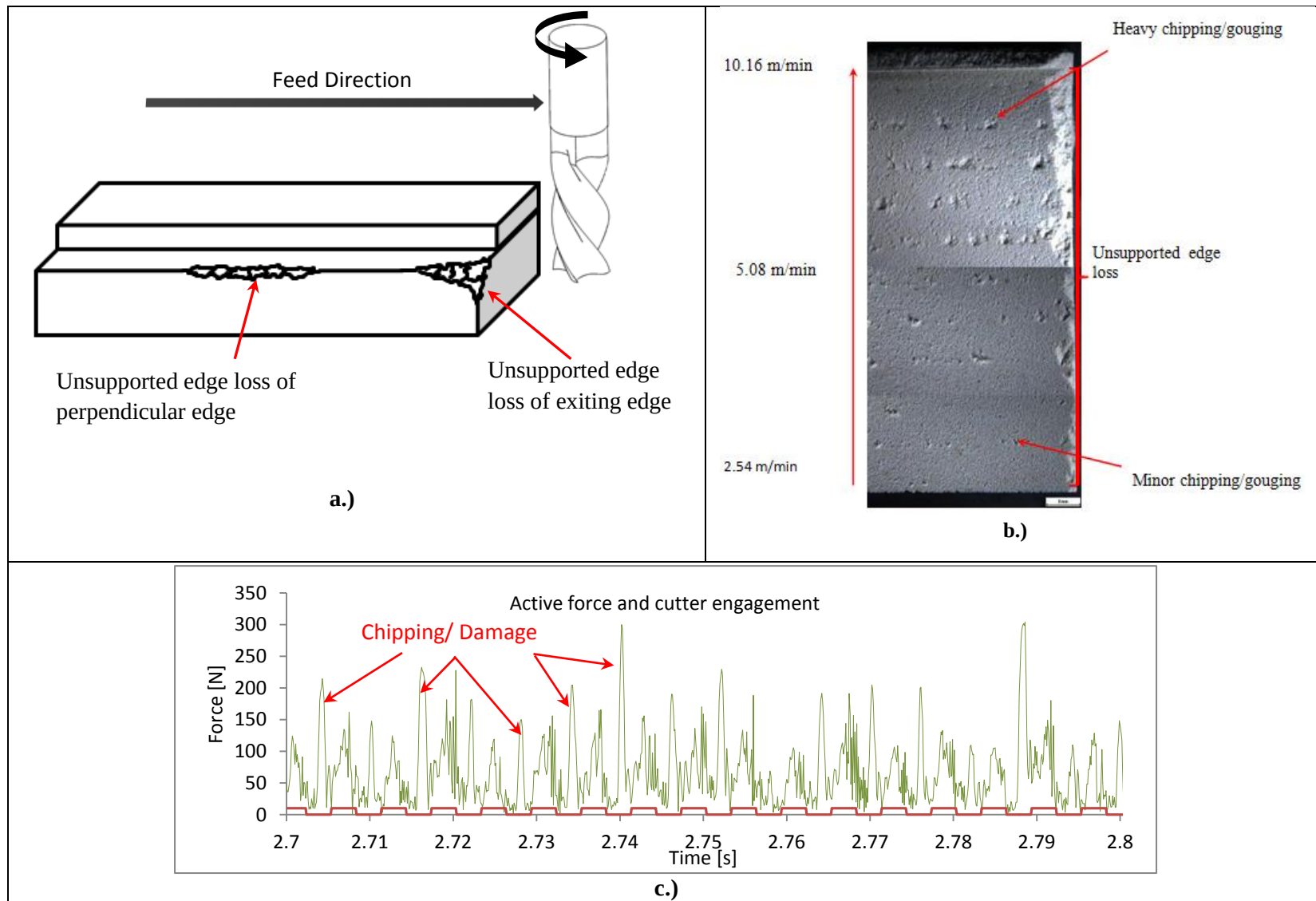


Figure 6-8: a.) Schematic diagram of types and location of unsupported edge loss b.) Machining induced damage at varying feed rates c.) Active cutting force and cutter engagement.

Scanning electron microscopy studies have shown that the micro scale damage induced during machining is typically a combination of two forms of damage: micro scale cracking and small scale fracture. Cracks were observed to traverse cell walls and ligaments. These cracks not only increase in frequency but also in crack length as cutting forces increase. Typical crack densities of the low cutting force case (6000 RPM and 2.54 m/min) were observed to be approximately 100 mm^{-2} . Typical crack densities of the high cutting force case (4000 RPM and 10.16 m/min) were found to be approximately 260 mm^{-2} .

Crack lengths were observed to increase in length for samples machined at high cutting force, Figure 6-9f when compared to those machined at lower cutting force conditions. Crack lengths as high as $200 \text{ }\mu\text{m}$ in length were observed in samples machined at 4000 RPM and 10.16 m/min. The induced micro cracks were found to preferentially traverse regions or boundaries of regions exhibiting anisotropy, Figure 6-9a. Anisotropic boundaries create a small scale stress concentration. Additional stress concentrations are created by the presence of small voids occurring in the ligaments as shown in Figure 6-9b-e. Machining induced micro-cracks preferentially travel between these voids leading to larger scale fracture of the ligament as shown in Figure 6-9c,d.

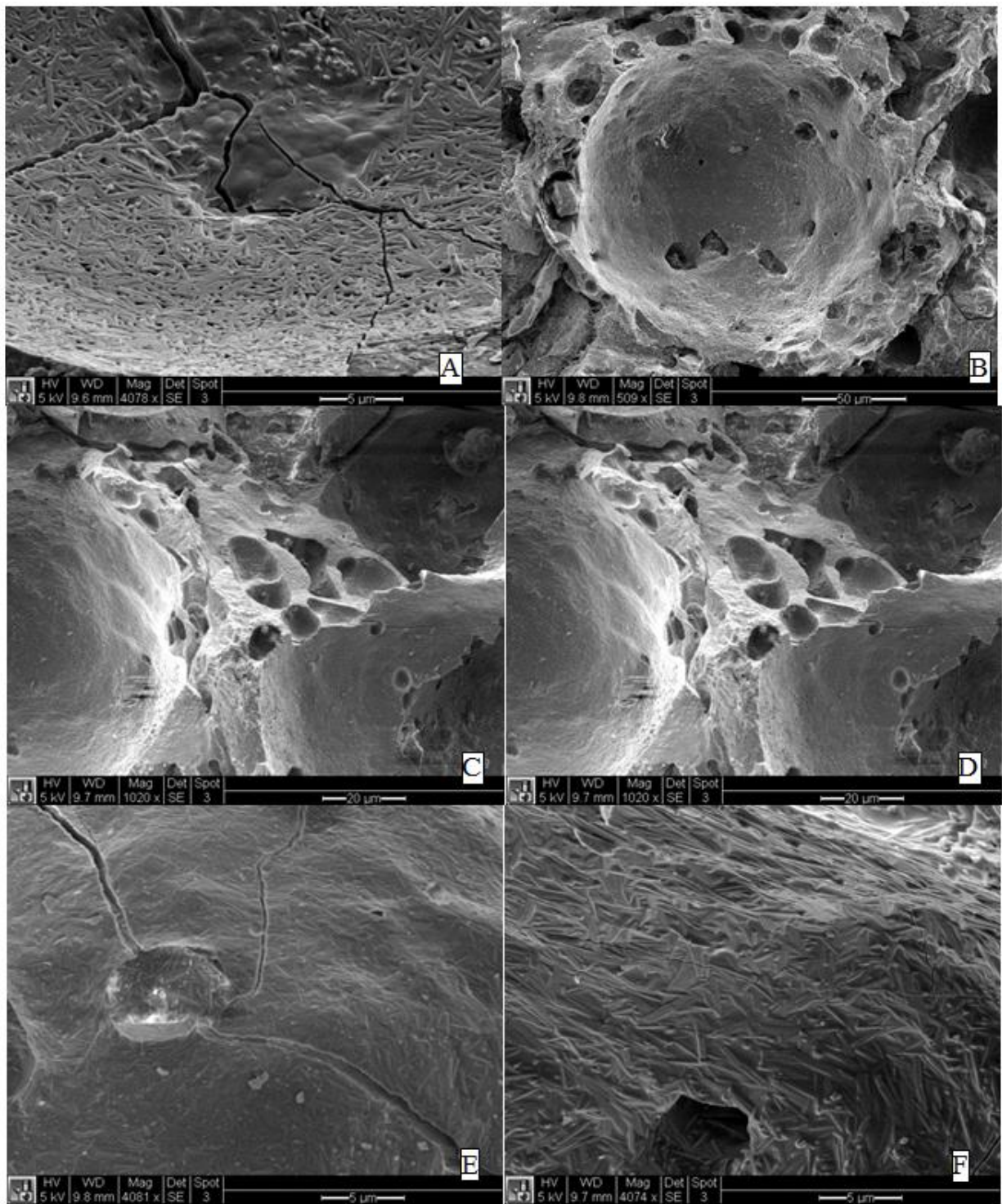


Figure 6-9: SEM images of CB1100 machined surfaces.

6.4.4 Machining Induced Damage in AAC

Large scale machining induced damage came in the form of unsupported edge loss. Exiting edge blow out and large area fracture was common. Due to the weak material properties of AAC, unsupported edge loss occurring at the exiting edge was found while employing even the lowest cutting force machining conditions. Severity of the edge loss increased with increasing chipload and cutting force as expected. Edge loss was found to occur as soon as within 20-25 mm of proximity to the unsupported edge. Unsupported edge loss of the surface parallel to the feed direction was not found however. In these situations the cutting edge can induce a fracture when the cutting velocity vector is perpendicular to the feed direction at the exit of the cutting path. Parallel edge loss was not found to be a severe or common occurrence in AAC. Resulting tensile forces producing the fracture are primarily due to the tangential cutting force. However, radial forces in AAC were found to be a significant contributor to the overall active cutting force. This force is at its maximum only when the cutting edge is already in very close proximity to the exit of the chip. It should be noted that parallel surface edge loss only occurs when conventional (up) milling and does not occur when climb (down) milling.

Chipping and gouging of the face machined surface was not observed. In other materials studied this form of damage was common as a result of chips passing underneath the center of the tool. When machining AAC, there are no large chips formed. Material is removed in the form of a fine powder. Powder does not cause gouges in the face machined surface as the larger chips do. Furthermore, unlike as in other materials studied gouging does not show up in the cutting forces. Cutting force peaks occurring in between cutter engagements were not observed.

From the SEM images shown in Figure 6-10 several observations of the micro-scale machining induced damage are made. The sample shown in Figure 6-10a,c was machined using

cutting conditions of 4000 rpm and 10.16 m/min, while the sample shown in Figure 6-10b,d was machining at 6000rpm and 2.54 m/min. While hard to distinguish, there is a clear increase in the planar nature of the surface in Figure 6-10b,d. There is also a lower incidence of damaged cell edges. Cell edges are more clearly defined and less chipped. Cracking and damage such as that shown in Figure 6-10c was also less predominant in samples machined at high speed and low feed. Samples machined at lower speeds with high feed rates showed the highest level and depth of damage.

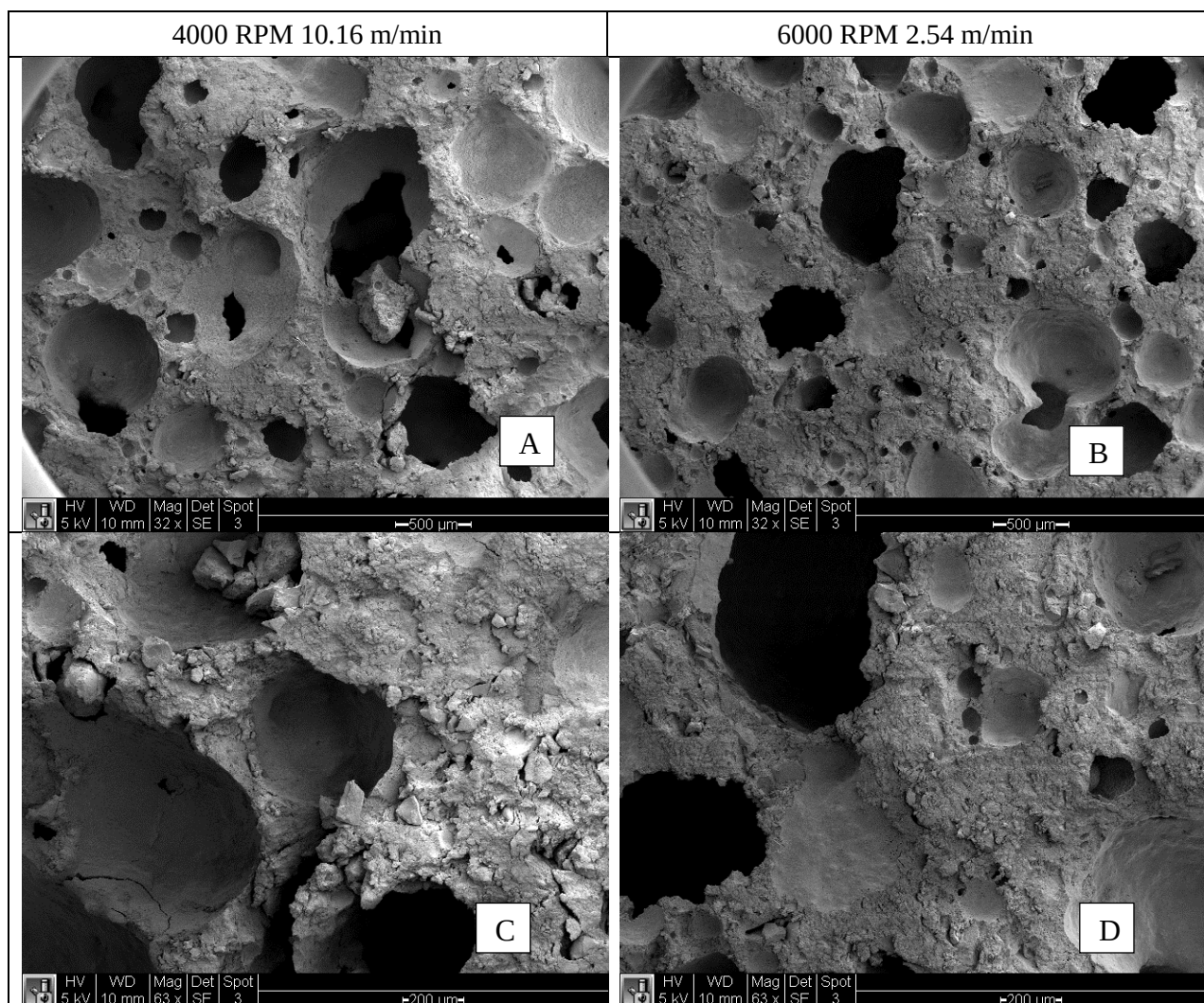


Figure 6-10: SEM images of machined AAC.

6.4.5 Machining Induced Damage in Cfoam

While the amount and severity of damage is difficult to quantify, the SEM images shown in Figure 6-11 illustrate an increase in damage over the polished state. Figure 6-11b shows an SEM image of a typical machined surface. Figure 6-11a shows a polished sample containing planar sections of the ligaments which are absent of the jagged fractured regions shown in Figure 6-11b. Ligaments are fractured and the damage extends far into to the surface in several areas.

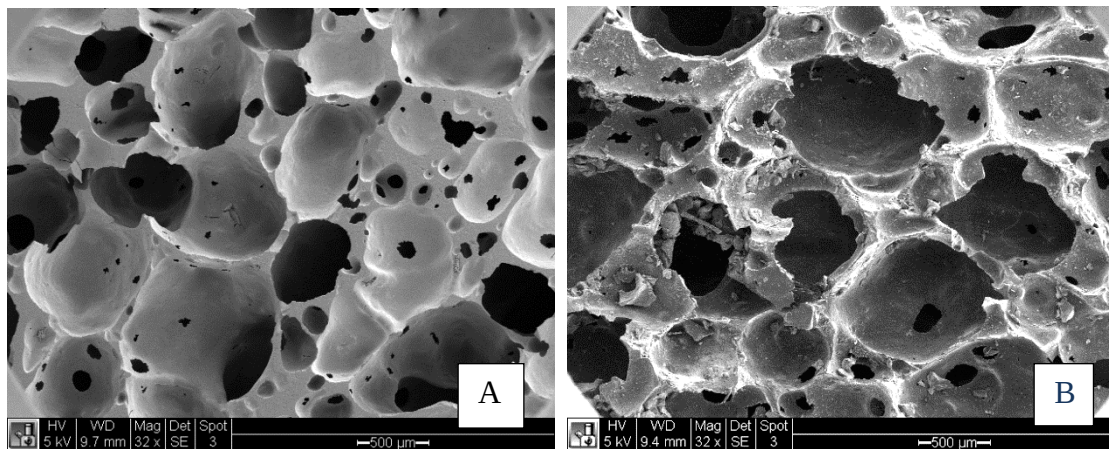


Figure 6-11: Sem images of polished and machined AAC surfaces.

Damage is highlighted in SEM images of machine samples depicted in Figure 6-12. Samples machined using cutting conditions of 4000 RPM and 10.16 m/min show more damage than those which were machined using 6000 RPM and 2.54 m/min. The fractured surfaces observed in samples machined at 4000 RPM and a feed rate of 10.16 m/min are larger and more jagged than those observed in samples machined at 6000RPM and 2.54m/min. Surfaces appear to extend deeper into the surface for higher cutting force cutting conditions. Cracks were also observed to traverse thin cellular walls. Again this was more commonly observed in the samples machined using conditions of 4000 RPM and 10.16 m/min.

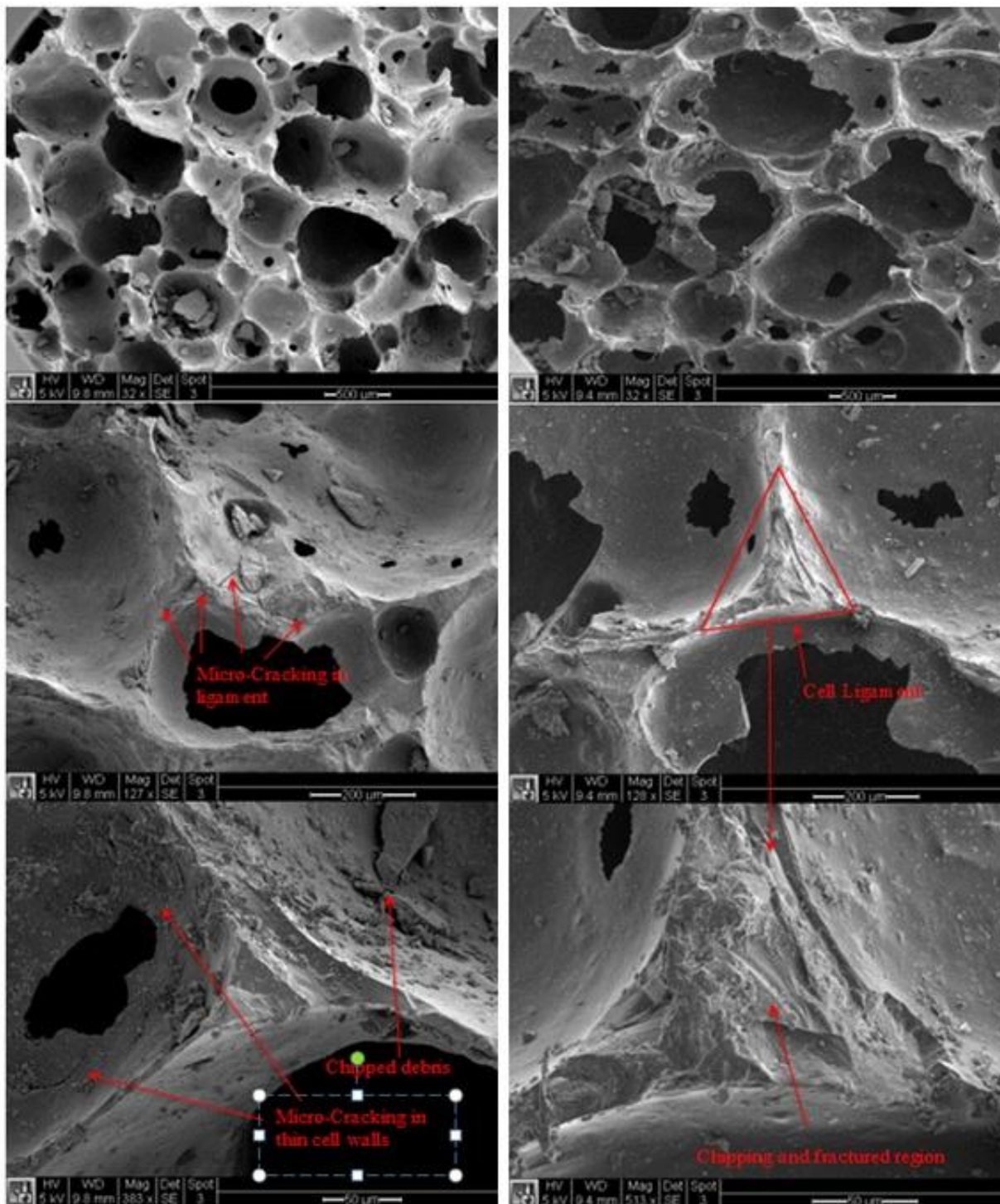


Figure 6-12: Typically observed damage in machined Cfoam.

6.5 Mechanical Testing / Surface Integrity

Four point bend tests were conducted on two sets of samples machined at two different combinations of cutting conditions. A feed rate of 2.54 m/min and a cutting speed of 6000 rpm were selected as the first set of cutting conditions. Results of these flexural tests would provide the baseline. A feed rate of 10.16 m/min and a cutting speed of 4000 rpm were selected as the second set of cutting conditions. High feed and low speed has been shown to produce the largest cutting forces and most induced damage. Specimens machined using the second set of conditions (referred to later as the high cutting force conditions) provide a contrast in residual flexural strength to the baseline samples.

6.5.1 CB1100

The typical crack path and fractured surface of the CB1100 samples is shown in Figure 6-13. All samples failed within the gage section of the specimen in a Mode I fracture. A singular through thickness crack initiating at the surface lead to the failure of all samples.

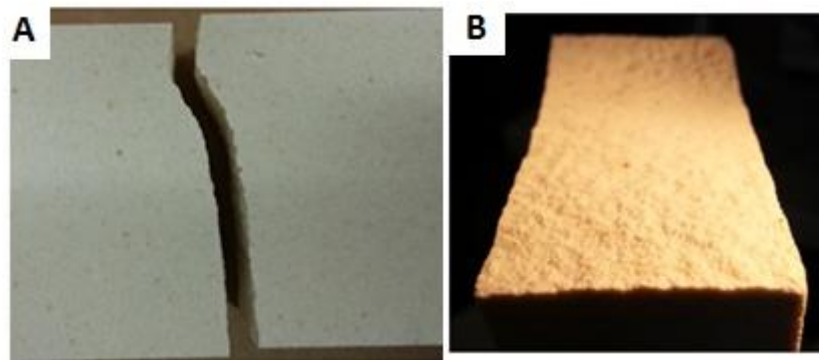


Figure 6-13: (a) Crack path and (b) fractured surface in CB1100 four-point bend samples.

Flexural load vs. extension for Cb1100 samples is plotted in Figure 6-14 and Figure 6-15 for cutting conditions of: 6000 RPM 2.54 m/min and 4000 RPM, 10.16 m/min, respectively. The average flexural load at fracture of the high cutting force specimens (4000 RPM 10.16m/min)

was found to be 14.22 N. Specimens machined using the low cutting force conditions (6000 RPM 2.54 m/min) had an average flexural strength of 15.53 N. The reduction in flexural strength is equal to an 8.43% decrease from samples machined using the low cutting force conditions. Flexural strengths had scatter within each specimen condition. Standard deviation in flexural strength of samples machined using the high and low cutting force conditions were 0.210 and 0.503 MPa, respectively.

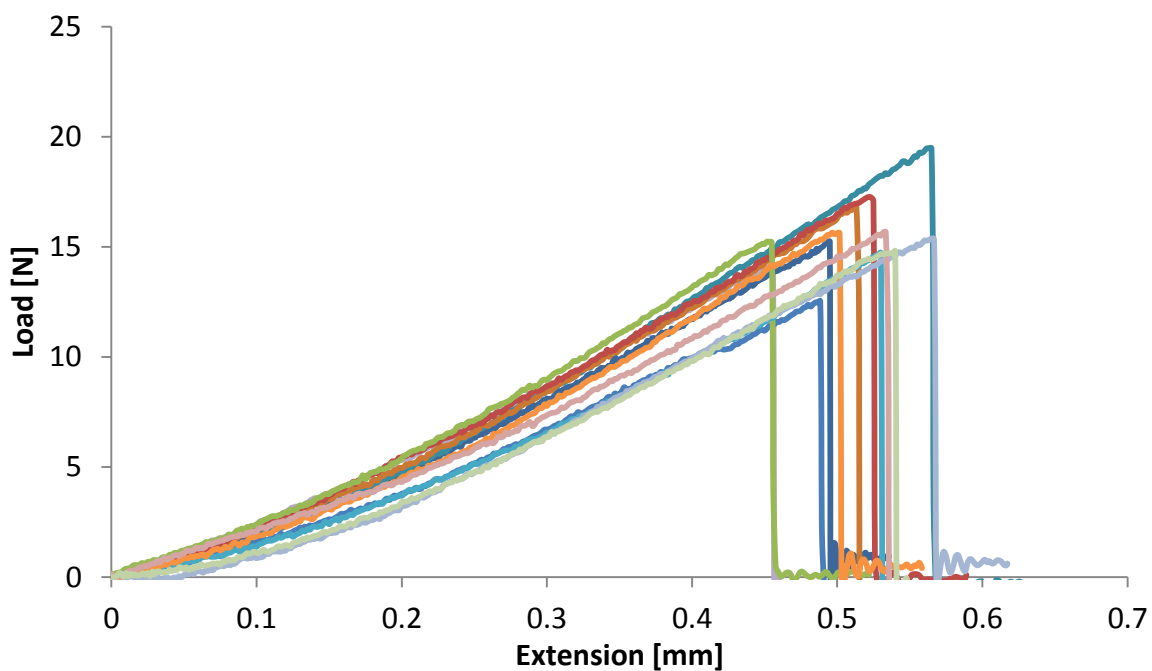


Figure 6-14: Flexural load vs extension of CB1100 four point bend specimens machined at 6000 RPM and 2.54m/min.

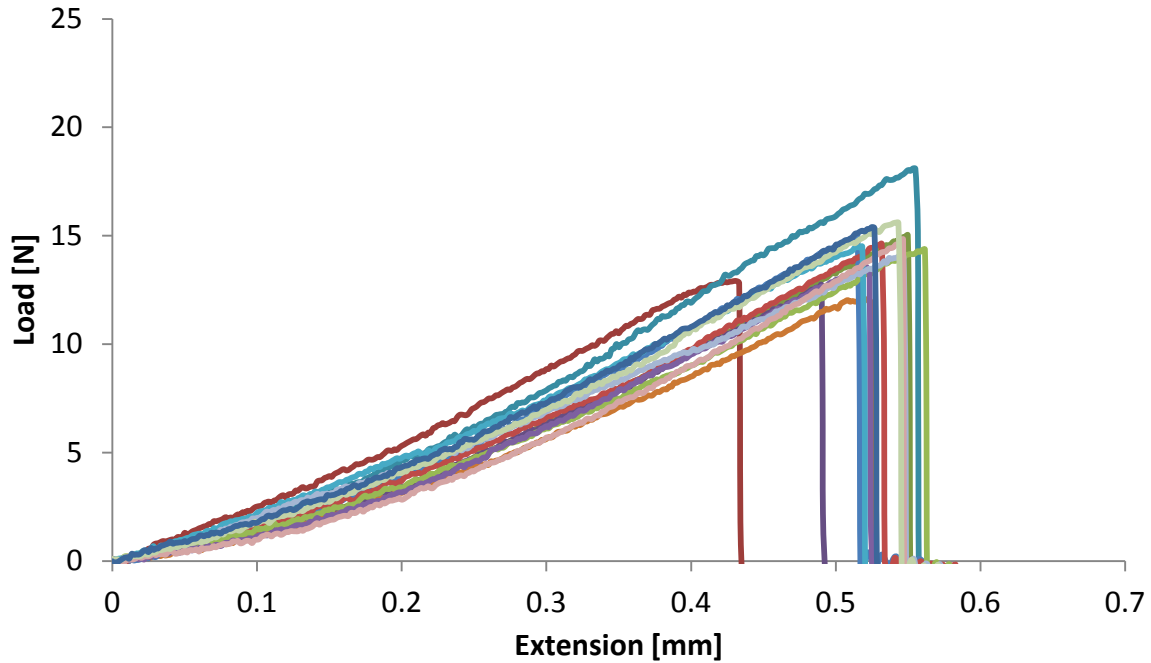


Figure 6-15: Flexural load vs. extension of CB1100 specimens machined at 4000 RPM and 10.16m/min.

The average flexural strength of specimens machined using low cutting force conditions of 6000 RPM and 2.54 m/min was 3.23 MPa, a reduction in residual flexural strength of 42% when compared to the advertised value of 5.6 MPa. Residual flexural strength for specimens machined using high cutting force conditions was 2.81 MPa. A reduction in flexural strength of 13% was measured.

6.5.2 AAC

A typical fractured sample and crack path for AAC samples is shown in Figure 6-16. All samples failed within the gage section of the sample. Branching of the crack near the compression surface side of the sample was common. Mixed mode fracture, is speculated to have been induced due to the porous material's local stress distribution upon loading. This is not believed to have affected the measured flexural stress at failure to any significant degree.

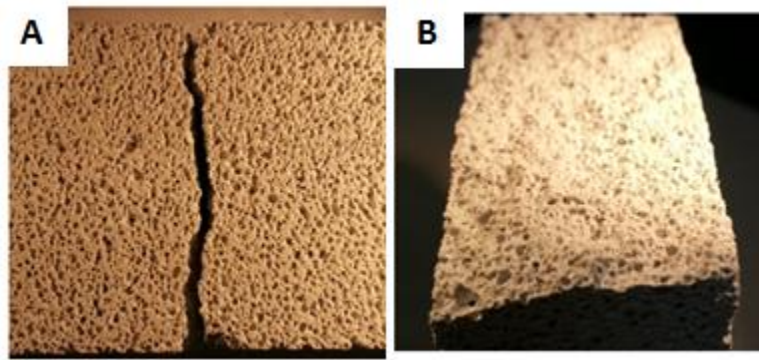


Figure 6-16: (a) Crack path and (b) fractured surface in AAC four-point bend samples.

Flexural stress vs. displacement plots are shown below in Figure 6-17. The average maximum flexural stress for specimens machined at 6000 RPM and 2.54 m/min was 0.675 MPa. Specimens machined at 4000 RPM and 10.16 m/min had an average flexural stress of 0.626 MPa. The nature of failure was consistent for all specimens, with failure initiating near the center of the gauge section. A significant increase in the amount of scatter in maximum flexural stress and strain to failure was found for specimens machined 6000 RPM and 2.54 m/min. This is counterintuitive to the assumption that increased amounts of damage should induce a more random nature.

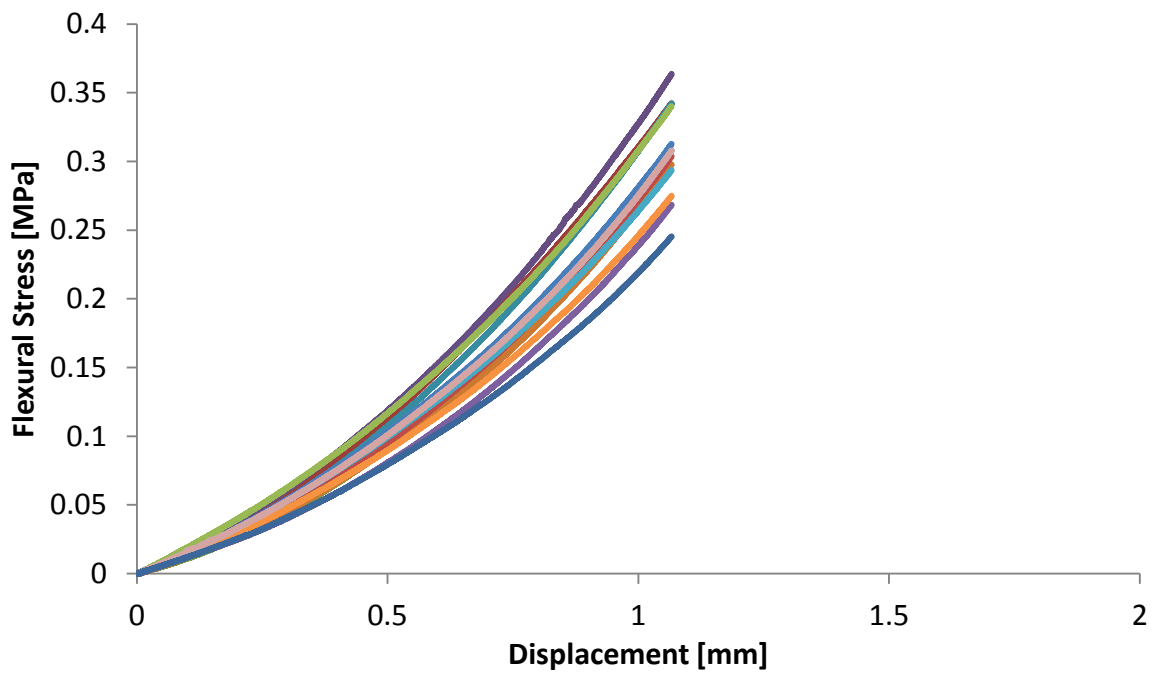
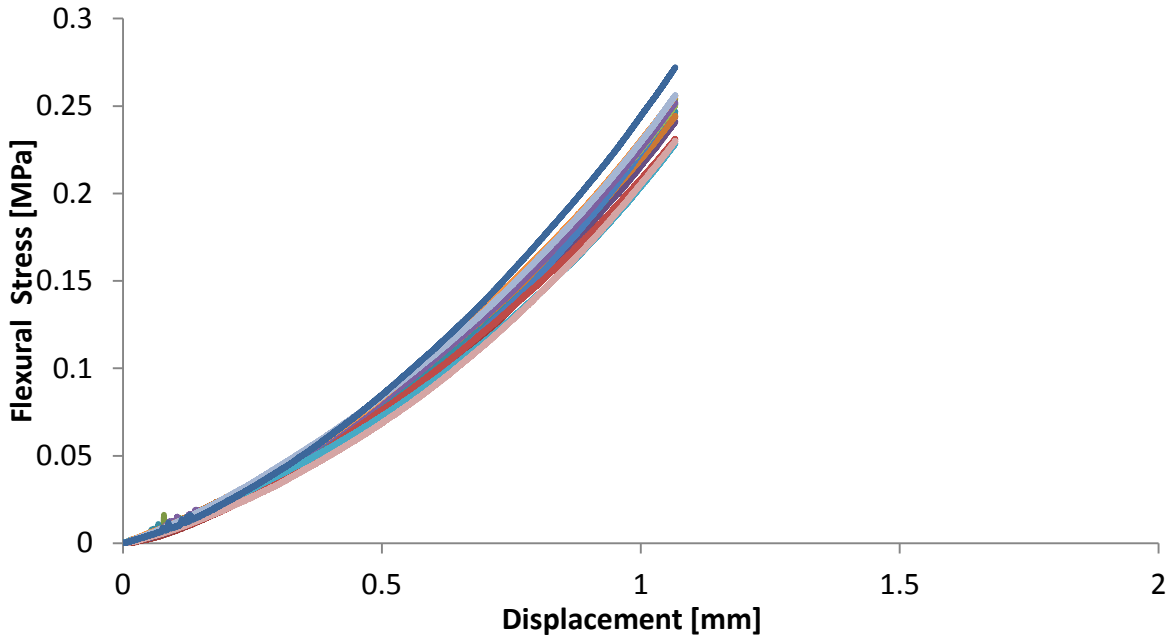


Figure 6-17: Flexural stress vs. extension of AAC specimens machined at: (a) 4000 RPM and 10.16m/min and (b) 6000 RPM and 2.54m/min.

6.5.3 Cfoam

Typical fractured specimens and crack paths in Cfoam are shown in Figure 6-18. All specimens fractured with a varying mode-mixity, in the manner shown. Mode-mixity, or mixed mode fracture, is speculated to have been induced due to the porous material's local stress distribution upon loading. However, this is not believed to have affected the measured flexural stress at failure to any significant degree.

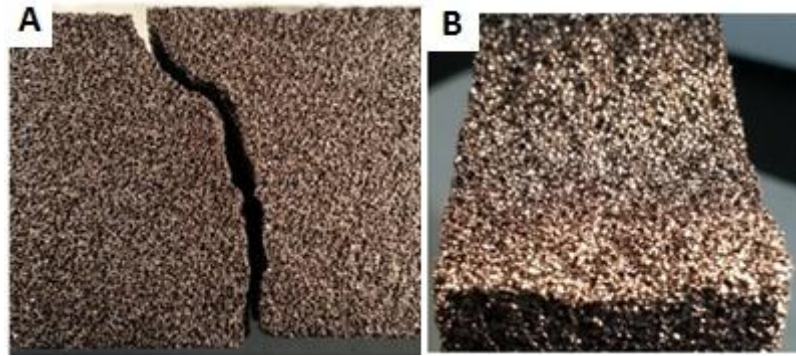


Figure 6-18: (a) Crack path and (b) fractured surface in Cfoam four point bend samples.

The average flexural stress at fracture of the high cutting force specimens was 1.15 MPa. The average flexural strength of the low cutting force specimens was 1.11 MPa. Flexural strength showed a 3.6% *increase* over specimens machined using low cutting force conditions. Flexural strengths were found to be more consistent for specimens machined using cutting conditions of 6000 RPM and 2.54 m/min. The degree of scatter in flexural strength values was increased for samples machined at 4000 RPM and 10.16 m/min. Flexural stress vs. extension for Cfoam samples are shown are plotted in Figure 6-19 and Figure 6-20.

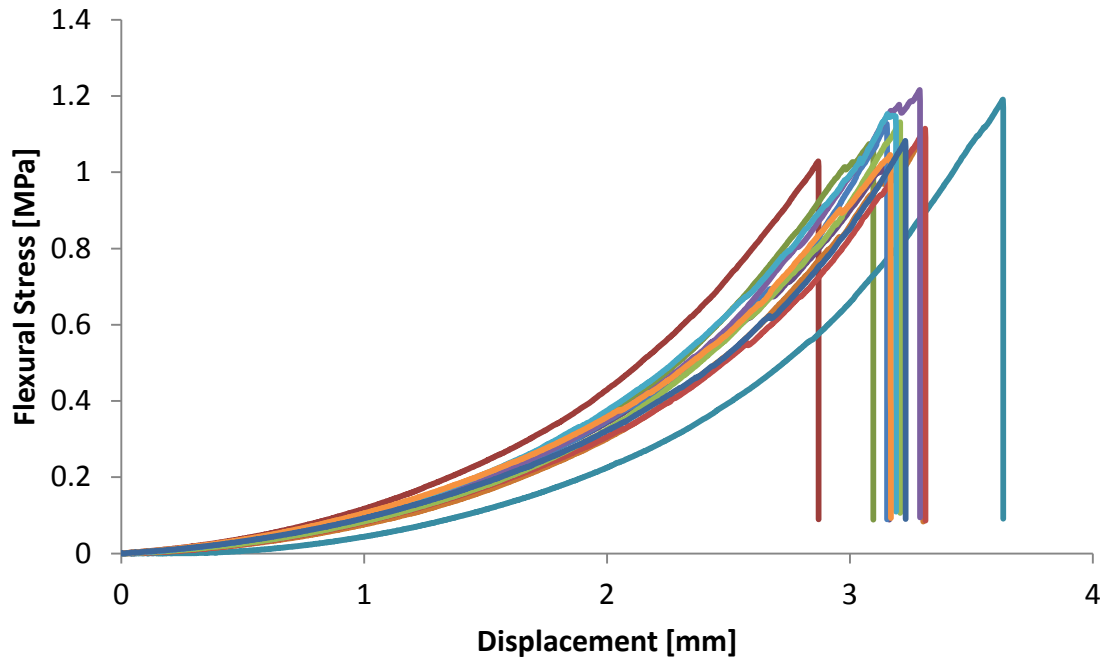


Figure 6-19: Flexural stress vs. displacement of Cfoam specimens machined at 4000 RPM and 10.16 m/min.

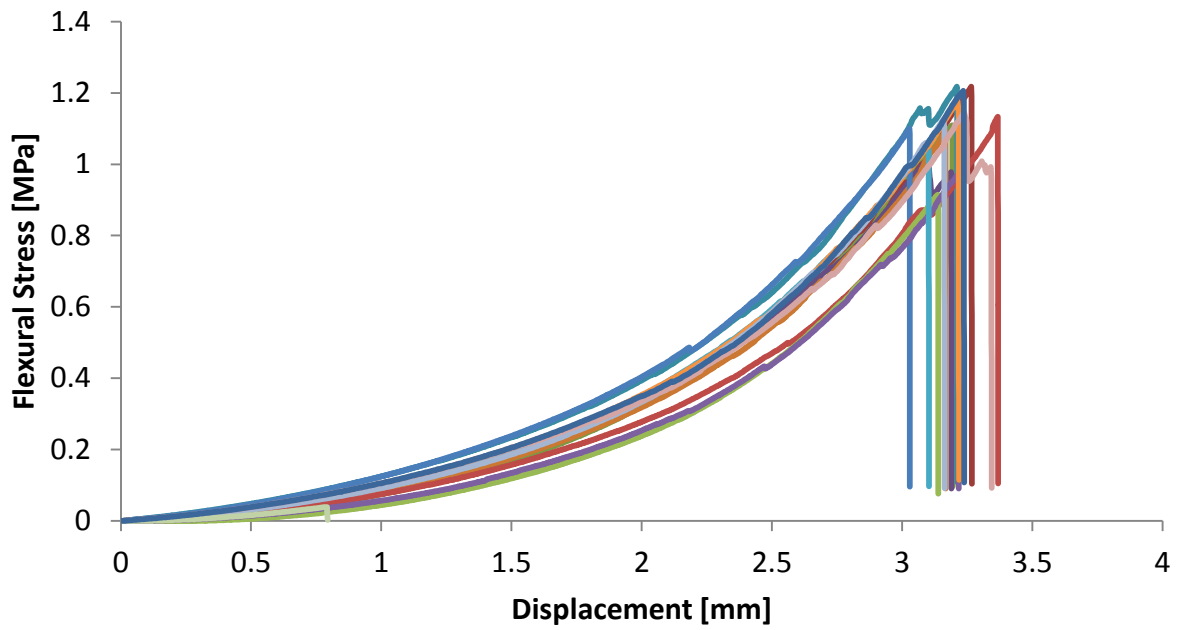


Figure 6-20: Flexural stress vs. displacement of Cfoam specimens machined at 6000 RPM and 2.54m/min.

6.6 Discussion

The results of the experimental optimization portion of the research will be interpreted and discussed in the order they were presented. Chip formation of the three materials will be compared and studied for changes in size and the ratio of dust to chips. ANOVA is performed on cutting forces and empirical models of tangential and radial force for each material are given. Attempts at quantifying machining induced damage through surface profilometry is made and presented combined with SEM and optical studies of machining induced micro-damage. The effects of machining induced damage on surface integrity are evaluated based upon the results of the mechanical testing.

6.6.1 Chip formation

Material removed during machining of Cfoam and AAC was primarily in the form of a dust or powder. No actual chips are formed. The powder produced from the two materials each have concerning affects. The dust produced while machining AAC was found to adhere to cutting tools. Abrasive type cutting tools *clogged* and quickly became less effective at cutting, leading to increased cutting forces and damage. Fluted tools were also adhered to by the powder. However, built up powder was not extensive enough to become detrimental on fluted tools. Dust produced while machining Cfoam must also be carefully controlled and monitored. Dust is carbon based and thus conductive. It is extremely hazardous to electrical machinery and equipment. It is also extremely abrasive and can lead to rapid wear and damage of sensitive machine components such as ways, guides, or bearings. The carbon dust is a possible health hazard. Proper material containment and disposal must be followed, increasing equipment and handling costs.

Material removed while machining CB110 was found to be in the form of both chips and powder. The ratio of chips to powder along with the size of the chips increased with increasing feed rate and chipload. Chips were observed to cause damage in the form of gouging and chipping of the face machined surfaces. Tooling with geometry better designed for material evacuation may be capable of avoiding damage. However, with the current tooling the achievable material removal rate of in CB1100 is limited. Achievable material removal rate is therefore limited by the amount of damage which is deemed acceptable. Levels of damage may be acceptable if subsequent finishing operations are planned.

6.6.2 CB1100 Cutting Forces

Measured peak cutting forces for each test were determined based upon an average of 5 cutting tooth profiles. The tabulated results were analyzed through ANOVA using Design Expert 8 software. The results of the ANOVA for tangential and radial cutting force are list in Table 6-4.

Table 6-4: Results of the ANOVA of cutting forces in CB1100.

	Analysis of variance table for Ft		Analysis of variance table for Fr	
Source	F Value	p-value Prob > F	F Value	p-value Prob > F
Model	257.3	< 0.0001	279.7	< 0.0001
A-Speed	142.2	< 0.0001	213.2	< 0.0001
B-Feed	1287.2	< 0.0001	1533.0	< 0.0001
C-RDOC	197.3	< 0.0001	254.8	< 0.0001
D-ADOC	578.1	< 0.0001	683.7	< 0.0001
AB	25.7	< 0.0001	24.1	< 0.0001
AC	19.7	< 0.0001	20.5	< 0.0001
BC	25.1	< 0.0001	25.7	< 0.0001
BD	108.2	< 0.0001	100.1	< 0.0001
CD	15.7	0.0001	16.6	< 0.0001

The F-value is a test for comparing the model variance with the residual variance, or error. The F-value is found by dividing model mean square by the residual mean square. The closer this ratio is to one the less likely the factor is significant. The greater the F-value, the greater the probability that the factor has a significant influence of the response. From Table 6-4 it is clearly evident that the linear terms: Speed, Feed, RDOC, and ADOC have greater probability of influence on the response than any of the factorial interactions. The P-value is the probability of obtaining the observed F-value if the null hypothesis is true (factor has no influence). If the probability is high the null hypothesis may be true. If the probability is low, the null hypothesis is rejected. As a general rule if the P-value is less than 0.05 the null hypothesis is rejected and the probability that the factor is influential on the response is high. All the terms in the Table 6-4 meet these criteria. Therefore, the factorial interactions do have a high probability of influencing the responses. However, their influence is simply not as significant as the linear terms; leading to the nearly linear behavior observed.

Equations Eq. (6.1) through Eq. (6.4) were obtained from the Design Expert software from the cutting force DOE and describe the modeled tangential and radial cutting forces F_t and F_r . Equation Eq. (6.1) and Eq. (6.3) are coded equations; meaning each factor has no units. Thus, the coefficients illustrate the relative influence each factor has on the response. In these equations “A” represents speed, “B” represents feed, “C” represents Radial Depth of Cut (RDOC), and “D” represents Axial Depth of Cut (ADOC). Equation Eq. (6.2) and Eq. (6.4) are in terms of the actual factors and have their associated relative units. Speed is in terms of RPM. Axial and radial depths of cut are in units of mm. Feed rate is in units of m/min.

$$F_t = 53.92 - 8.97 * A + 26.26 * B + 8.62 * C + 14.76 * D - 4.53 * (A * B) - 3.31 * (A * C) + 3.67 * (B * C) + 7.61 * (B * D) + 2.41 * (C * D) \quad \text{Eq. (6.1)}$$

$$F_t = -24.03 + (8.41E - 03) * Speed + 3.393 * Feed + 7.39 * RDOC - 3.20 * ADOC - (1.19E - 03) * Speed * Feed - (2.07E - 3) * Speed * RDOC + .61 * Feed * RDOC + 1.25 * Feed * ADOC + .95 * RDOC * ADOC \quad \text{Eq. (6.2)}$$

$$F_r = 50.2 - 9.11 * A + 23.78 * B + 8.13 * C + 13.32 * D - 3.65 * (A * B) - 2.8 * (A * C) - 2.31 * (A * D) + 3.08 * (B * C) + 6.08 * (B * D) + 2.06 * (C * D) \quad \text{Eq. (6.3)}$$

$$F_r = -50.00 + .012 * Speed + 3.64 * Feed + 6.53 * RDOC + 5.94 * ADOC - (9.26E - 03) * Speed * Feed - (1.7E - 3 * Speed * RDOC) - (1.52e - 3 * Speed * ADOC) + .52 * Feed * RDOC + .99 * Feed * ADOC + .79 * RDOC * ADOC \quad \text{Eq. (6.4)}$$

The tangential and radial cutting forces are predominately influence by the feed rate and axial depth of cut. The coefficients of feed (B) in the equations above are larger than any of the other factors or factorial interaction contributions. Axial depth of cut is the second most influential factor with approximately half the influence of feed rate. Furthermore, the coefficients of factorial interactions are small in comparison to the coefficients of all the linear terms. This linear behavior is also further illustrated below in Figure 6-21 and Figure 6-22. Figure 6-21 illustrate the influence of feed and speed on tangential cutting force at high and low levels of axial and radial depths of cut. The linear behavior is evident with respect to both factors. The full list of plots covering all influential factors is available in Appendix H.

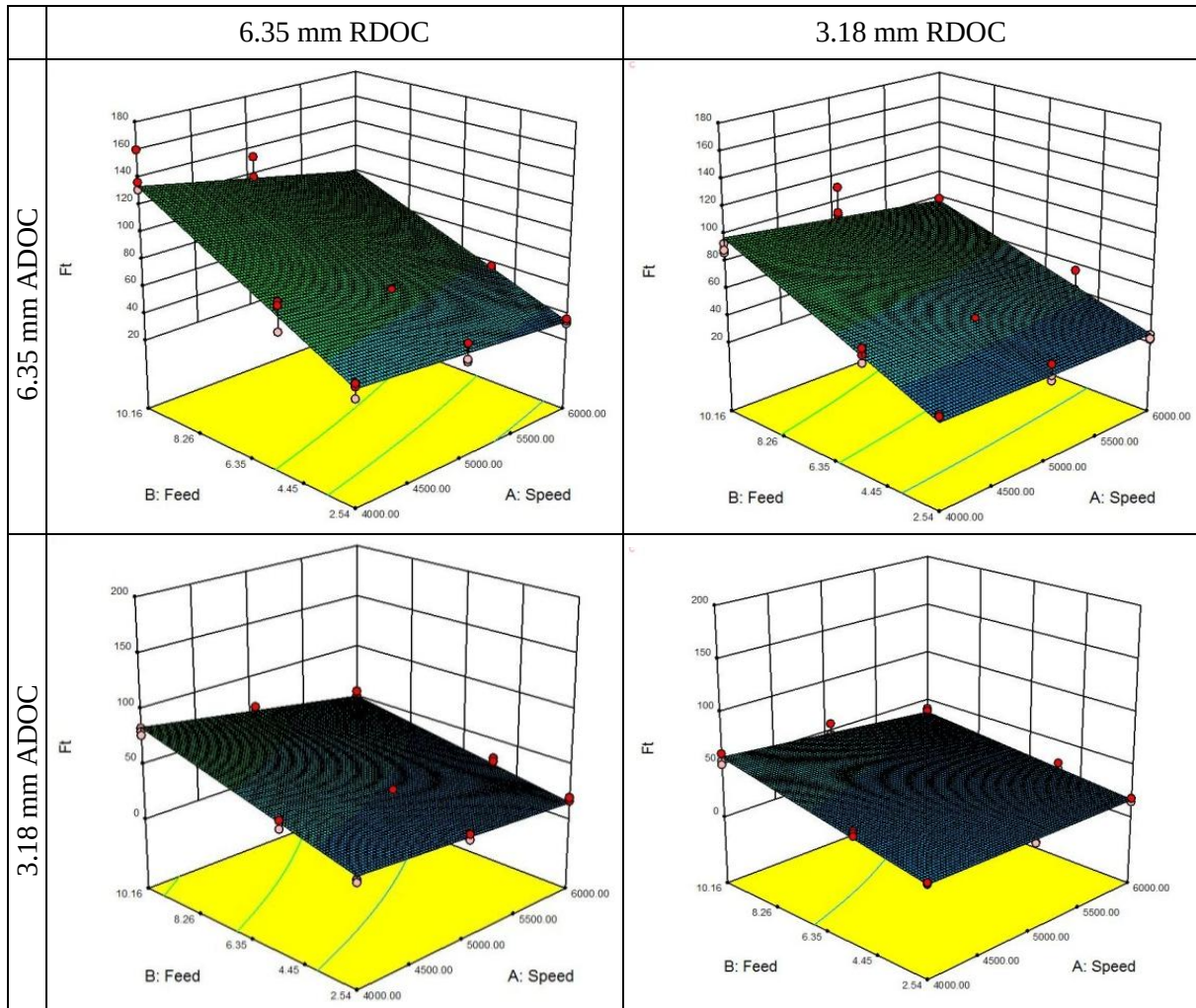


Figure 6-21: Regression plots of tangential cutting forces in CB1100.

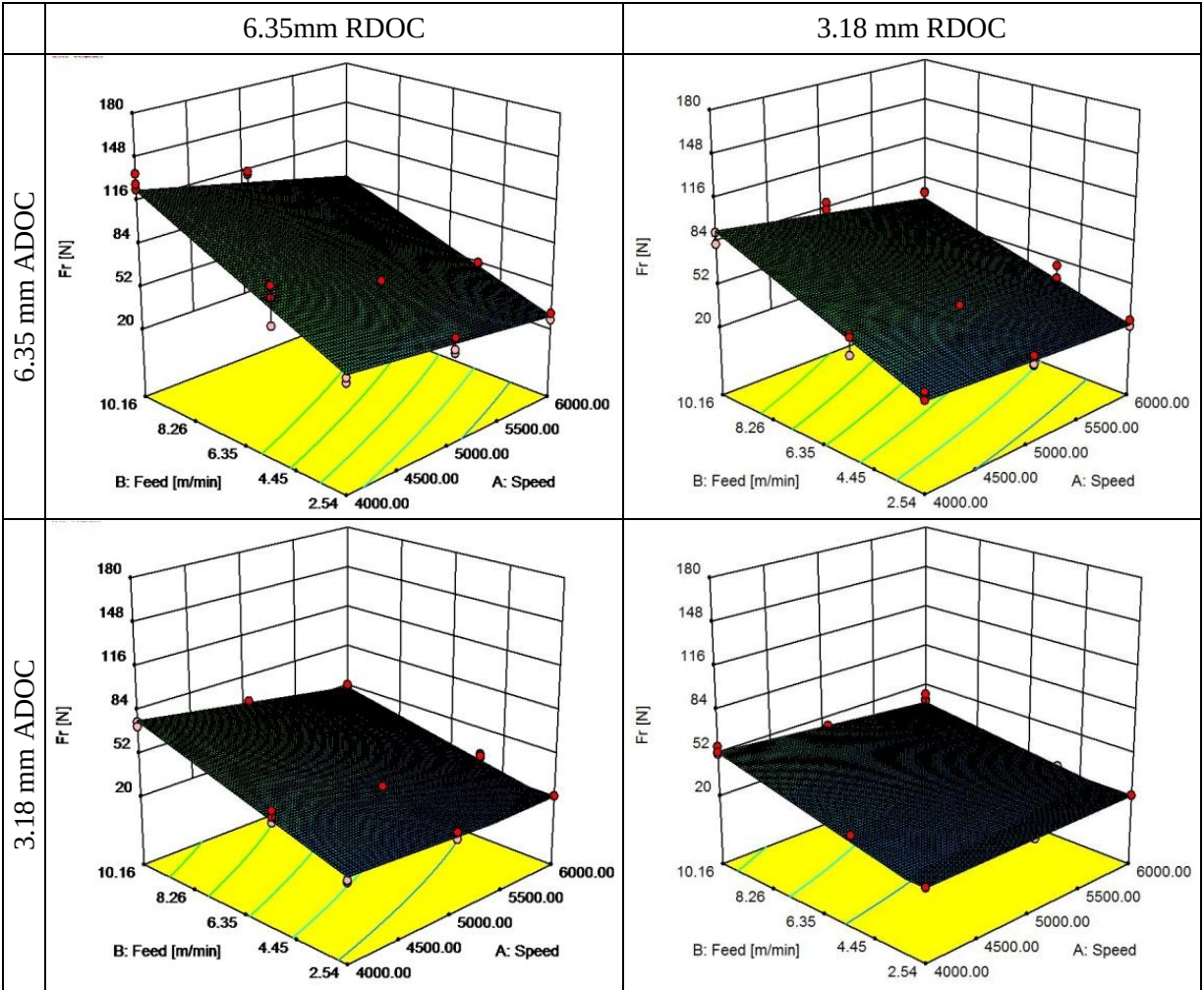


Figure 6-22: Regression plots of radial cutting forces in CB1100.

6.6.3 AAC Cutting Forces

Peak cutting forces were found to be predominantly influenced by the feed rate and axial depth of cut, the two parameters which most influence chip thickness and cutting edge contact area. Interaction effects (non-linear terms or behavior) between factors were also present. Results of the regression modeling and ANOVA analysis are given in Equations Eq. (6.5) through Eq. (6.8). Equation Eq. (6.5) and Eq. (6.7) are coded equations in terms of unitless factors. Equation Eq. (6.6) and Eq. (6.8) are in terms of the actual factors and have their associated relative units. Speed is in terms of RPM. Axial and radial depths of cut are in units of mm. Feed rate is in units of m/min.

$$F_t = 26.17 - 2.96 * A + 10.16 * B + 5.3 * C + 3.76 * D - 1.28 * (A * D) + 1.4 * (B * C) + 1.49 * (B * D) + 2.67 * (A^2) \quad \text{Eq. (6.5)}$$

$$F_t = 58.96 - (.026) * \text{Speed} + .39 * \text{Feed} + 1.87 * \text{RDOC} + 4.84 * \text{ADOC} - (8.08E - 04) * \text{Speed} * \text{ADOC} + 0.23 * \text{Feed} * \text{RDOC} + 0.25 * \text{Feed} * \text{ADOC} + (2.68E - 06) * \text{Speed}^2 \quad \text{Eq. (6.6)}$$

$$F_r = 24.49 - 3.45 * A + 9.68 * B + 4.74 * C + 3.78 * D - 1.47 * (A * D) + 1.73 * (B * C) + 1.66 * (B * D) + 2.1 * (A^2) \quad \text{Eq. (6.7)}$$

$$F_r = 47.48 - .02 * \text{Speed} - 0.13 * \text{Feed} + 1.17 * \text{RDOC} + 5.26 * \text{ADOC} - (9.23E - 04) * \text{Speed} * \text{ADOC} + 0.29 * \text{Feed} * \text{RDOC} + 0.27 * \text{Feed} * \text{ADOC} + .27 * \text{RDOC} * \text{ADOC} + (2.10E - 06) * \text{Speed}^2 \quad \text{Eq. (6.8)}$$

The tangential and radial cutting forces are predominately influence by the feed rate and axial depth of cut. The coefficients of feed (B) in the equations above are larger than any of the other factors or factorial interaction contributions. Axial depth of cut is the second most influential factor with approximately half the influence of feed rate. Furthermore, the coefficients of factorial interactions are small in comparison to the coefficients of all the linear terms. This behavior is also further illustrated in Figure 6-23 and Figure 6-24.

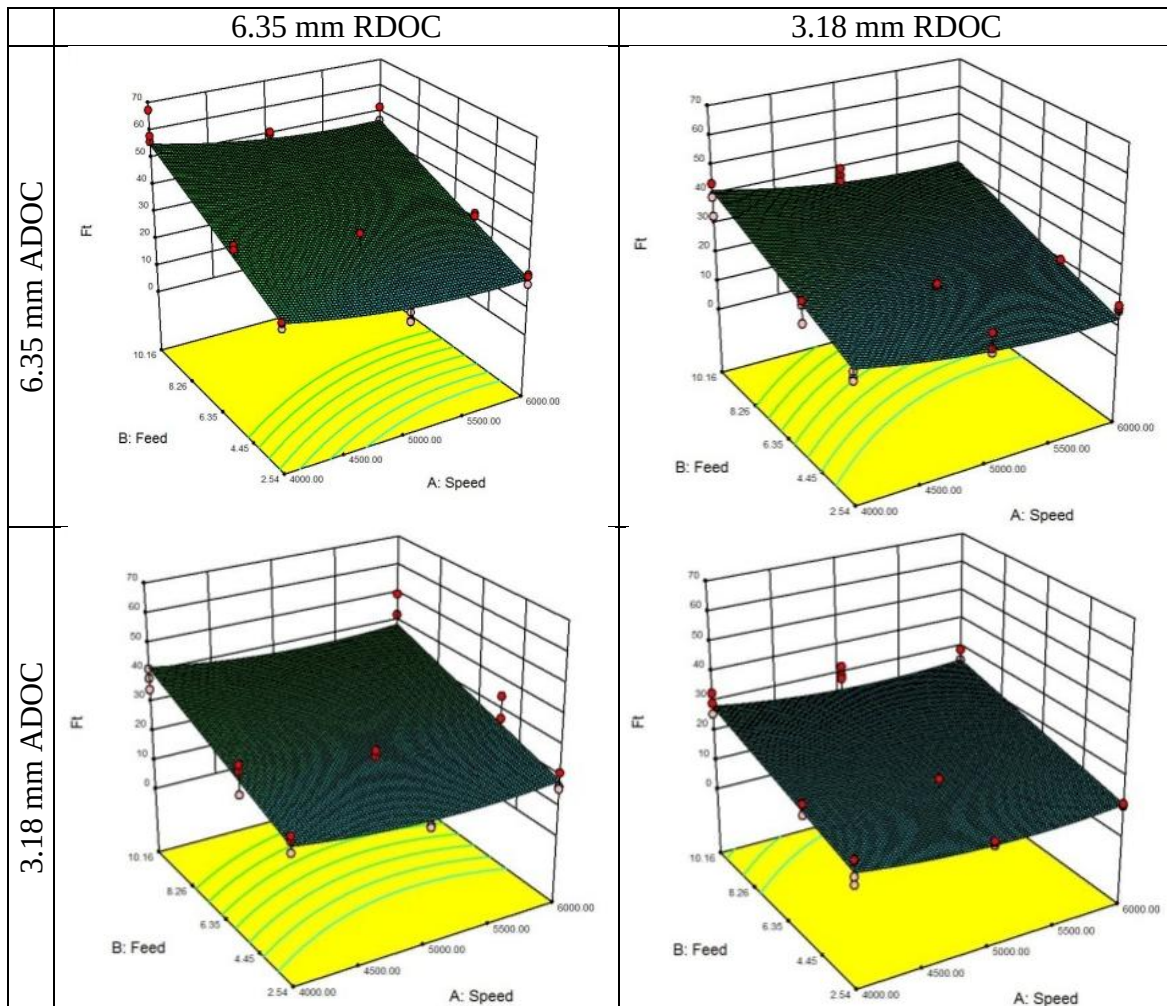


Figure 6-23: Regression plots of tangential cutting forces in AAC.

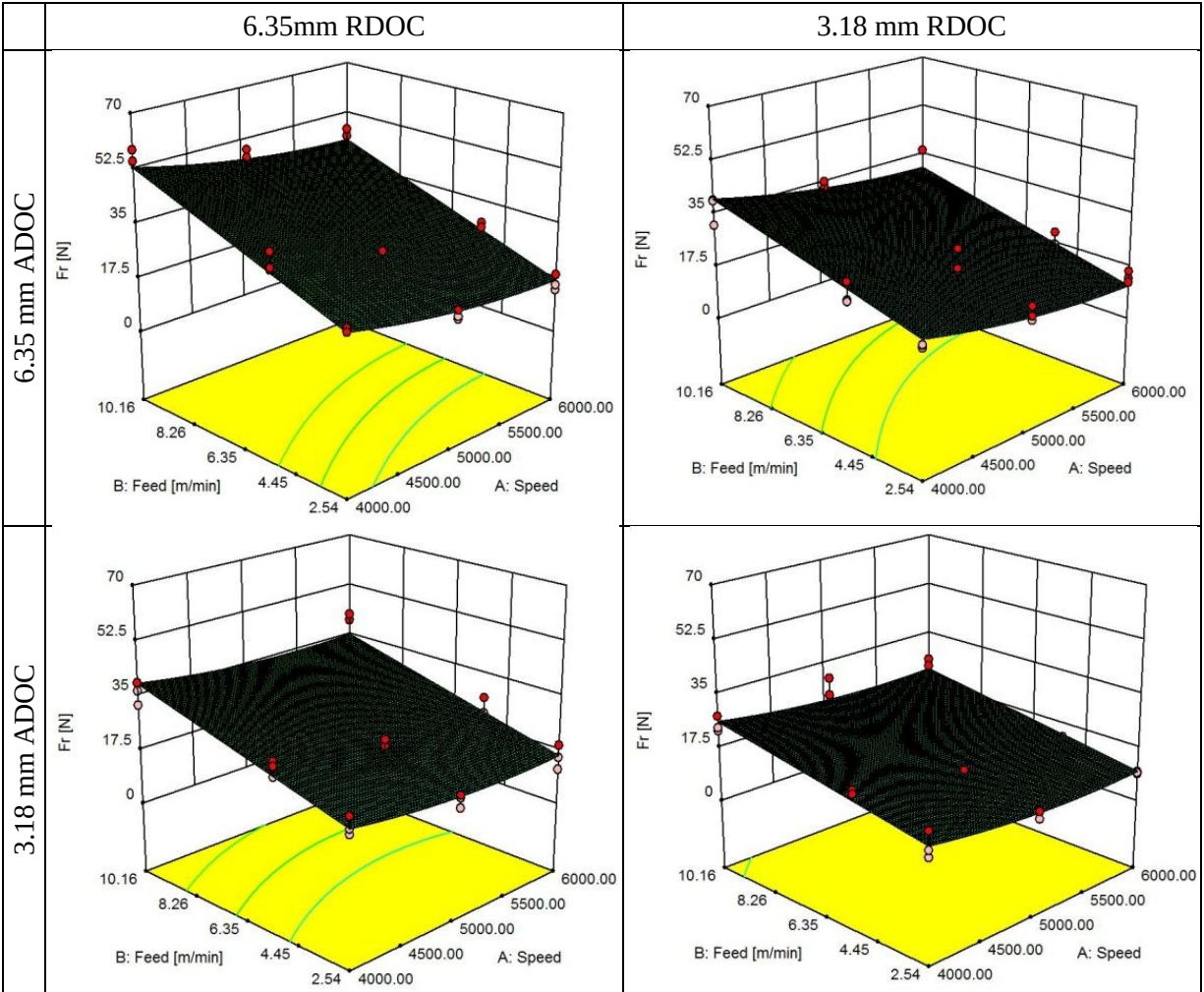


Figure 6-24: Regression plots of radial cutting forces in AAC.

6.6.4 Cfoam Cutting Forces

Cfoam showed the very low cutting forces which were also the most random in magnitude of the three materials. Cutting force profiles varied both in shape and magnitude in response to random nature of the material's porosity. The results of the ANOVA analysis for each factor are given in Table 6-5. The same method of analysis described in the CB1100 cutting force section is used here.

Table 6-5: Results of the ANOVA of cutting forces in Cfoam

	Analysis of variance for Ft		Analysis of variance for Fr	
Source	F Value	p-value Prob > F	F Value	p-value Prob > F
Model	94.95	< 0.0001	148.26	< 0.0001
A-Speed	88.67	< 0.0001	126.12	< 0.0001
B-Feed	607.93	< 0.0001	725.02	< 0.0001
C-RDOC	120.82	< 0.0001	156.49	< 0.0001
D-ADOC	151.78	< 0.0001	167.46	< 0.0001
AB	44.59	< 0.0001	59.77	< 0.0001
AC	4.59	0.0348	10.25	0.0019
AD	18.1	< 0.0001	22.75	< 0.0001
BC	27.89	< 0.0001	33	< 0.0001
BD	100.48	< 0.0001	99.57	< 0.0001

From the listed F-values it is evident that the linear terms: Speed, Feed, RDOC, and ADOC have a strong probability of influencing the response. It is also evident that the interaction of terms B and D (feed and axial depth of cut) has a significant probability of influencing the responses. The p-value is low for all terms except the factorial interaction of A and C, Speed, and RDOC. Therefore the terms which are most influential in the model are: A Speed, B Feed, C RDOC, D ADOC, and BD Feed x ADOC.

Equations Eq. (6.9) through Eq. (6.12) were obtained from the Design Expert software from the cutting force DOE and describe the modeled tangential and radial cutting forces Ft and

Fr. Equation Eq. (6.9) and Eq. (6.11) are coded equations; meaning each factor is unitless. Equation Eq. (6.10) and Eq. (6.12) are in terms of the actual factors and have their associated relative units.

$$F_t = 17.49 - 3.23 * A + 8.38 * B + 3.08 * C + 3.45 * D - 2.73 * (A * B) - 0.73 * (A * C) - 1.45 * (A * D) + 1.76 * (B * C) + 3.35 * (B * D) - 1.44 * A^2 \quad \text{Eq. (6.9)}$$

$$F_t = -19.69 + (5.66e - 3 * speed) + 1.76 * feed + .09 * RDOC + 3.22 * ADOC - (7.17E - 4) * (speed * feed) - (9.11e - 4) * (speed * ADOC) + 0.30 * (feed * RDOC) + .55 * (feed * ADOC) \quad \text{Eq. (6.10)*}$$

$$F_r = 15.76 - 3.22 * A + 7.51 * B + 2.93 * C + 3.03 * D - 2.64 * (A * B) - 0.91 * (A * C) - 1.36 * (A * D) + 1.60 * (B * C) + 2.78 * (B * D) \quad \text{Eq. (6.11)}$$

$$F_r = -32.58 + (7.98e - 3 * speed) + 1.98 * feed + 3.02 * RDOC + 3.25 * ADOC - (6.93E - 4) * (speed * feed) - (5.73e - 4) * (speed * RDOC) - (8.54e - 4) * (speed * ADOC) + 0.265 * (feed * RDOC) + 0.46 * (feed * ADOC) \quad \text{Eq. (6.12)}$$

The tangential and radial cutting forces are predominately influence by the feed rate. The coefficients of feed (B) in the equations above are larger than any of the other factors or factorial interaction contributions. Axial and radial depths of cut are the second most influential factors with approximately 40% the influence of feed rate. Factorial interactions were also present contributing to a slightly non-linear model. Tangential and radial cutting forces both illustrated a significant influence due the interaction of feed rate and axial depth of cut. In both tangential and radial cutting force models the interaction effect of feed and speed has an influence similar to the either axial or radial depth of cut alone. Figure 6-25 and Figure 6-26 illustrate the influence of feed and speed on tangential and radial cutting force at high and low levels of axial and radial depths of cut.

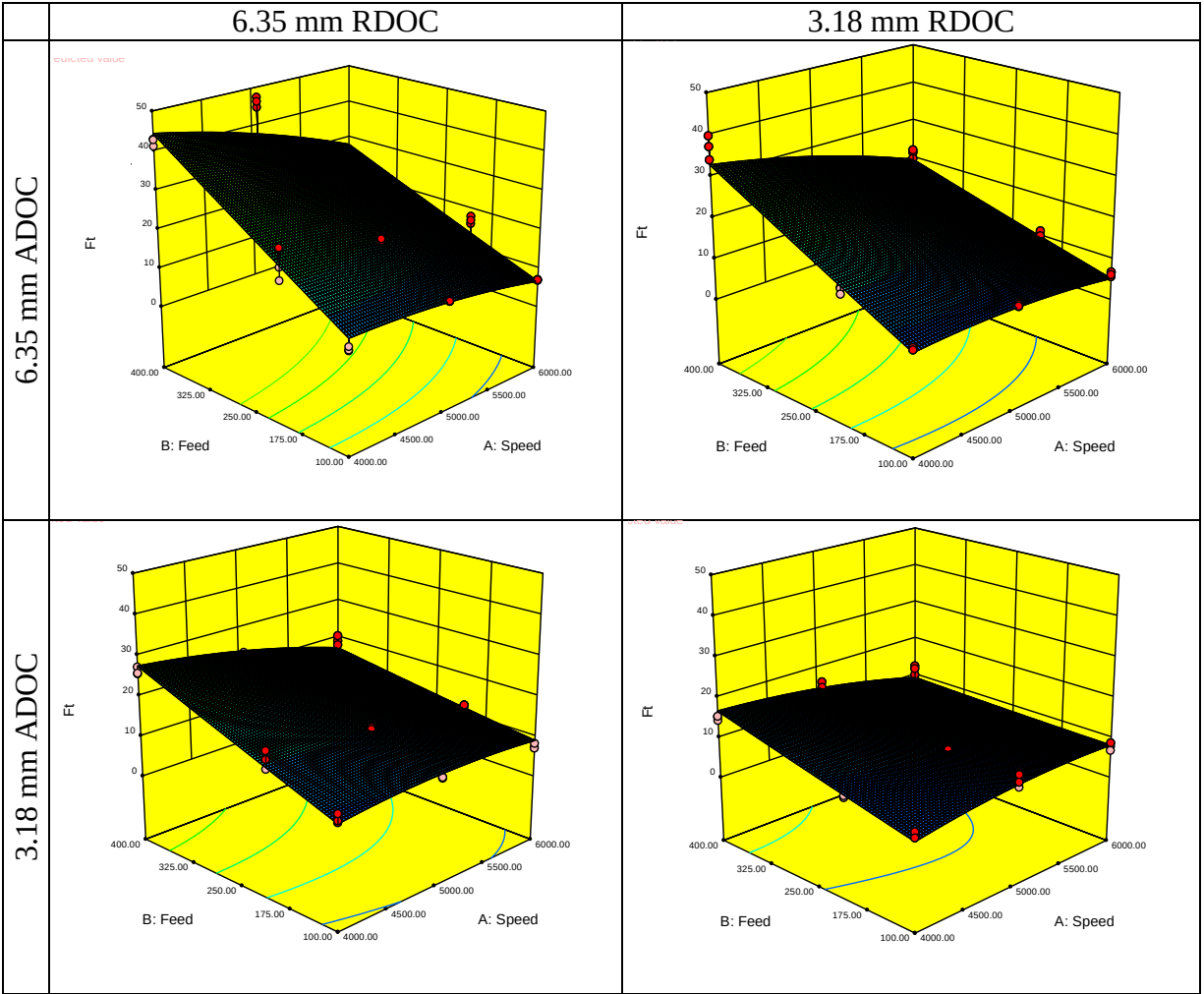


Figure 6-25: Regression plots of tangential cutting forces in Cfoam.

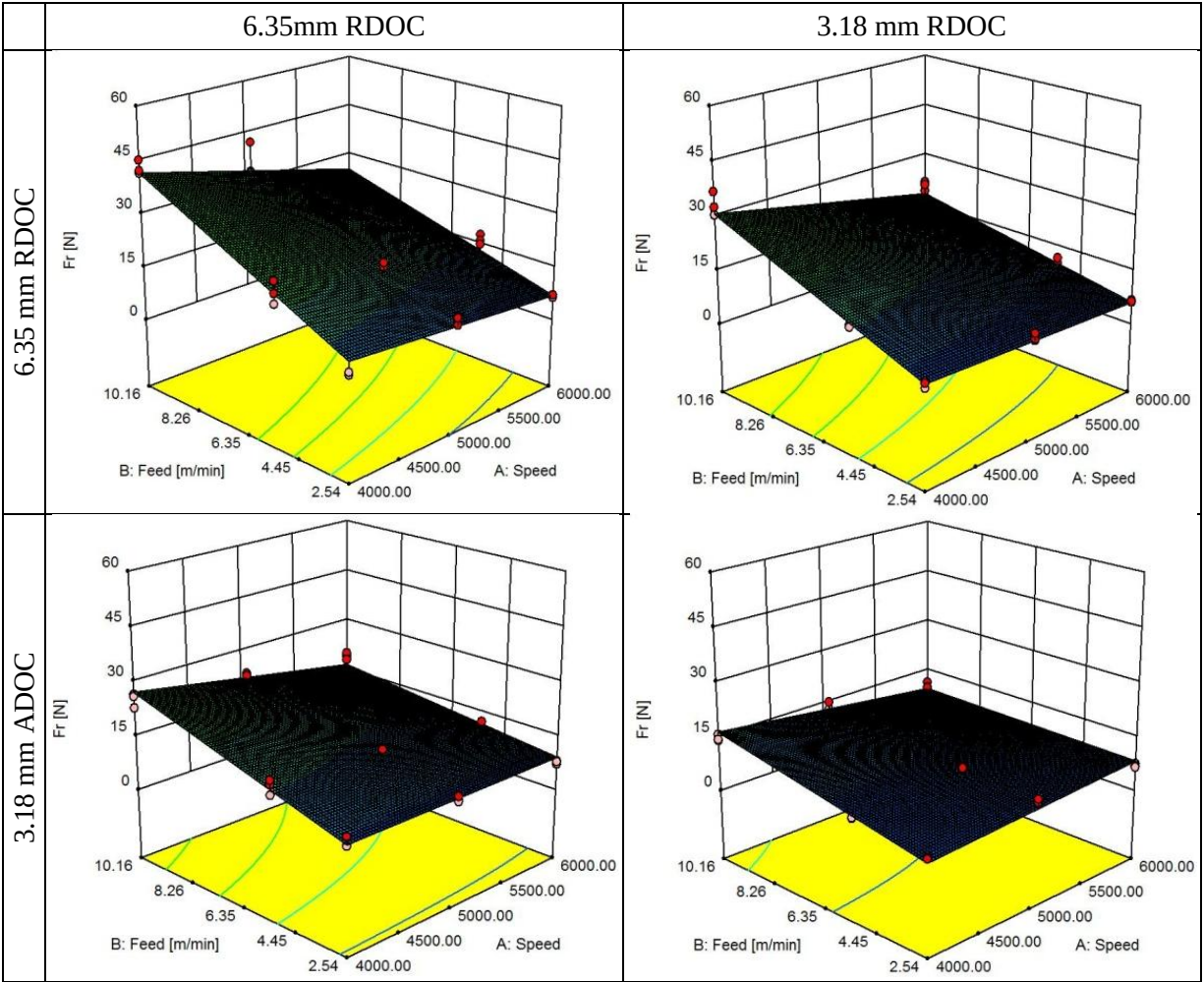


Figure 6-26: Regression plots of radial cutting forces in Cfoam.

6.6.5 Cutting force comparison

Cutting forces for all three materials were found to behave predominantly linearly with respect to nearly all cutting parameters. Higher levels of non-linearity were found in Cfoam. The obtained coded factor coefficients are given below in Table 6-6. The coefficients of all the linear terms and the most significant non-linear terms are provided.

Table 6-6: Comparison of model coefficients for Ft of each factor in each material.

Factor	AAC	CB1100	Cfoam
Speed	2.96	8.97	3.23
Feed	10.16	26.26	8.38
Radial depth of cut	5.3	8.62	3.08
Axial depth of cut	3.76	14.76	3.45
Speed * Feed	0	4.53	2.73
Feed * ADOC	1.49	7.61	3.35
Speed*Speed	2.67	0	1.44

In order to draw comparisons between these materials, the values in Table 6-6 were normalized with respect to their most influential factor, which in all cases was feed rate. These normalized values are given in Table 6-7. The cells which are highlighted represent the most influential factors following feed rate. Cfoam has three cells highlighted. This is because these factors have approximately the same relative level of influence with approximately 40% the influence of feed rate. One of these terms is the non-linear factorial interaction of feed and axial depth of cut. This is the highest non-linear influence found in any material. AAC is influence more strongly by radial depth of cut than any other material. Conversely, CB1100 is influence more strongly by axial depth of cut than any other material.

Table 6-7: Comparison of normalized model coefficients for Ft of each factor in each material.

Factor	AAC	CB1100	Cfoam
Speed	0.29	0.34	0.39
Feed	1.00	1.00	1.00
Radial depth of cut	0.52	0.33	0.37
Axial depth of cut	0.37	0.56	0.41
Speed * Feed	0.00	0.17	0.33
Feed * ADOC	0.15	0.29	0.40
Speed*Speed	0.26	0.00	0.17

Radial cutting force coefficients and the normalized coded factorial coefficients are shown in Table 6-8 and Table 6-9. As in the tangential cutting forces the most influential term was the feed rate. Cfoam was most strongly influence by speed following feed rate. The non-linear terms of (speed *feed) and (feed*ADOC) both have significant influences with 35% and 37% the influence of feed. It is important to keep in prospective that the second most influential factor only has 43% the influence of feed itself.

Table 6-8: Comparison of model coefficients for Fr of each factor in each material.

Factor	AAC	CB1100	Cfoam
Speed	3.45	9.11	3.22
Feed	9.68	23.78	7.51
Radial depth of cut	4.74	8.13	2.93
Axial depth of cut	3.78	13.32	3.03
Speed * Feed	0	3.65	2.64
Feed * ADOC	1.66	6.08	2.78
Speed*Speed	2.1	0	0

Table 6-9: Comparison of normalized model coefficients for Fr of each factor in each material.

Factor	AAC	CB1100	Cfoam
Speed	0.36	0.38	0.43
Feed	1.00	1.00	1.00
Radial depth of cut	0.49	0.34	0.39
Axial depth of cut	0.39	0.56	0.40
Speed * Feed	0.00	0.15	0.35
Feed * ADOC	0.17	0.26	0.37
Speed*Speed	0.22	0.00	0.00

6.6.6 CB1100 Surface Topography

For AAC and Cfoam it was decided that large numbers of surface roughness traces would be damaging to the surface profilometer's probe. Therefore, surface topography studies were limited to CB1100. For analysis purposes, it is convenient to normalize the surface roughness values with respect to chipload. Chipload is an important factor when considering surface quality of machined surfaces. Chipload is directly related to cutting force and the size and distribution of feed/tooling marks. From optical studies of all three materials, only CB1100 had distinguishable feed marks, Figure 6-27.

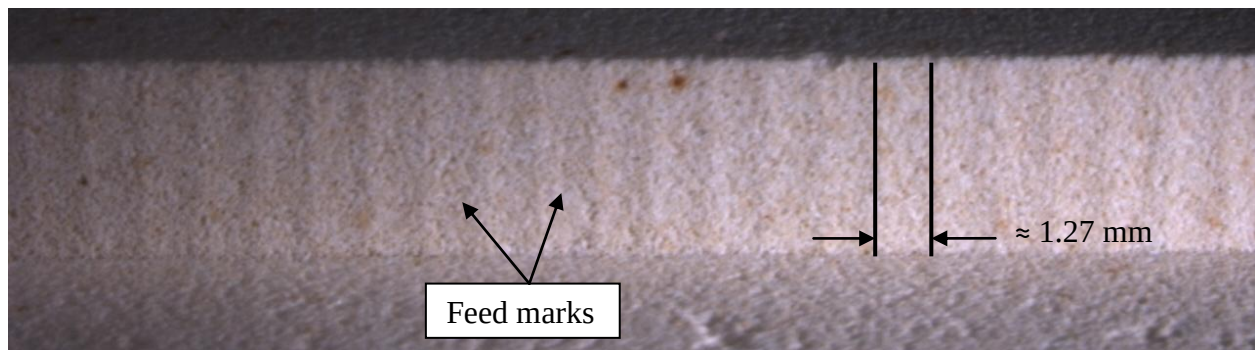


Figure 6-27: Feed marks in CB1100 surface peripherally milled at 4000 RPM and 10.16 m/min.

The results of the surface profilometry performed on CB1100 shows a slight linear behavior with respect to cutting parameters. Only small increases in average surface roughness were observed as cutting force is increased. Figure 6-28, shows measured surface roughness parameters: R_a , R_z , and R_t versus chipload for the peripherally milled surfaces (left) and face milled surfaces (right).

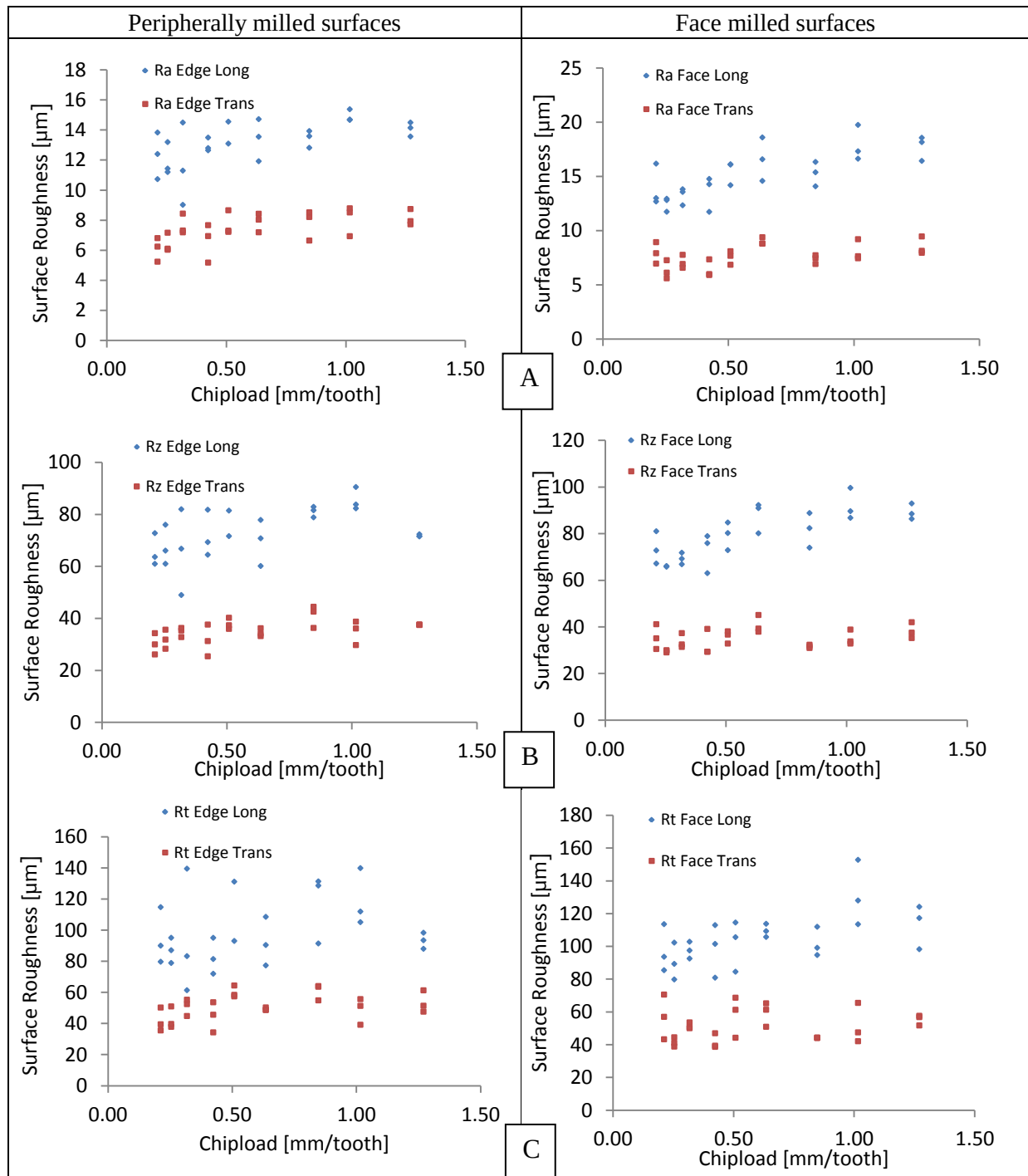


Figure 6-28: Measured surface quality parameters (a)Ra of peripherally and face milled surfaces, (b)Rz of peripherally and face milled surfaces, (c)Rt of peripherally and face milled surfaces.

In an effort to characterize the machining process values of R_q/R_a were determined. For a perfectly sinusoidal curve the value of R_q/R_a equal approximately 1.12. Values of R_q/R_a were found to be in the range of 1.2 – 1.3 for both high and low cutting force samples and in all directions. This is an average increase of approximately 10% over the ideal sinusoidal case and is found to reflect a similarity to the process of grinding isotropic materials.

CB1100 showed a high degree of directional dependency of the surface topography. There is also a dependency upon type of milling action used, peripheral or face milling. Average surface roughness (R_a) values in the range 12 - 14 μm were found in the peripherally milled surface in the longitudinal direction. Values of R_a in the same direction on the face milled surface averaged between 14 - 18 μm . Average surface roughness in the transverse direction regardless of the milling action were in the range of 6 -9 μm .

6.6.7 Machining induced damage

Two forms of machining induced damage were found throughout the study: micro-cracking, and fracture. The extent of each type of damage changed with material and cutting conditions. In AAC the severity of fractured regions and their depth increased with increased feed rates and chiploads. Micro-cracking was also found to increase. While the average observed crack length did not change, the frequency of cracks increased. Surfaces machined in Cfoam frequently exhibited micro-cracking and fractured ligaments. Surface area and depth of the fractured regions and ligaments was found to increase with increasing feed rate and chiploads. CB1100 also showed an increase in the average length and frequency of crack. Cracks showed a propensity to occur near or in ligaments. Micro-cracks were uniformly distributed and frequently traversed cell walls.

A comparison of SEM images of the typical machined surfaces and polished surfaces for each material is given in Figure 6-29. In each case several types of damage can be seen. Non-planar regions of damage, jagged cell walls, fractured and chipped regions and ligaments can all be identified. The machining induced damage is truly significant because of the induced stress concentrations they create in these brittle materials. This can lead to significant reductions in residual strength and degradation of surface integrity.

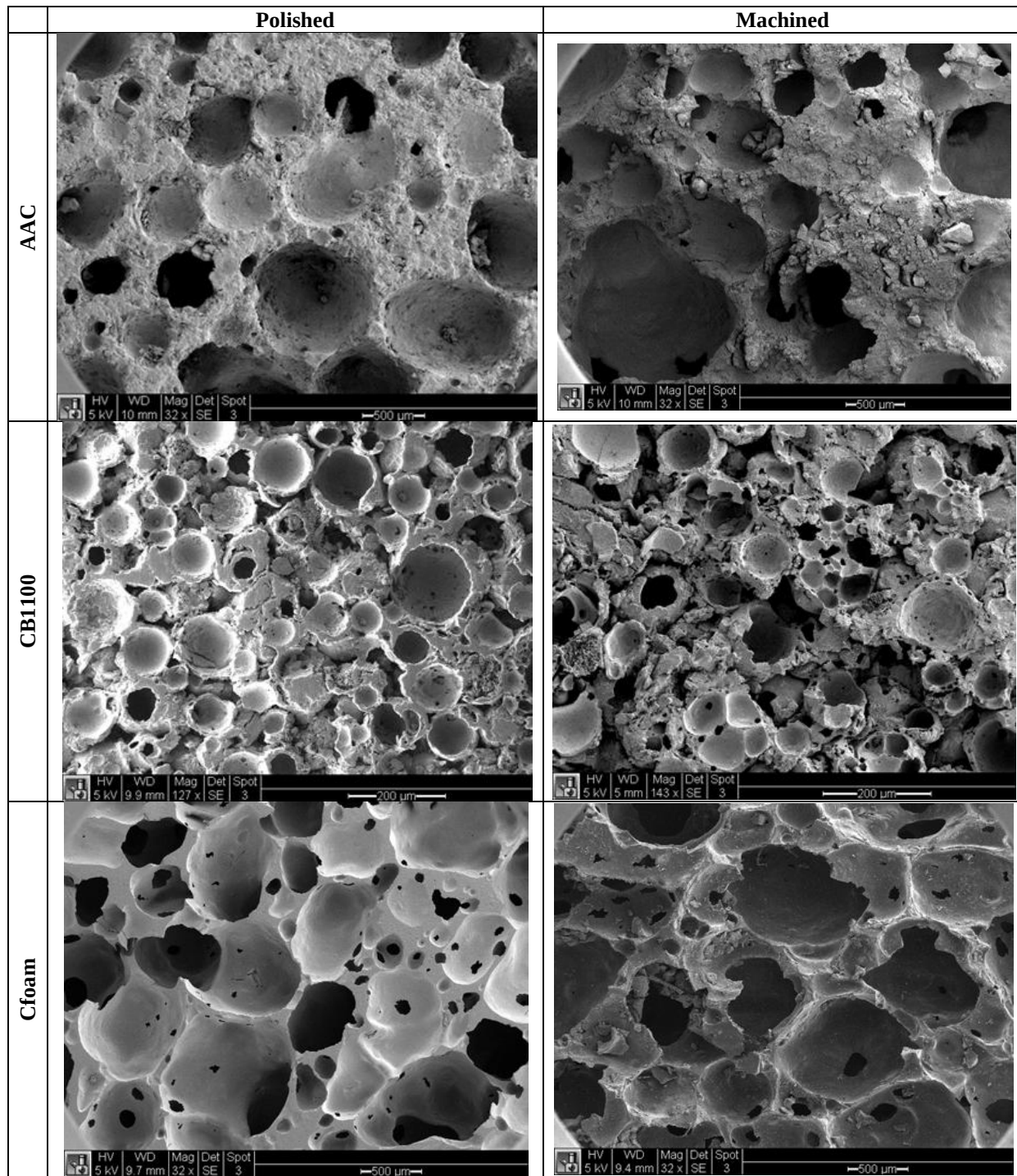


Figure 6-29: Sem images of polished and machined AAC surfaces.

6.6.8 Surface integrity

The damage induced during machining varied in combination of type and severity for each material. Induced damage has the potential to reduce the surface integrity through the creation on stress concentrations. The effect of rough cutting conditions vs. light cutting conditions on residual flexural strength and surface roughness is shown below in Figure 6-30.

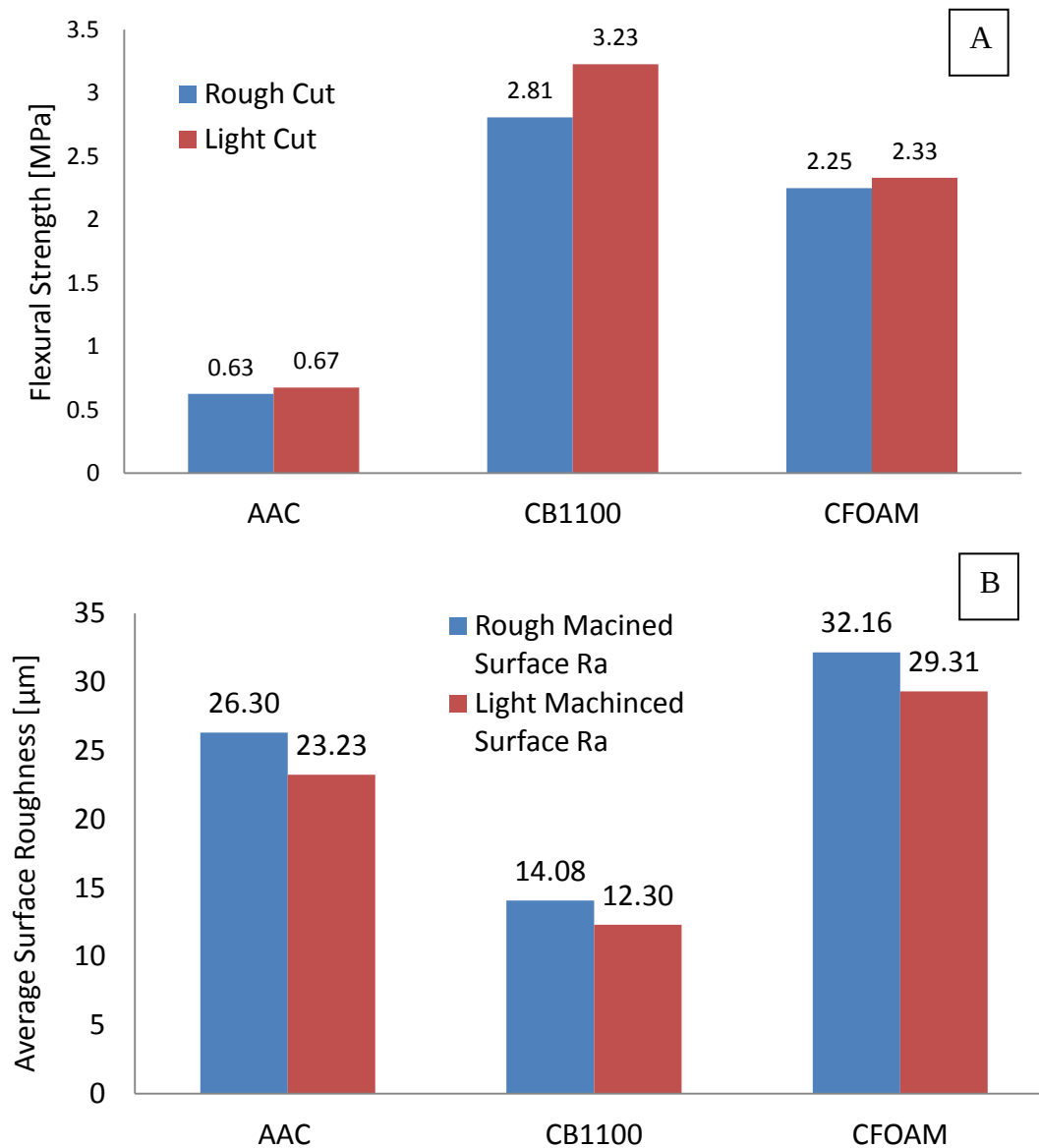


Figure 6-30: Effect of rough cutting Vs light cutting conditions on (a.) residual flexural strength and surface integrity and (b.) average surface roughness.

All three materials exhibited a decrease in average residual flexural strength and an increase in surface roughness when using rough cutting conditions. However, reductions in flexural strength in AAC and Cfoam were less significant than CB1100 which exhibited a 13% decrease from 3.23 MPa to 2.81 MPa. The probability of failure versus stress for each material obtained via weibull analysis is plotted in Figure 6-31.

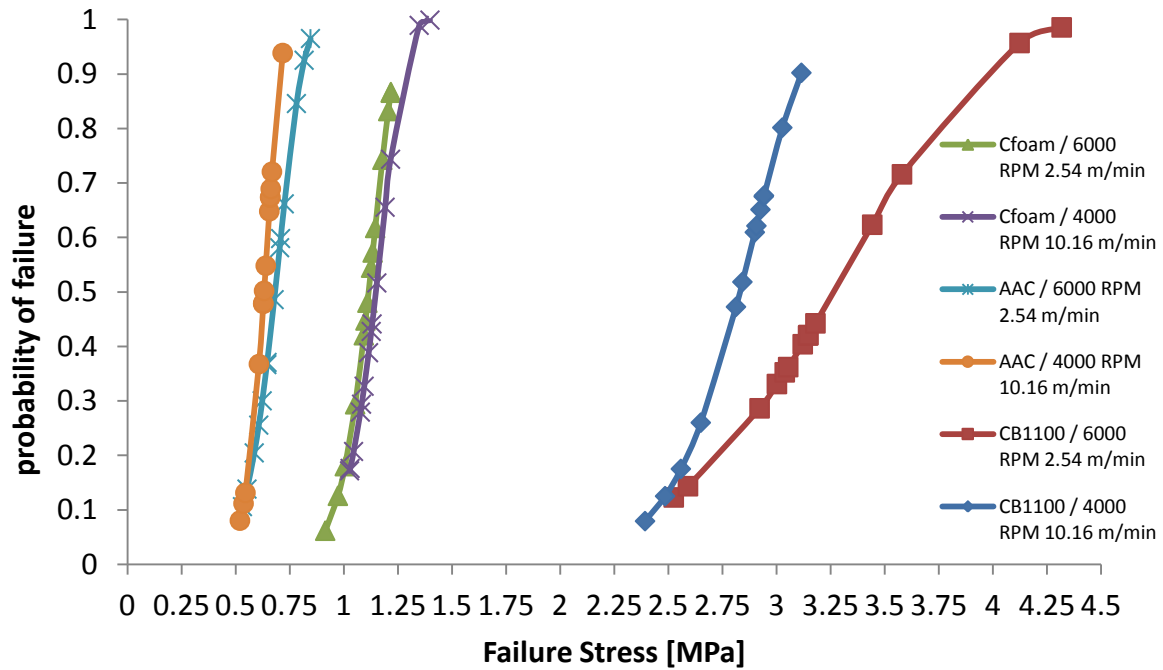


Figure 6-31: Probability of failure vs. stress in tooling substrate materials machined at two different cutting conditions.

From Figure 6-31 the clear difference in strength between these three materials can be seen. The immediate observation is the significant change in strength that is exhibited in CB1100. The measured 13% reduction in residual flexural strength corresponds to a 16% reduction in characteristic strength from 3.46 MPa to 2.91 MPa. Loss of flexural strength in CB1100 is significantly greater than either AAC or Cfoam. The Characteristic strengths and Weibull moduli of all materials and conditions is listed in Table 6-10.

Table 6-10: Weibull modulus and characteristic strength

Material	Condition	σ_0 [MPa]	m
CB1100	(1) 6000rpm/ 2.54m/min	3.46	6.48
	(2) 4000rpm/ 10.16m/min	2.91	12.64
Cfoam	(1) 6000rpm/ 2.54m/min	1.18	11.67
	(2) 4000rpm/ 10.16m/min	1.14	12.05
AAC	(1) 6000rpm/ 2.54m/min	0.70	7.3
	(2) 4000rpm/ 10.16m/min	0.65	10.9

The Weibull modulus of CB1100 increased from 6.48 to 12.64, indicating a more consistent distribution of critical flaws which were induced by machining at 4000rpm and 10.16 m/min over 6000rpm and 2.54m/min. The increase of the weibull modulus in CB1100 is an increase of approximately 95%. Smaller changes in modulus were observed in Cfoam and AAC. AAC showed an increase of approximately 49% while Cfoam increased only 3%. This suggests that the machining process is inducing a more consistent controlling flaw distribution in CB1100 and AAC. Therefore, the machining conditions selected for these materials can have a controlling effect on the surface integrity and strength of the workpiece.

6.7 Conclusions and recommendations

The specific application of each tool and its design will really dictate which of these materials is suitable. CB1100 and Cfoam both have a wide range of possible tool designs and applications. AAC, due to its low strength is only suitable for small part prototyping. Furthermore, AAC should only be used in applications where the substrate can be designed in a non-structural way. Although, CB1100 and Cfoam both have wide applicability they both have several performance compromises which must be taken into consideration.

CB1100 surface roughness was the lowest of all the materials due to the small pore size. Small pores can decrease the amounts of sealants, fillers, or adhesives required during post machining stages of tooling manufacture. CB1100, while the strongest, has the highest density and will thus result in the highest mass tools. Additional mass increases weight along with

thermal mass and handling costs. Higher density also increases cutting forces leading to micro scale damage which was shown to degrade the surface integrity by up to 16%. However, even with the reduced surface integrity and strength it remained the strongest material of the three. Large cutting forces also cause unsupported edge loss and gouging/chipping of the machined surface, limiting the rate of material removal.

Cfoam was the second strongest of the materials tested but the lowest density. Cfoam's low density reduces its mass which makes heating and handling less costly. Unlike AAC or CB1100 unsupported edge loss was minimal and Cfoam was found to be damage tolerant to large scale fracture as well as micro scale damage. While low in strength, Cfoam exhibited damage tolerance which was capable of maintaining the surface integrity regardless of the machining conditions. In addition, machining conditions did not affect the surface roughness which was controlled by the pore size and distribution. There were no limiting factors on the achievable material removal rate. Cutting forces were extremely low. However, as discussed in the feasibility investigation, Cfoam is extremely abrasive. Expensive diamond based cutting tools are required in order to reduce tool change time and provide long tool life. The carbon based dust produced while machining Cfoam is also hazardous to electrical equipment and a possible health hazard. Therefore, additional waste material handling costs are incurred. Cfoam is also the most expensive base material of all three tested.

Only once all the performance aspects of the application are defined can an appropriate choice of a tooling material be made. All advantages and disadvantages of each material must be evaluated when making a choice of tooling materials. A table listing the performance of each material with respect to the issues discussed in this study is given in Table 6-11. Recommendations in Table 6-11 are related to the use of carbide fluted tools and are based upon

ensuring final part quality and reliability. Recommended maximum MRR is based upon the approximate cutoff above which damage to the workpiece is likely and quality degrades. Methods of avoiding unsupported edge loss are listed for each material as well as the expected surface integrity. These recommendations and values are valid within the machining conditions tested during this research only. Machine tools with higher speed and feed capabilities may be capable of exceeding these recommendations.

Table 6-11: Material performance comparison.

Property	AAC	CB1100	Cfoam
Achievable MRR	300 cm ³ /min	820 cm ³ /min	3300 cm ³ /min
Cutting forces	10-70 [N]	10-160 [N]	5-50 [N]
Unsupported edge loss	Severe: Workpieces should be machined from the outside in whenever possible.	Severe: Feed rates should be reduced below 2.54m/min near unsupported edges and thin sections	Fair: Feed rates should be reduced below 5.08m/min when axial depth of cut is greater than 12.70mm near unsupported edges and thin sections
Machined surface quality	Poor	Fair	Poor
Surface integrity under heavy machining conditions	No reduction in surface integrity	Up to 16% reduction	No reduction in surface integrity
Tool life	Excellent: Carbide fluted tools are recommended	Excellent: Carbide fluted tools are recommended	Poor: High grade carbide tools are acceptable. Diamond abrasive type tools are recommended
Chip/dust handling Problems	Clogging of diamond abrasive type tools is problematic	Slightly abrasive dust. Easily handled with vacuum equipment	Dust is extremely abrasive and conductive. May be hazardous to machinery and personal. Sealed enclosure is recommended

Chapter 7: Peripheral milling force model for porous brittle materials

This chapter presents a model for predicting end milling cutting forces in porous brittle materials. A new cutting coefficient and method of calculation which describes the variation in cutting forces due to porosity is proposed and compared to experimental results of Chapter 6. The proposed porous material coefficient is a function of pore geometry and statistics. This coefficient adapts existing traditional metallic cutting force modeling approaches and allows them to be applied to brittle porous materials. The programming language used to perform the calculation was the Matlab coding language and the code is given in Appendix I.

7.1 Model formulation

The following section describes the process, assumptions and their rational used in the formulation and use of the developed model. The model is based on cutting force algorithms defined by Altintas [75][83] and adapted to brittle porous materials. The proposed model takes the following approach to determine the cutting forces: Firstly, it is assumed that the cutting edges are divided into N equally sized elements of height dz . Each of these elements experiences a cutting force determined by its position, tool geometry, cutting conditions and the material properties. Cutting forces of each element are assumed to be proportional to the instantaneous contact area. The sum of the forces acting on all the elements at any given time is the total cutting force. A schematic representation is shown in Figure 7-1.

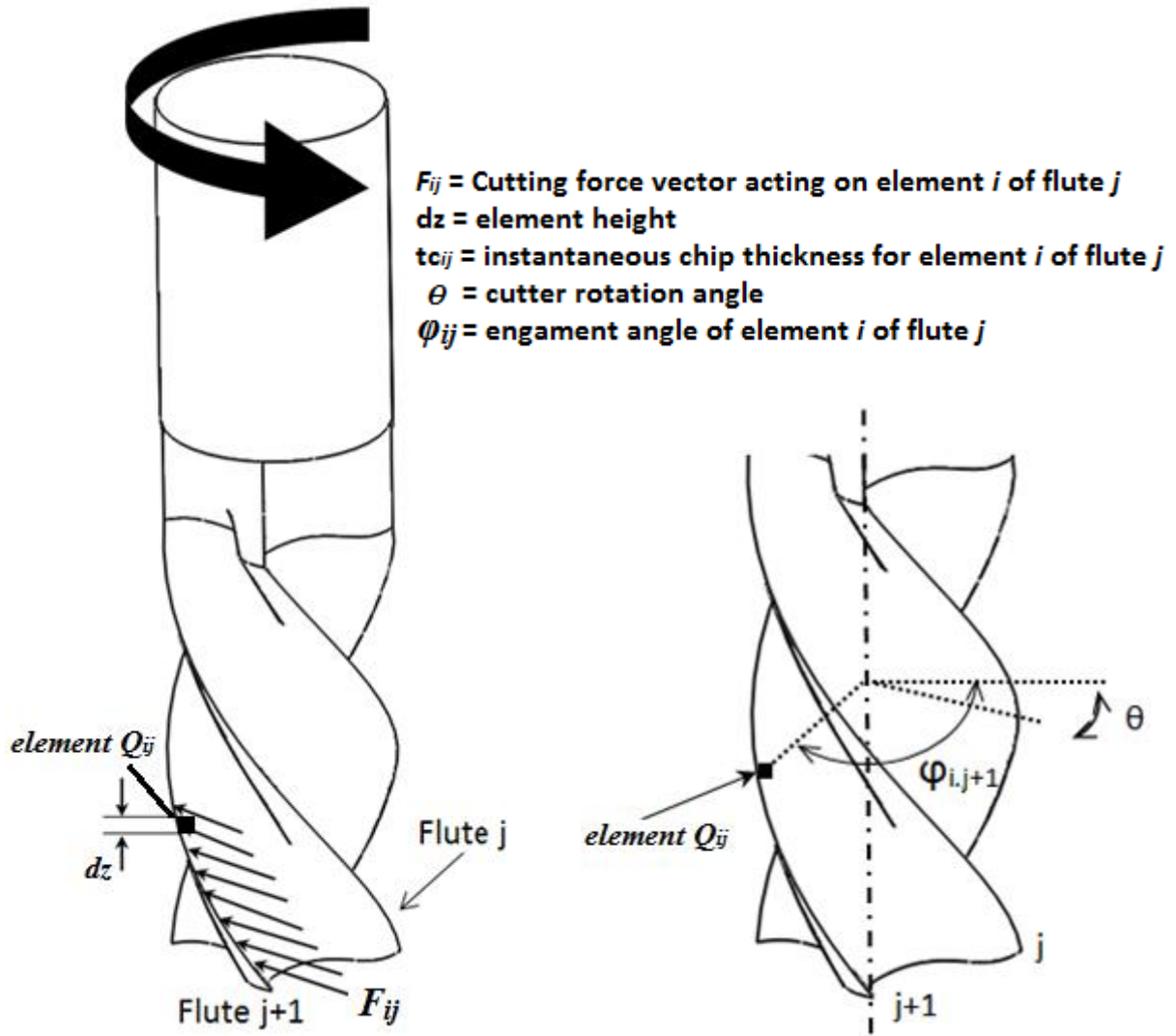


Figure 7-1: Schematic diagram of elemental cutting force modeling approach.

The model requires three basic inputs for the calculation: element number, pore number, and rotation angle or time. Elemental cutting forces are uniquely determined based upon which element it is related to, the pore the element is currently in, and the location within the pore the cutting edge is currently at. Each element is individually defined in space and no two elements will be in the same location at any point in time. In other words, the cutting path of each element through the material is particular to that element. Calculation of the cutting force for element $Q_{i,j}$ will yield a different result than the same instant in time for element $Q_{i+1,j}$ because they will be in

different locations. Also, the cutting force determined for an element at a given angle of rotation will not be the same at the same angle of rotation from one revolution to the next. This is due to the variation in pore size which leads to the second domain of the calculation.

The second input is pore the number, or current pore size. At the onset of a simulation each pore's diameter is determined. The pore diameter varies according to a defined statistical distribution. A selected number of data points are chosen to define the equivalent or effective contact area through the pore. The number of data points through the pore is constant. Yet, the pore size is not constant. This causes data points of unequal spacing. *The relationship between cutter rotation and time is assumed to be constant. However, the spacing between data points and time is not constant in the calculation.* Therefore, the data points are spaced at different increments of rotational angle. Thus, there is a requirement for the third and final input, rotational angle or time. Rotational angle and time are assumed to be proportionate. This assumes a constant spindle RPM.. *Time or rotation angle are the only way of correlating force between elements at any instant.* The forces on the cutter are determined by summing elemental forces at a given time or rotation angle. Small deviations in the data point spacing between elements introduce error into the model. Increasing the number of data points through each pore reduced the size of the deviation between elements. A high resolution is used in the developed model and the error due to point spacing discrepancy is assumed to be negligible.

The specifics of the individual calculations will now be presented. The parameters of the model such as tool geometry and RPM are stored in an excel file which reads the values into the code. Any information which is said to be determined by the user is entered here. The most basic but critical user input is the number of elements in the computation.

7.1.1 Basic force formulation

The cutting force acting on element Q_{ij} whose length is dz can be decomposed into the three component forces given in Equation 7.1. The component forces are the tangential, radial, and axial forces: $dF_{i,t}(z)$, $dF_{i,r}(z)$, and $dF_{i,z}(z)$, respectively. K_t , K_r , and K_z are the static cutting force coefficients. K_d is the proposed dynamic cutting coefficient which is responsible for reproducing the unloading effect on the cutting forces created by the pores. K_p is a material dependent coefficient which is used for all component forces. It will be discussed in detail in a later section. The addition of the dynamic coefficient is one of the final steps of the calculation. The instantaneous uncut chip thickness associated with element Q_{ij} is $h_i(z)$. Chip thickness will vary as a function of rotational angle and z position. The total force acting on the cutting edge for a specific cutter rotation angle can be expressed as Equation 7.2. The integration boundaries in Equation 7.2 are the cutter immersion boundaries. To obtain the total instantaneous cutting force at cutter rotation angle ϕ the forces acting on all cutting edges, J , are summed.

$$\begin{aligned} dF_{i,t}(z) &= K_t K_p h_i(z) dz \\ dF_{i,r}(z) &= K_r K_p h_i(z) dz \\ dF_{i,z}(z) &= K_z K_p h_i(z) dz \end{aligned} \quad \text{Eq.(7.1)}$$

$$\begin{aligned} F_{i,x}(\phi) &= \int_{z_{i,1}}^{z_{i,u}} h_i(z) [-K_t \cos(\theta(z)) - K_r \sin(\theta)(z)] dz \\ F_{i,y}(\phi) &= \int_{z_{i,1}}^{z_{i,u}} h_i(z) [K_t \sin(\theta(z)) - K_r \cos(\theta)(z)] dz \end{aligned} \quad \text{Eq.(7.2)}$$

$$\begin{aligned} F_{i,z}(\phi) &= \int_{z_{i,1}}^{z_{i,u}} K_z h_i(z) dz \\ F_s(\phi) &= \sum_{j=1}^J F_{j,s}(\phi) \quad s = x, y, z \end{aligned} \quad \text{Eq.(7.3)}$$

7.1.2 Element size and position

The number of elements used in the model is designated by the user. However, certain limitations exist due to the assumptions used by the model. The number of elements must be high enough to capture the geometry of the cutting edge. If the count is too small the effect of the helix will be lost. If the count is too high, complications due the relative size of an element to the pore size may arise. A high element count may lead to cutting forces which appear less random and give the appearance of a more homogeneous material than is actually being modeled. Higher errors are observed when the element/pore ratio is greater than 4 or less than 0.5. Whenever possible an element size within $\pm 20\%$ of the mean pore diameter is suggested.

Each elements individual position on is determined by the helix angle of the cutter and the rotation of the tool. The instantaneous rotation angle of element $Q_{i,j}$ is designated by $\phi_{i,j}$. The radial position is assumed to remain constant. A constant radial position is an assumption of a perfectly rigid tool. For the materials studied here the largest of the measured cutting forces was still negligible in comparison to the stiffness of the tool. Therefore, cutter runout was assumed to also be negligible. However, the inclusion of cutter runout is a possible addition to the model if desired. Derivation and methods used to determine runout parameters are included in Appendix K.

7.1.3 Instantaneous chip thickness

In the absence of cutter runout, the chip thickness at the position of each element is calculated using Equation 7.8.

$$h_{ij}(\theta) = f_z \sin(\theta(Q_{ij})) \quad \text{Eq.(7.4)}$$

$\theta(Q_{ij})$ is the position of element Q_{ij} , which is the sum of the rotation due to the helix angle, κ , and the overall rotation of the cutter θ . κ is a function of the axial position z , and can be found using Equation 7.5.

$$\kappa(z) = \frac{z \tan \beta}{R} \quad \text{Eq.(7.5)}$$

Where, R and β represent the nominal radius and helix angle of the cutter.

The product of the instantaneous chip thickness and the height of the elements results is the instantaneous contact or cutting area, referred to here as the geometric contact area. All that is required in order to determine the force on the element is the coefficients, namely the: cutting force coefficients and the porous cutting coefficient.

7.1.4 Porous cutting coefficient

The porous cutting coefficient is responsible for modeling the unloading effect on the cutting forces caused by the presence of the pores. The porous cutting coefficient creates a ‘representative porous cutting path’ which models the variation in cutting force due to the presence of pores. As the cutting edge passes through the chip it encounters a series of randomly sized pores. The porous cutting coefficient randomly determines the degree of unloading caused by the reduction in contact area due to the presence of the pores. The process is represented in a schematic flow chart in Figure 7-2.

Process Parameters:

- Tool geometry
- RPM and feed rate
- Axial depth of cut
- Radial depth of cut

From process parameters, uncut chip thickness is determined

Elemental forces can now be summed across all elements to get the total cutting force

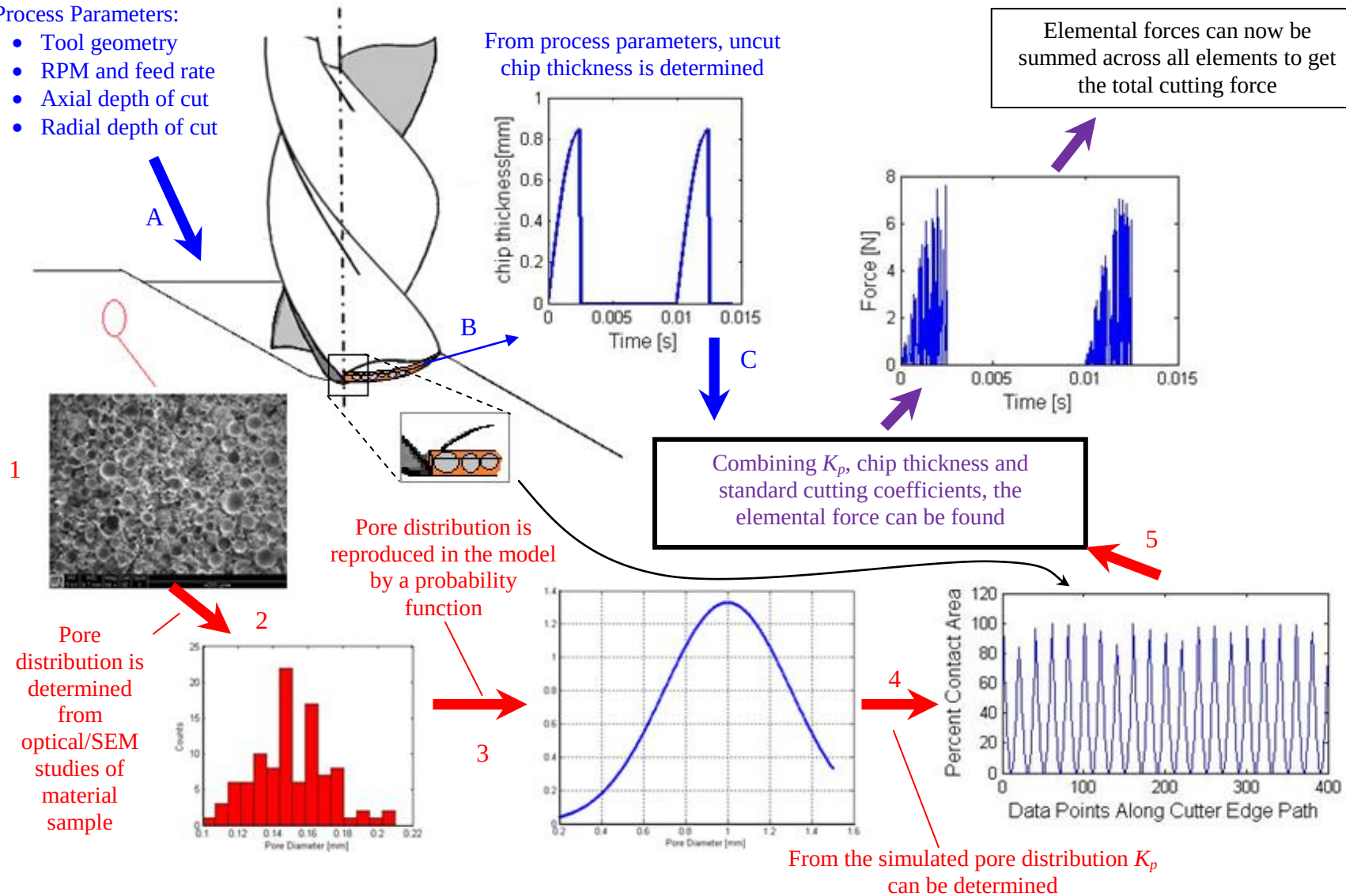


Figure 7-2: Flow chart of brittle porous material end milling model

The size and distribution of the pores is specific to the material. Therefore, the randomness and magnitude of the unloading effect is also determined by this distribution. A continuous function is not capable of reproducing the experimentally observed behavior. The solution is the use of a random number generator stream *with the desired distribution*. The following method was used to produce the desired result: From the material's maximum, minimum, mean, and standard deviation of pore size the probability density function can be determined, Figure 7-3a.

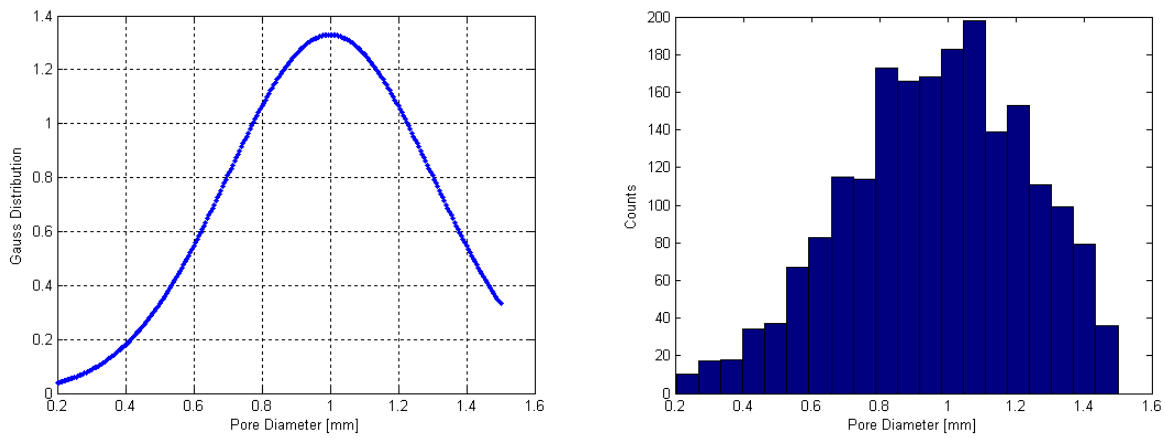
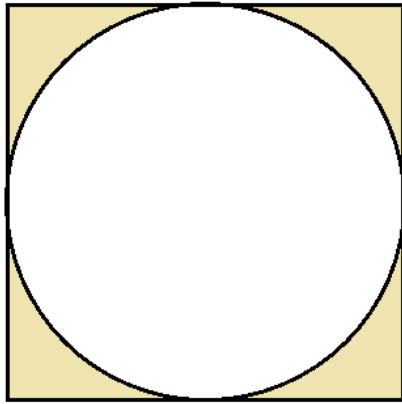


Figure 7-3: (a) User defined pore size distribution (b) generated pore size distribution of model

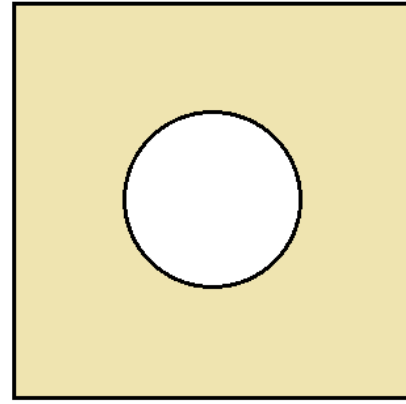
Here, the pore size distribution is assumed to be Gaussian in nature, but can be assumed to have any distribution desired. This allows the model to be tailored to match the distribution of materials which may not have a Gaussian distribution. From the probability density function a weight is selected for each possible pore size. The pore size is then selected at random using the weighted probabilities assigned to them from the distribution function, Figure 7-3b. With the pore size determined, the amount of material in contact with the element can be found, expressed as a positive value less than one or as a percentage.

$$K_p = \frac{A_n - A_p(\varphi)}{A_n} \quad \text{Eq.(7.6)}$$

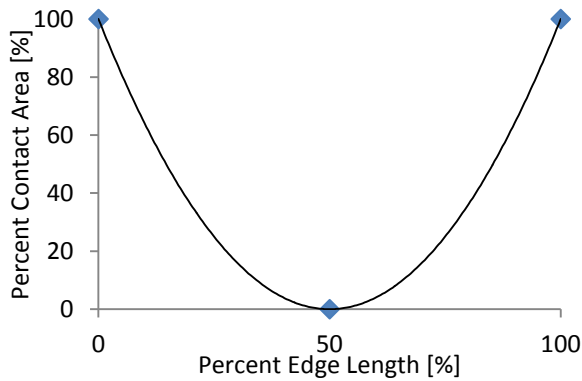
Where A_n is the nominal surface area of the element and $A_p(\varphi)$ is the area of the pore at cutter angle φ . K_p varies as a function of rotation angle due to the pore geometry. A spherical shaped pore is assumed here. However, as in the pore distribution, the shape of the pore can be defined as any shape representative of the materials pores. Contact may be assumed to begin at the tangent point of the pore and the surface area is assumed to be 100%. Contact may also be assumed to be 100% at the exit of the pore. This assumes that the element is sized to match the pore diameter, as shown below in Figure 7-4a,b. Sizing the element larger than the pore diameter, Figure 7-4b, and using a pore geometry function which describes the ligament size, Figure 7-4d is also possible. This geometry is appropriate when pore spacing or ligament thicknesses are large.



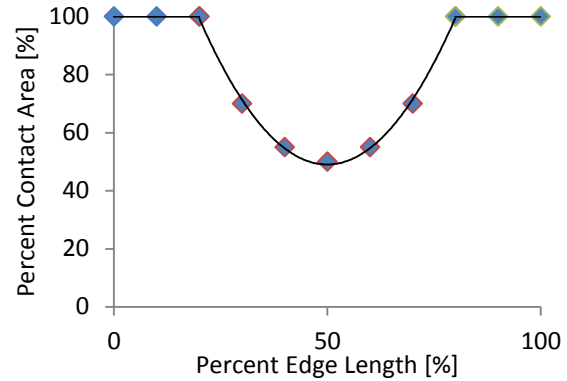
a.)



b.)



c.)



d.)

Figure 7-4: a.) 2-D Representation of element with size matching pore diameter b.) 2-D Representation of element with pore modeling thick ligament c.) Percent contact area plot of element with size matching pore diameter d.) Percent contact area of element with pore diameter small than element edge length.

For the materials modeled here a varying sized element is used. The element is assume to be the full size of the pore up to a defined maximum edge length. The maximum edge length is the uncut chip thickness or feed per tooth. Typical plots of K_p for a given section of cutting path are presented in Figure 7-5. K_p is plotted for three different levels of standard deviation of pore diameter.

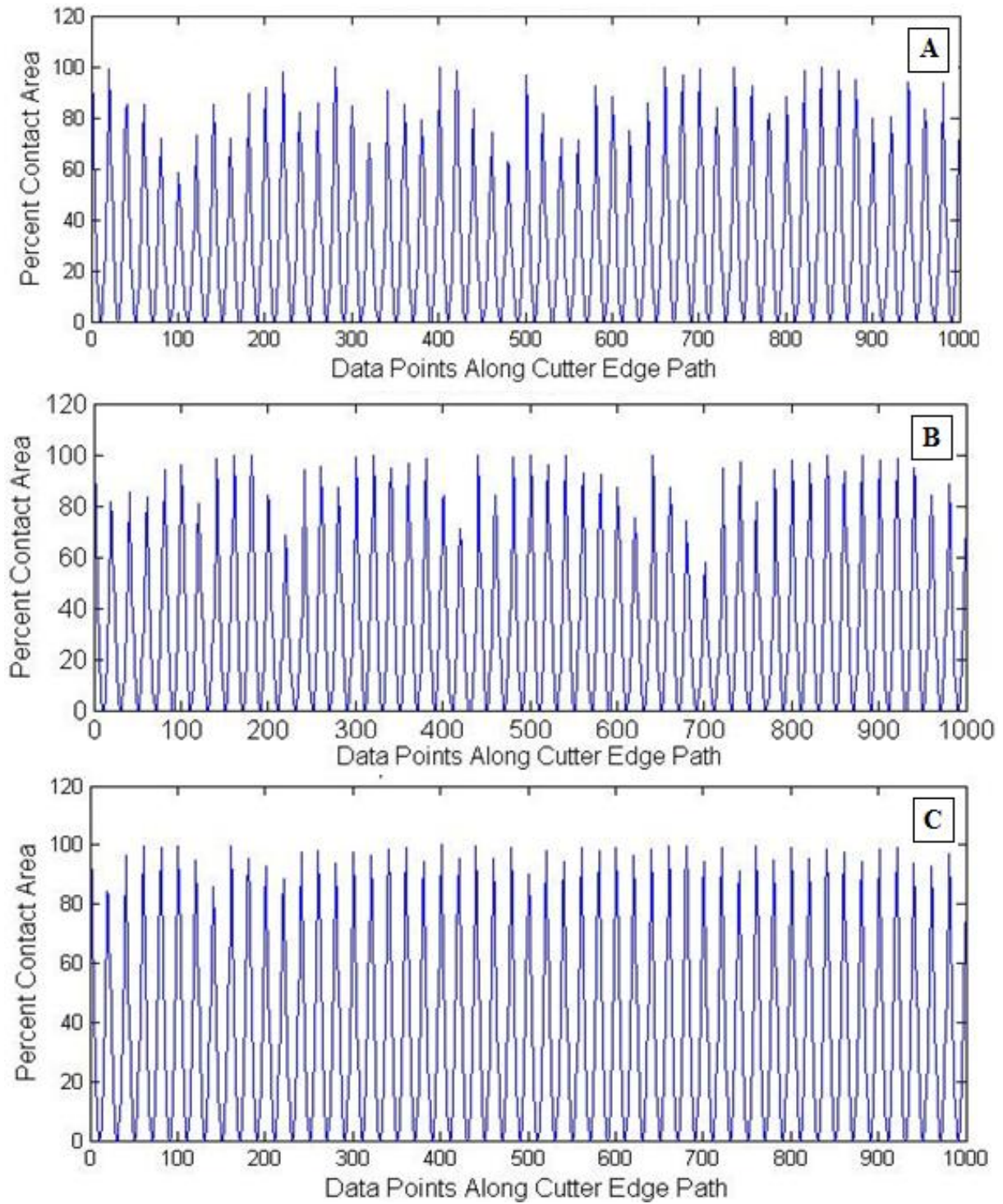


Figure 7-5: Typical percent contact area (K_p) plotted along cutter path for an arbitrary element with pore diameter standard deviation equal to (a) 0.64 (b) 0.32 and (c) 0.16.

Although the maximum edge length of the element is limited, the maximum size of the pore can exceed the maximum edge length of the element. Therefore, the percent contact may not reach 100% for that particular element. This is visible in Figure 7-5. When the standard deviation of the pore diameter is low and pores are smaller on average than the uncut chip thickness, as in Figure 7-5c, the edges of the elements or the peaks, are at 100% contact area more consistently than in Figure 7-5b. The standard deviation of the pore diameters in Figure 7-5b is twice that of Figure 7-5c. Further increased occurrences of pores with diameters exceeding the uncut chip thickness are seen in Figure 7-5a, when the pore diameters standard deviation is doubled again. Although the spacing between peaks is constant the size of the pores are varying. There are a set number of data points per pore or cell. Data points are plotted equidistantly in Figure 7-5. In Figure 7-6 below, K_p is plotted versus time.

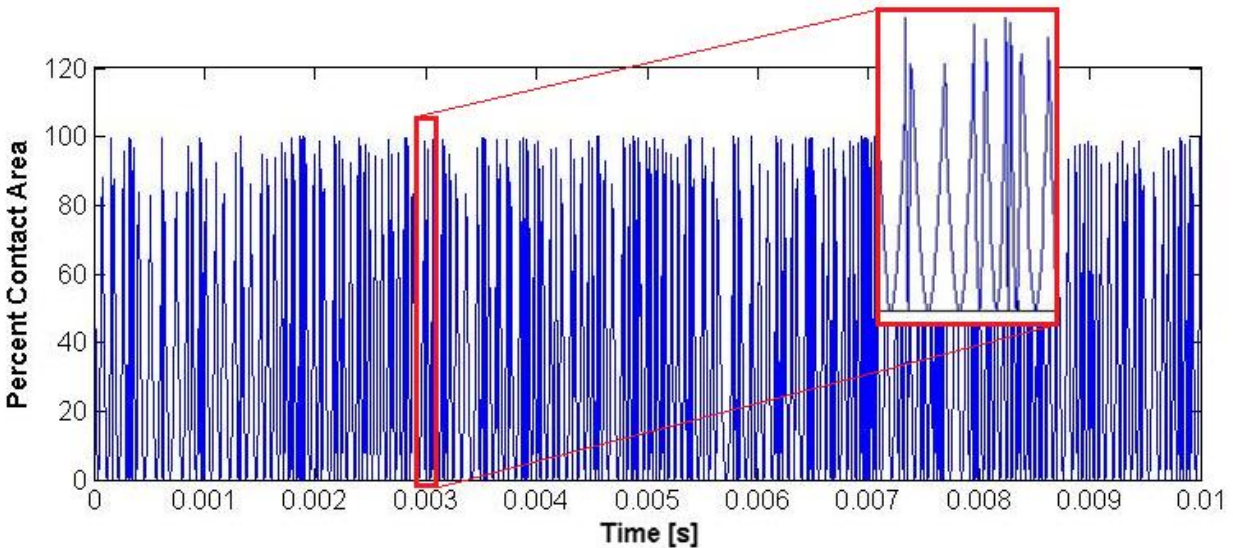


Figure 7-6: Typical percent contact area (K_p) versus time of an arbitrary element versus time

The variation in the size of the pores is much more visible in the variation of the spacing of the peaks. The time period of Figure 7-6 is approximately equal to that of one full revolution at 6000 RPM. Here large and small pores can be seen in with random variation in size. Interspersed regions of high density where numerous small pores are adjacent are also visible. The average value of K_p in the plot shown is approximately 35%. Peak values range from 80 – 100% while the upper average (average of top 20%) is 88%.

7.1.5 Determining the cutting force coefficients

The cutting force coefficients and the porous coefficient work together in order to determine the resultant cutting forces. Thus the porous coefficient must be present during the determination of the cutting force coefficients. Due to the random nature of cutting forces observed in porous media, average values of force must be used in order to determine the cutting force coefficients. Further, the porous coefficient is random in nature and thus the average value must also be used.

Cutting tests using two fluted end mills are the most convenient means of determining the coefficient values. A radial engagement of greater than 50% of the diameter of the cutting tool should be used to further simplify the determination. Ensuring that a chip thickness equal to the full feed per tooth, f_t , is achieved and that only one flute is in the cut allows for straightforward determination of the cutter contact area. Cutting tests are performed at varying feeds. This will vary the instantaneous uncut chip thickness and contact area. The average of the maximum cutting force for several cutting edge profiles is then calculated. This maximum force will occur at the maximum uncut chip thickness. The average peak force is then plotted against the instantaneous uncut chip thickness. The edge force contributions due to friction F_f are found to be negligible in the material tested here. However, if found these forces must be removed. Measured values are then related to the analytical equivalent as follows

$$\begin{aligned} F_{tm} - F_f &= K_{pa} K_t f_t Z_t \\ F_{rm} - F_f &= K_{pa} K_r f_t Z_t \\ F_{zm} - F_f &= K_{pa} K_z f_t Z_t \end{aligned} \quad \text{Eq.(7.7)}$$

Where, F_{tm} , F_{rm} and F_{zm} are the measured radial, tangential and axial force respectively. K_{pa} is the average value of the porous coefficient and Z_t is the total axial depth of cut. The average of the porous coefficient can be found by using the average pore diameter then taking

the mean value over the selected shape function. A linear regression of the plotted average measured peak cutting force versus maximum uncut chip thickness is performed. The slope of the regression line normalized with respect to K_{pa} is now equal to the cutting force coefficient.

$$\begin{aligned} K_t &= \frac{Slope_t}{K_{pa}} \\ K_r &= \frac{Slope_r}{K_{pa}} \\ K_z &= \frac{Slope_z}{K_{pa}} \end{aligned} \quad \text{Eq.(7.8)}$$

7.2 Results

The process parameter inputs of the model are defined by the user through a Microsoft Excel spreadsheet. A typical input spreadsheet along with approximate input values is shown below in Table 7-1. The inputs in Table 7-1 were used for the simulation which produced Figure 7-7 and Figure 7-8.

Table 7-1: Typical input spreadsheet for model.

Number of elements/ Edge			
5			
Cutter Properties			
Diameter[mm]	Length of cut [mm]	number of flutes	Helix Angle [deg]
12.70	25.40	2	0
Material			
Pore min diam. [mm]	Pore max diam. [mm]	Pore mean [mm]	Pore stdev.
0.5	2	1.2	0.4
Cutting conditions			
RPM	Feed [m/min]	ADOC [mm]	RDOC [mm]
6000	2.54	6.35	6.35

Parameters characterizing the material porosity were measured using SEM and optical studies. Material parameters used during the simulation of cutting forces for AAC, CB1100 and Cfoam are presented in Table 7-2. Standard cutting coefficients are shown here un-normalized with respect to K_{pa} in order to draw comparisons.

Table 7-2: Model inputs for material porosity of AAC, CB1100, and Cfoam.

Material	Min. Pore Diameter [μm]	Max. Pore Diameter [μm]	Mean Pore Diameter [μm]	Standard Deviation of Pore Diameter [μm]	K_t	K_r
AAC	50	4000	1800	425	5.51 MPa	5.37 MPa
CB1100	30	220	90	42	15.34 MPa	13.24 MPa
Cfoam	50	2000	800	231	4.79 MPa	4.81 MPa

This high cutting coefficient of CB1100 is approximately three times as large as AAC or Cfoam as a result of the higher strength of the material. Although Cfoam is stronger than AAC the cutting coefficient is lower. The higher density of AAC increases cutting forces and contact area as evident by the increased cutting coefficient. As previously discussed, the total number of data points in the model is constant. These data points span different total lengths of time for each element. They also span different total rotational degrees per pore. In other words, the time spacing between data points is almost constantly varying. They must be correlated relative to time before they can be summed. As a back-check that the model is operating properly a plot of the data points vs. time is studied to ensure there are no anomalies. For example, if the pore size selected was an erroneous size such as negative or extremely large, the plot would not appear smooth continuous and linear. Discontinuities or rapid change in slope would occur. A typical data point vs. time plot of a properly operating model is shown in Figure 7-7.

The theoretical chip thickness of a homogenous material vs. time that is produced by the defined inputs is shown above. Observing this plot ensures that the chip thickness and mechanics of the process match those defined by the input values. A plot of the typical K_p values found over the full span of the simulation is shown above in Figure 7-7. This represents the path characterization component of the force calculation for one element. The theoretical elemental contact area, determined by the chipload and element height, combined with the characterized

path results in the elemental cutting forces. A typical plot of the elemental cutting force is shown below in Figure 7-7.

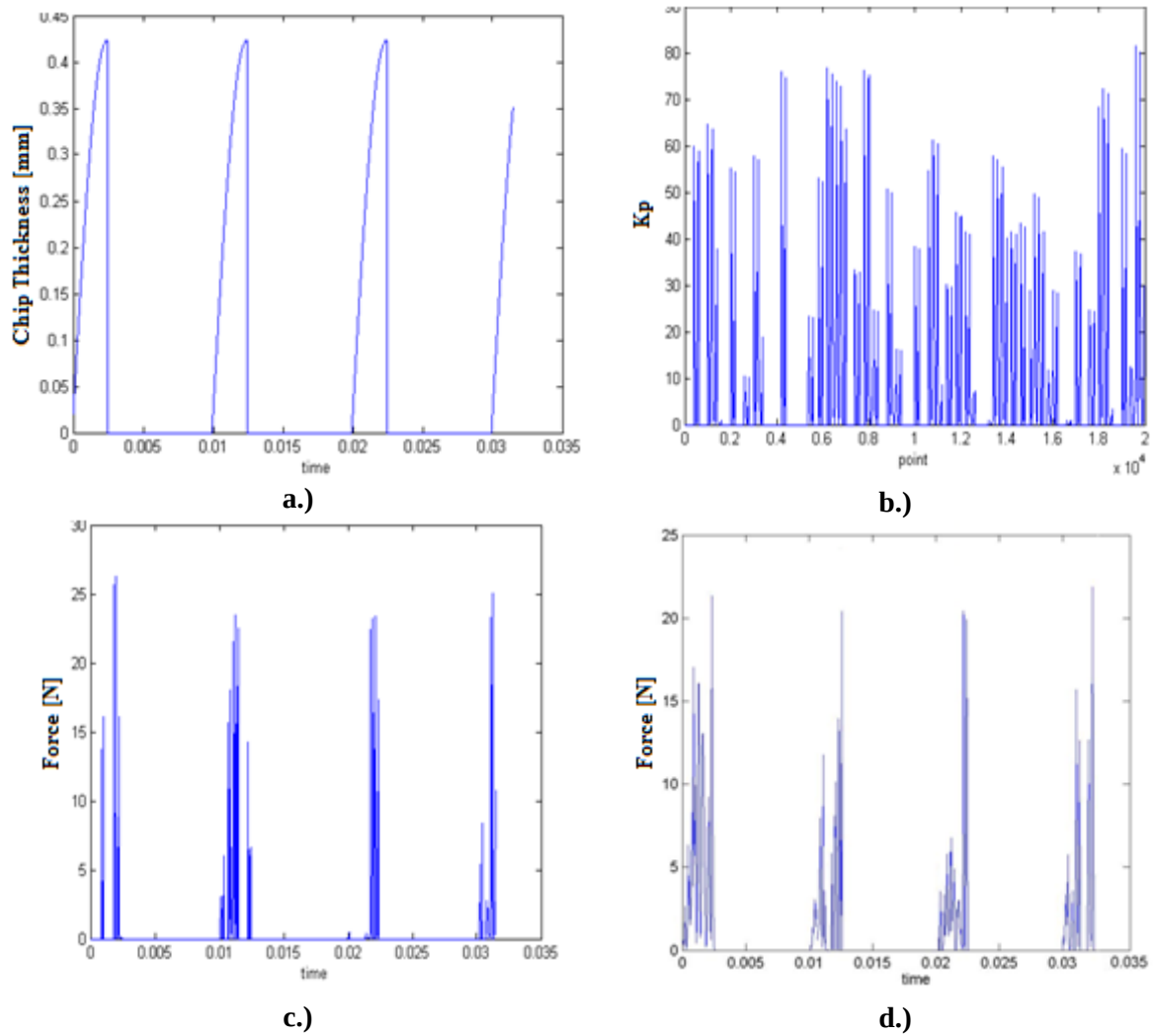


Figure 7-7: a.) Theoretical homogenous chip thickness b.) Typical elemental K_p values c.) Typical elemental tangential cutting force. d.) Typical elemental radial cutting force.

The sum of all elemental cutting forces across any time t is the total cutting force. The sum of the tangential elemental cutting forces is the total tangential cutting force. A typical predicted tangential cutting force profile is shown in Figure 7-8. The predicted force profiles are random and jagged in nature. Most profiles produce at least two distinctive peaks. The largest magnitude peak does not always occur at the thickest chip thickness values. This was also observed experimentally. Peak magnitudes are not consistent from one profile to the next. The degree of scatter depends upon the standard deviation of the pore size.

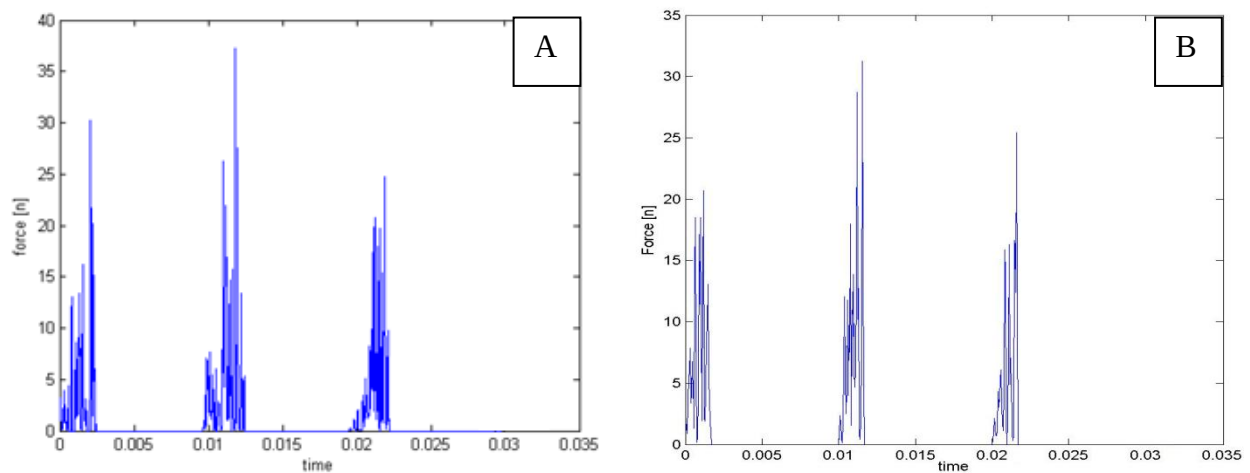


Figure 7-8: Typical predicted a.) tangential and b.) radial cutting force profile.

Summary results of the simulation of the same DOE performed in Chapter 6 are shown below in Table 7-3. A total of 108 conditions were simulated per material. As an example of typical results, three point averages of the simulated tangential cutting forces in AAC are given.

Table 7-3: Summary of simulated tangential cutting forces in AAC.

RPM	Feed [m/min]	RDOC [mm]	ADOC [mm]	Ft (simulated)	Fr (simulated)
4000	2.54	3.18	3.18	16.09	15.69
5000	2.54	3.18	3.18	10.43	10.17
6000	2.54	3.18	3.18	14.93	14.56
4000	5.08	3.18	3.18	22.07	21.52
5000	5.08	3.18	3.18	13.75	13.41
6000	5.08	3.18	3.18	17.55	17.11
4000	10.16	3.18	3.18	26.32	25.66
5000	10.16	3.18	3.18	25.13	24.50
6000	10.16	3.18	3.18	21.75	21.21
4000	2.54	6.35	3.18	18.55	18.09
5000	2.54	6.35	3.18	16.73	16.31
6000	2.54	6.35	3.18	16.02	15.62
4000	5.08	6.35	3.18	25.32	24.69
5000	5.08	6.35	3.18	21.77	21.23
6000	5.08	6.35	3.18	23.17	22.59
4000	10.16	6.35	3.18	37.31	36.38
5000	10.16	6.35	3.18	27.74	27.05
6000	10.16	6.35	3.18	29.48	28.74
4000	2.54	3.18	6.35	23.54	22.95
5000	2.54	3.18	6.35	16.51	16.10
6000	2.54	3.18	6.35	16.04	15.64
4000	5.08	3.18	6.35	30.92	30.15
5000	5.08	3.18	6.35	27.57	26.88
6000	5.08	3.18	6.35	23.98	23.38
4000	10.16	3.18	6.35	50.24	48.98
5000	10.16	3.18	6.35	37.59	36.65
6000	10.16	3.18	6.35	39.11	38.13
4000	2.54	6.35	6.35	24.20	23.60
5000	2.54	6.35	6.35	21.28	20.75
6000	2.54	6.35	6.35	20.11	19.61
4000	5.08	6.35	6.35	37.24	36.31
5000	5.08	6.35	6.35	28.48	27.77
6000	5.08	6.35	6.35	29.70	28.96
4000	10.16	6.35	6.35	52.15	50.85
5000	10.16	6.35	6.35	48.37	47.16
6000	10.16	6.35	6.35	41.17	40.14

7.3 Discussion

7.3.1 Cutting force profiles

Measured tangential cutting force profiles for CB1100 are shown in Figure 7-9 with the predicted cutting force profiles. The cutting force of one tooth is shown here in order to remove any possible variation from one profile to the next. The shape of the predicted profiles and measured profiles close resemble one another. The appearance of increased scatter in the prediction is the result of a larger number of data points in the simulation than the sampling rate of the dynamometer. The signal was not averaged here to match the dynamometer's resolution in order to illustrate the raw signal of the model.

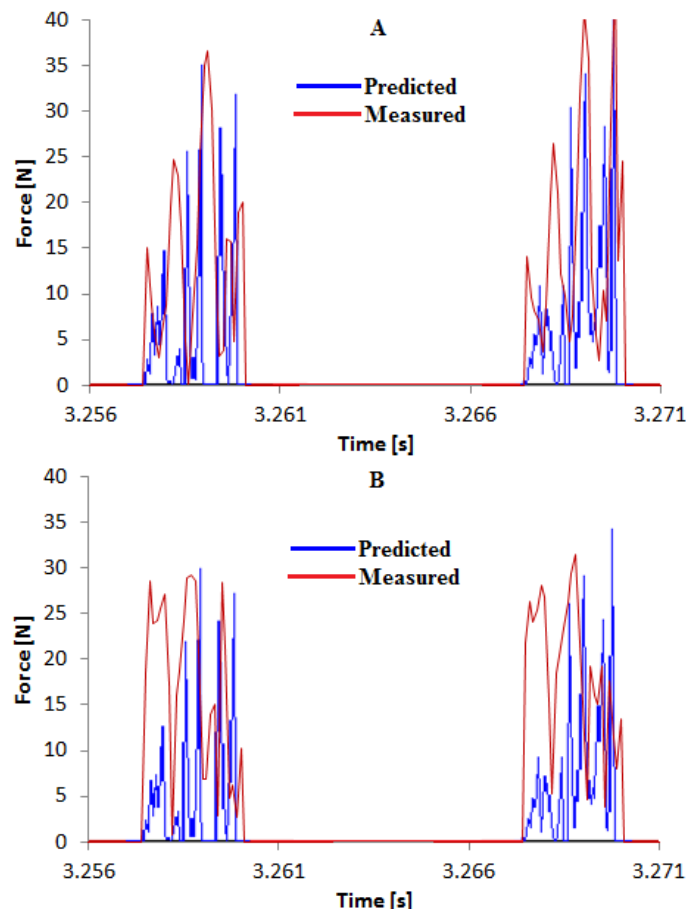


Figure 7-9: Comparison of measured and predicted a.) tangential and b.) radial cutting force profiles in CB1100 (6000 rpm, 5.08m/min) for tooth 1 only.

The magnitude of the peak forces and the overall shape approximately match measured forces, within the expected scatter range. Therefore, the model is capable of reproducing the behavior of the experimentally observed cutting forces on an individual cutting profile level within the degree of variation observed experimentally.

A comparison of the predicted cutting forces to the measured cutting forces over the full range of cutting conditions was conducted. The same 108 test cuts which were performed during the experimentation stage were simulated using the porous cutting coefficient model. Simulated forces were compared to experimental results of the experimental optimization in two manners. The first method of comparison plots the forces together as a function of the cutter contact area. Cutting forces are directly proportional to cutting area. Therefore, plotting force vs. cutting area is a convenient normalization for comparison purposes. The measured and predicted cutting forces are plotted vs. maximum chip thickness/cutting area in Figure 7-10 - Figure 7-12. Cutting area referred to here is *geometric* cutting area, the area of the cutting surface which is available for contact with the material. The active cutting area is the geometric cutting area minus the instantaneous area of the pores. Predicted cutting forces closely match experimentally measured forces both in magnitude and range.

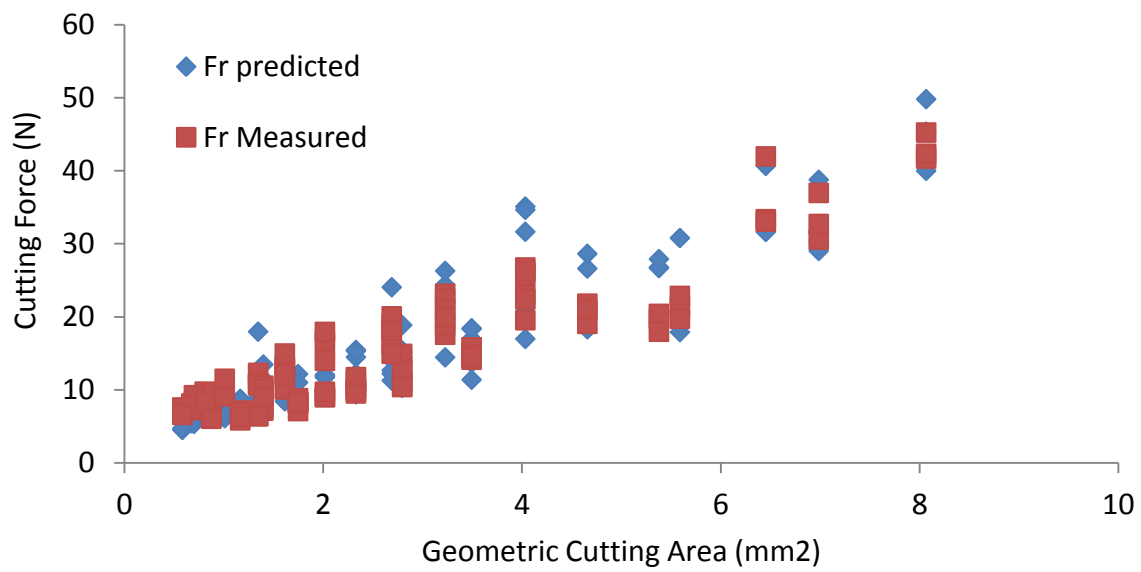
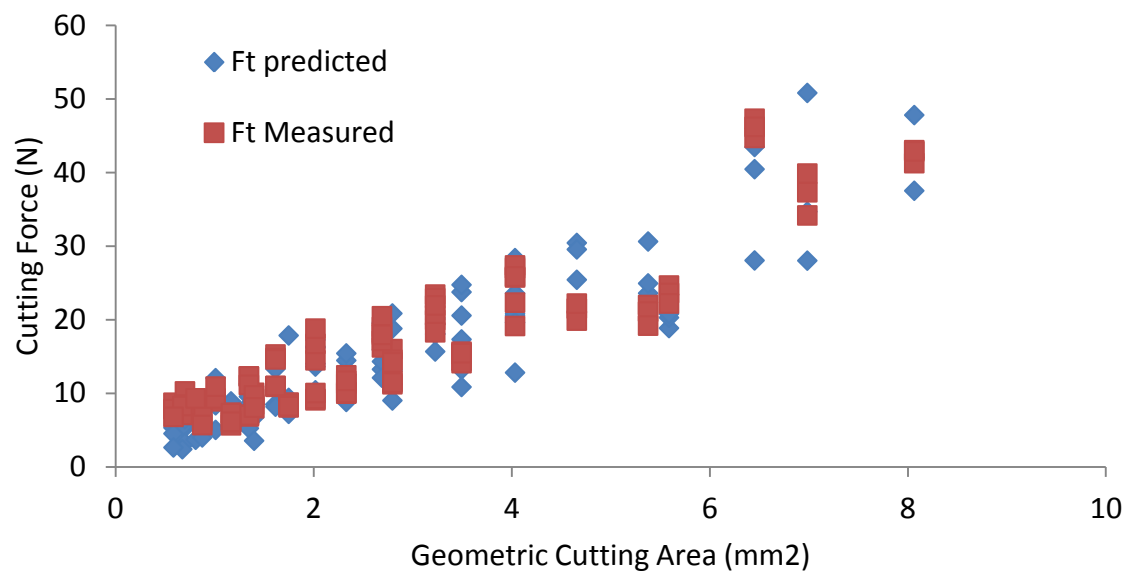


Figure 7-10: Predicted vs. Measured Tangential Cutting Force in Cfoam.

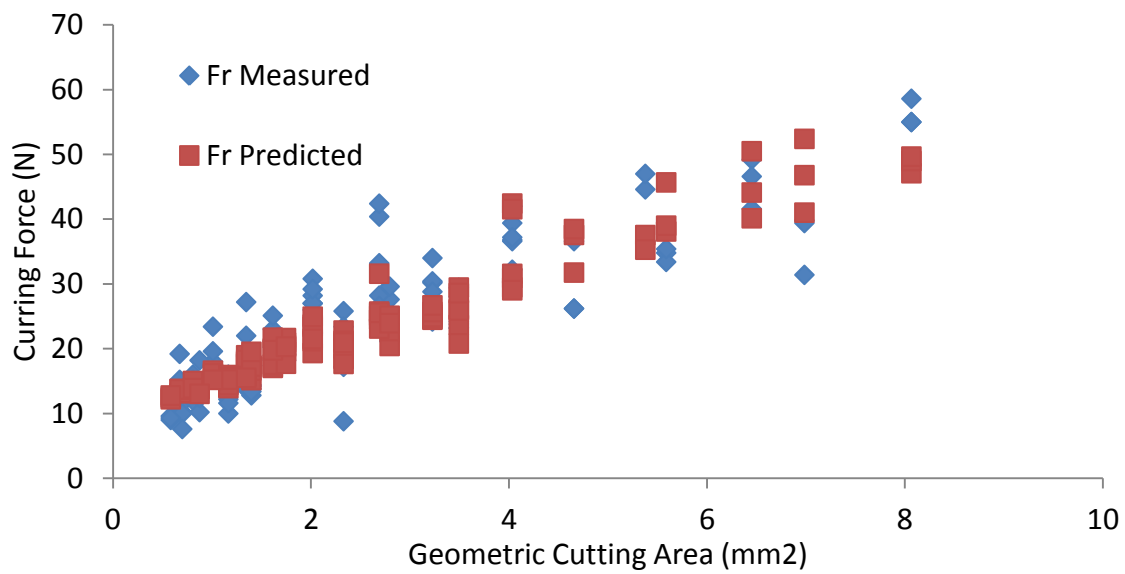
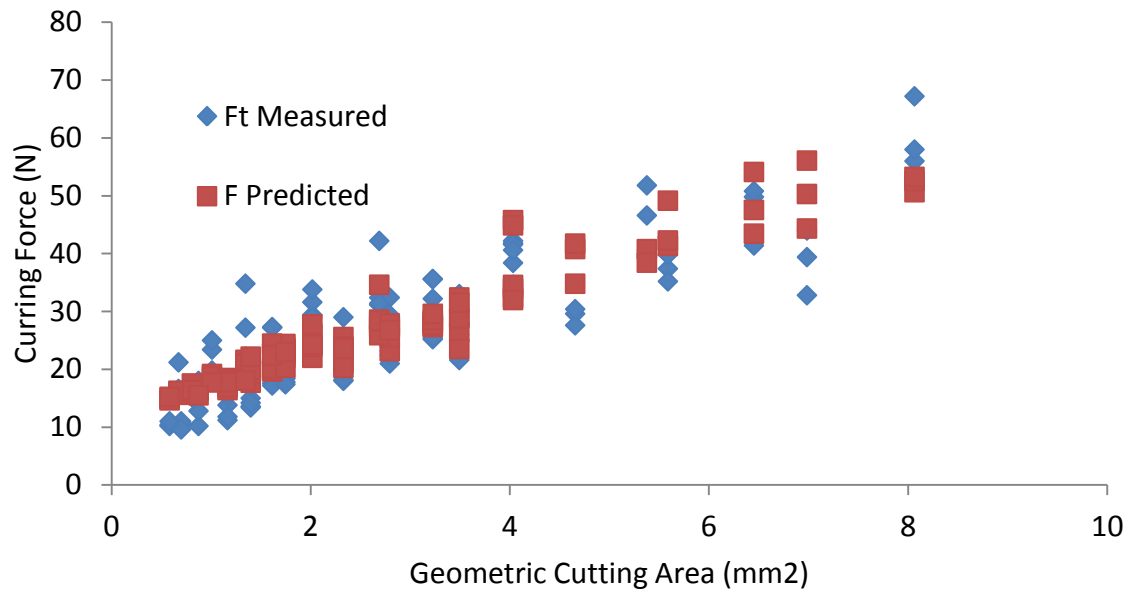


Figure 7-11: Predicted Vs. Measured Tangential Cutting Force in AAC.

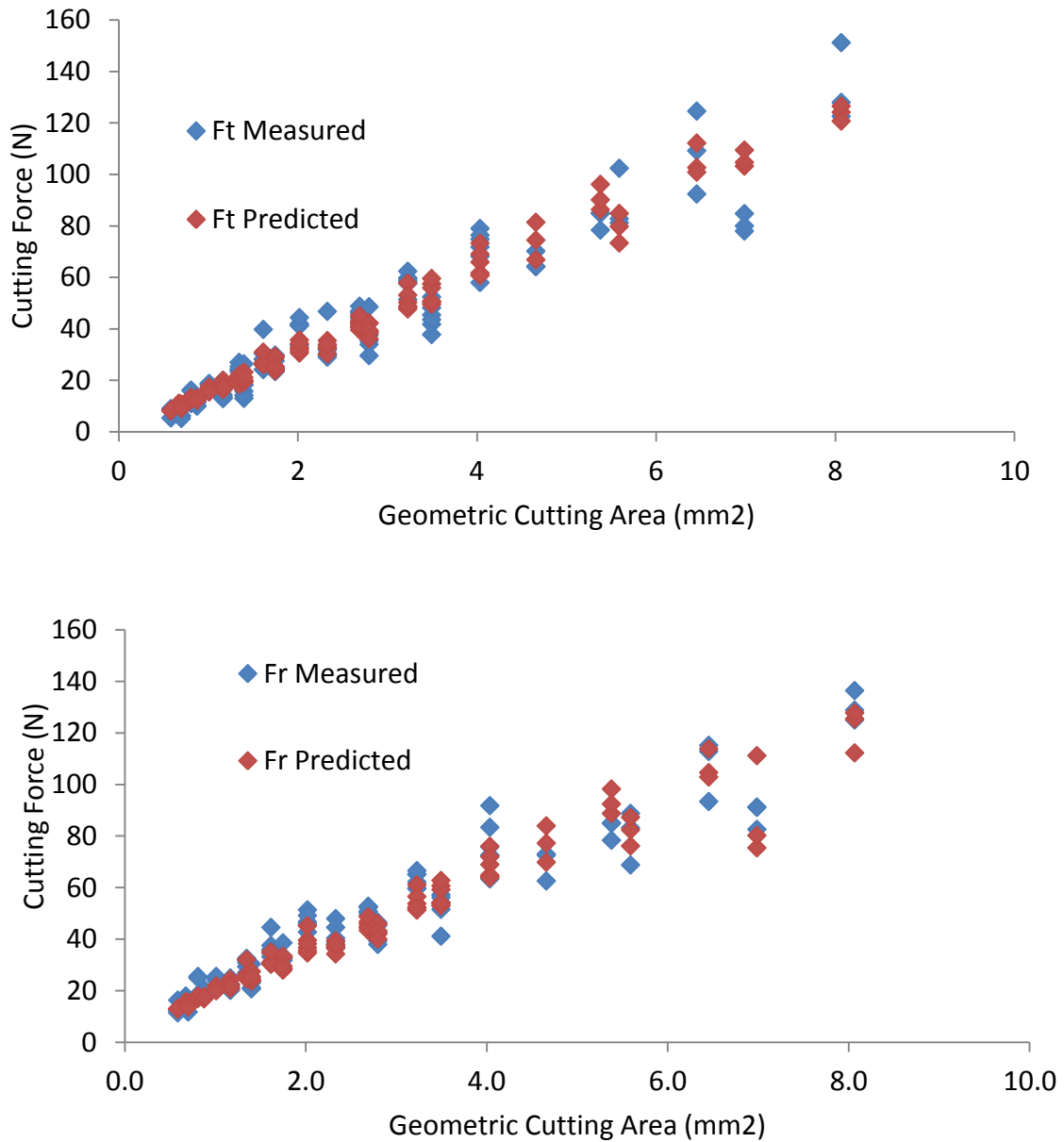


Figure 7-12: Predicted Vs. Measured Tangential Cutting Force in CB1100.

Cutting forces predicted by the model in CB1100 are less scattered than experimental results. This is likely the result of a smaller standard deviation in the pore distribution than the material actually possesses being used in the model. Only one polished sample was used to determine pore distribution. More samples should be measured in order to define the pore distribution with more confidence. In addition, variation in density of CB1100 was observed

during the feasibility investigation in certain samples. Given the large number of samples used during experimental optimization study, variation in density could result in increased scatter.

The second method of comparison between the predicted and measured cutting forces relies on ANOVA conducted on both sets of data. Predicted cutting forces from the simulation were entered into the Design Expert⁸ software and ANOVA was conducted in the same manner as it was on the results of the experimental optimization study. Surface plots of the simulated and measured cutting forces are compared in order to evaluate similarities and differences in the influence of cutting parameters on cutting force. Surface plots of tangential force are shown here. Radial force plots are included in Appendix L.

Predicted response surfaces from simulated and measured cutting forces in Cfoam are shown in Figure 7-13 and Figure 7-14. The overall planar behavior is constant with both simulated and measured data sets. Scatter in the data and error between the predicted surface and the data points of each model is consistent in the case of 6.35mm axial depths of cut. Increased scatter is seen in the 3.18 mm axial depths of cut. Further, the slope or gradient of the surfaces differ in some cases as a result of differences in the dependency/relationship with cutting parameters found between the two models. The greatest differences in both scatter and relationship are observed when the axial depth of cut is small.

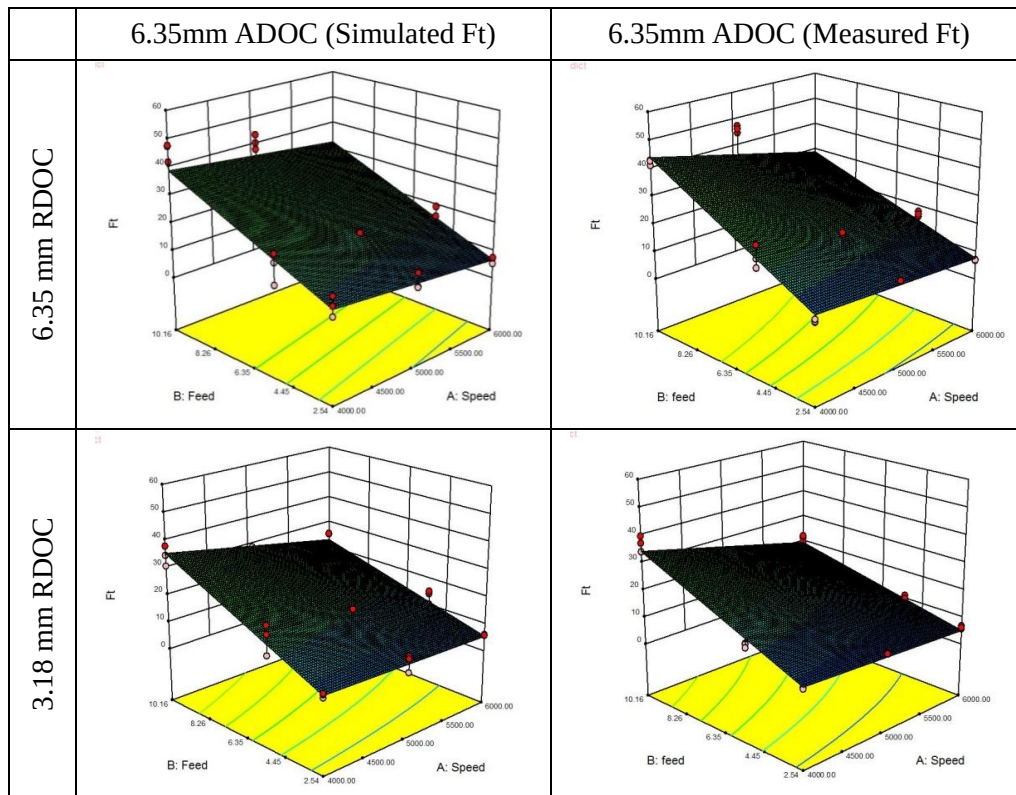


Figure 7-13: Surface plots of simulated and measured tangential cutting force in Cfoam, 6.35mm ADOC.

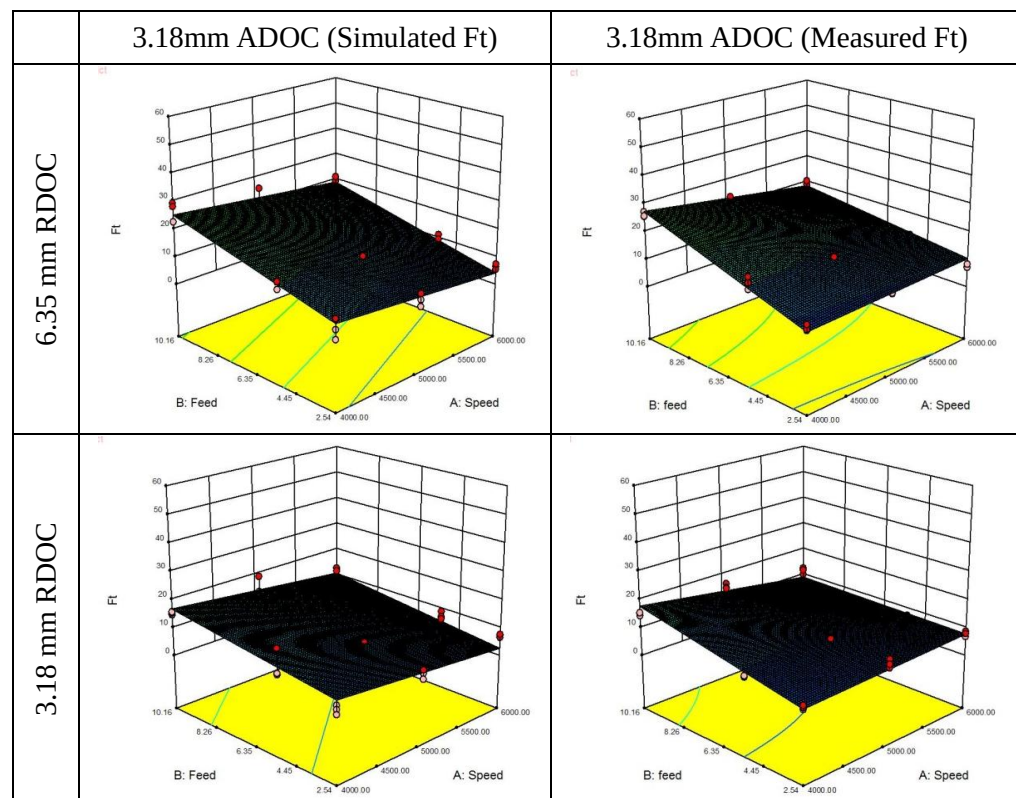


Figure 7-14: Surface plots of simulated and measured tangential cutting force in Cfoam, 3.18mm ADOC.

Surface response plots of simulated and measured cutting forces in CB1100 are given in Figure 7-15 and Figure 7-16. Magnitudes of the cutting forces are consistent between the simulated and measured data sets. Error is largest near the center of the region due to the non linear behavior of the measured forces. Predicted scatter is more consistent with measured scatter than in Cfoam. CB1100 illustrated the highest level of correlation between the response surfaces of simulated and measured cutting forces. Overall planer behavior, magnitudes, and slope are consistent with the analysis of the measured cutting forces. A less significant increase in scatter at low depths of axial cut was observed in CB1100 than in other materials studied.

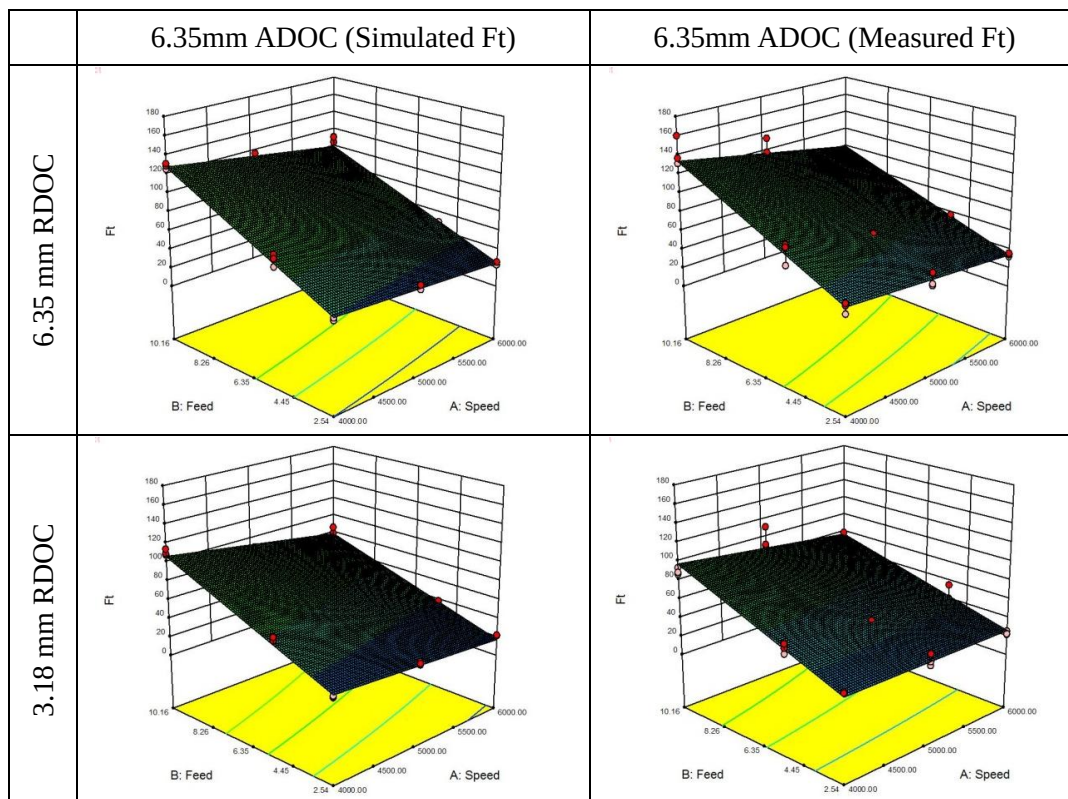


Figure 7-15: Surface plots of simulated and measured tangential cutting force in CB1100, 6.35mm ADOC.

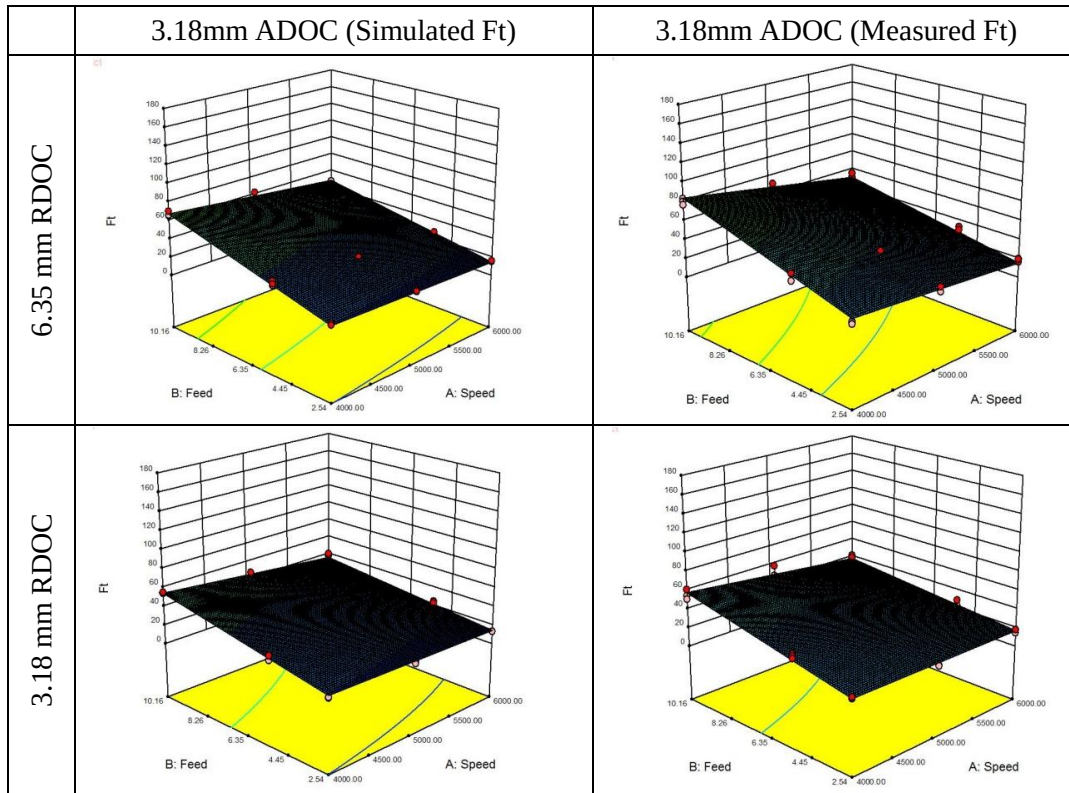


Figure 7-16: Surface plots of simulated and measured tangential cutting force in CB1100, 3.18mm ADOC.

Response surfaces of predicted and measured cutting force in AAC are plotted in Figure 7-17 and Figure 7-18. Tangential cutting force predictions from the regression model of measured cutting forces are non-linear as evident by the curved surface. In order to simulate this behavior, the cutting force model must include a higher order cutting force coefficient. The static coefficient used in the model currently is not capable of replicating this behavior. However, for consistency with respect to the other two materials in the study, a static coefficient was kept in place.

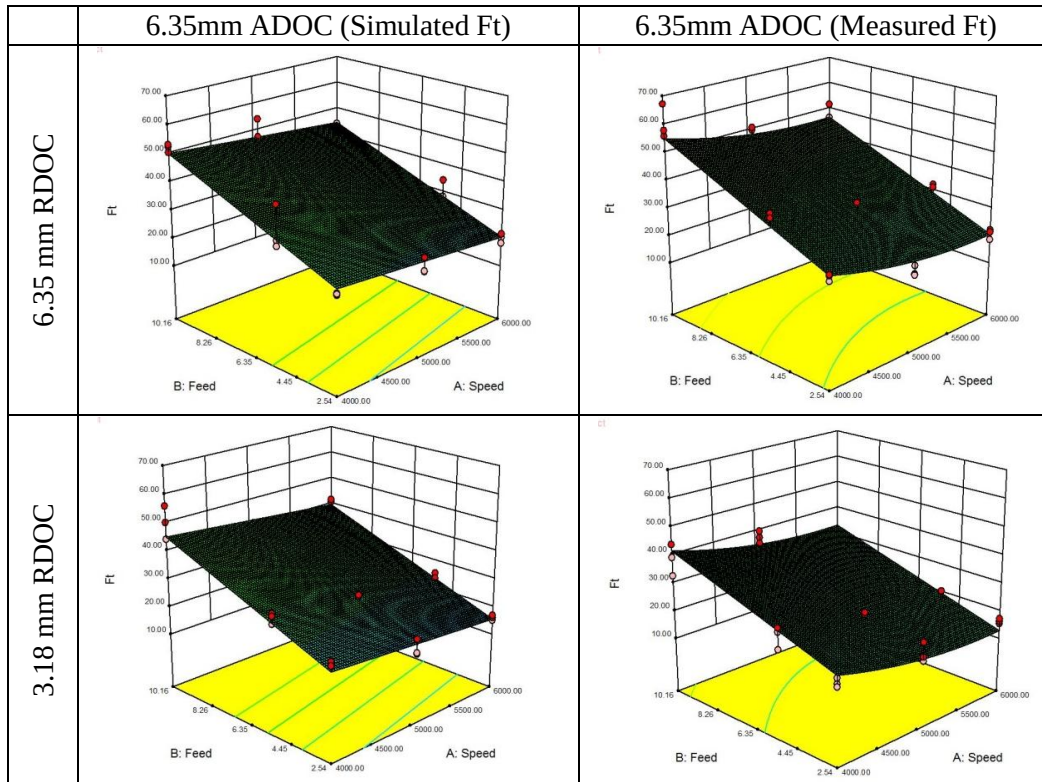


Figure 7-17: Surface plots of simulated and measured tangential cutting force in AAC, 6.35mm ADOC.

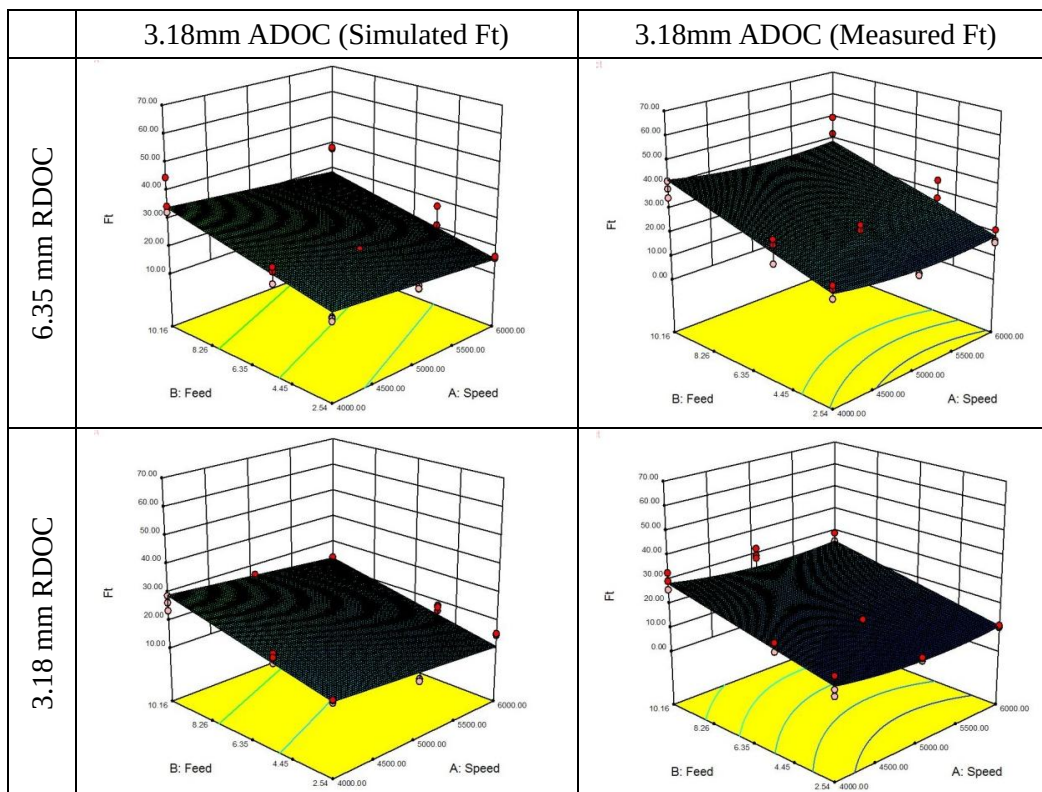


Figure 7-18: Surface plots of simulated and measured tangential cutting force in AAC, 3.18mm ADOC.

As with CB1100, variation in measured cutting forces is larger than predicted forces in some instances. Again, this is due the fact that standard deviation of the pore diameter was measured from optical images of polished samples. Only a single sample was used to determine the input parameters regarding pore geometry. However, cutting tests were conducted using numerous coupons from different parent blocks of material. Variation in density of AAC was also significant from one parent block of material to the next. Using a larger number of samples to determine the pore parameters could better capture the degree of variation in cutting forces.

As a validation of this comparison method, the R^2 values of both models were compared. Comparing the R^2 values of both simulated and measured response surfaces ensures that both models are similar in accuracy to their respective data sets. R^2 values of predicted forces based upon simulated cutting force and measured cutting force data for each material is given bellow in Table 7-4. Values of the R^2 for both data sets are approximately 0.9. Therefore, a comparison of the results of these models is a comparison of the data sets which produced them as opposed to a measure of how well the statistical models curve fit the data.

Table 7-4: R-Squared values of models.

AAC		
Simulated	R-Squared	0.89
Measured	R-Squared	0.89
Cfoam		
Simulated	R-Squared	0.91
Measured	R-Squared	0.88
CB1100		
Simulated	R-Squared	0.96
Measured	R-Squared	0.98

As a final validation, a comparison between the predicted response surfaces of the simulated cutting force to the actual measured data points was also conducted. In other words, the response surfaces of both models are compared to the actual measured data points. If the

accuracy of the simulated response surface is similar to the accuracy of the measured response surface, it follows that the simulation is capable of yielding results with the similar predictive power as the conducted experimental DOE. Root mean square (RMS) values of the deviation (residues) and percent error were compared. Results of the comparison are given in Table 7-5. RMSDM stands for root means square deviation of the measured cutting force data set. Likewise RMSDS stands for root means square deviation of the simulated cutting force data set. ‘RMS(M/S) % Err’ is the root mean square of the % error.

Table 7-5: Results of comparison between measured cutting forces and predicted cutting forces of models based upon measured and simulated cutting forces.

AAC		
RMSDM =	5.32 [N]	RMSD Measured
RMSDS=	5.80 [N]	RMSD Simulated
Delta:	0.48 [N]	
RMSM % Err	12.26%	RMS Measured
RMSS % Err	15.74%	RMS Simulated
Delta:	-3.48%	
Cfoam		
RMSDM =	3.75 [N]	RMSD Measured
RMSDS=	2.84 [N]	RMSD Simulated
Delta:	-0.91 [N]	
RMSM % Err	16.53%	RMS Measured
RMSS % Err	14.93%	RMS Simulated
Delta:	+1.60%	
CB1100		
RMSDM	6.20 [N]	RMSD Measured
RMSDS	8.65 [N]	RMSD Simulated
Delta:	2.45 [N]	
RMSM % Err	9.71%	RMS Measured
RMSS % Err	13.81%	RMS Simulated
Delta:	4.09%	
Average Loss of Accuracy	-3.00%	Range: -4.09 – 1.6+

An average loss of only 3% accuracy when compared to the accuracy of the predicted cutting forces based upon measured cutting forces was observed. While the deviation of both models may seem large, it is important to keep in mind the difficulty in measuring randomized processes. Error's associated with measurement are approximately equal to those associated with the simulated data. Considering the reduced effort and time required to produce the results, the loss of accuracy is acceptable given the benefits.

Chapter 8: Summary of Conclusions and Recommendations

An experimental investigation on the machinability of three brittle porous materials for use in composite repair tooling was conducted. Research encompassed not only two experimental stages but also a modeling component. An initial feasibility investigation was conducted to determine feasible cutting conditions and cutting tool types for machining porous heterogeneous materials. In addition, studies on surface finish, machining induced damage, and tool wear were also conducted.

Three types of cutting tools were tested: PCD, diamond abrasive, and HSS. It was found that the HSS was not capable of sustained machining in Cfoam. Tool wear was greatly accelerated by the abrasive nature of the material. PCD based cutting tools were able to survive the abrasive material, such as Cfoam. However, it was discovered that the initial sharp edge of the PCD insert had been worn and 80 μ m of flank wear was found soon after machining began. Fortunately edge wear did not continue once the initial edge sharpness had been reduced. The achievable material removal rate of the available PCD cutting tools was limited due to the short flute length and limited axial depths of cut. Larger geometry PCD cutters were cost prohibitive to further research. The high cost of PCD cutting tools in combination with the limited geometry outweighed the benefits of the extended tool life. Long tool life was achieved by diamond abrasive type cutting tools at a much small price than PCD based tools. Diamond abrasive type tools were able to sustain continued machining in Cfoam without measurable tool wear throughout the research.

Although tool wear was found to be inconsequential in AAC and CB1100 for all cutting tool materials, the performance of diamond abrasive type cutting tools was limited in these materials. The fine dust created by machining AAC and CB1100 bonded to the diamond

abrasive tool and cause clogging. Material rapidly built up between the diamond particles and rapidly increased radial thrust forces and heat. Therefore, while diamond abrasive cutting tools are exclusively recommended for Cfoam they are not recommended for use in AAC or CB1100. Fluted based cutting tools are required in these two materials in order to ensure material evacuation is not problematic.

Another distinguishing result from the feasibility study was the identification of several types of machining induced damage. Types of damage consisted of several forms of unsupported edge damage and form of chipping and gouging. The types of damage and their locations were documented and presented. Damage of differing size and type were visible in cutting forces and often exceeded the magnitude of the cutting forces themselves. Large peaks and valley resulting from damage were documented. The most severe form of damage was unsupported edge loss of the exiting edge. It was found to be the most common and create the largest sections of damage. As the cutter nears the exit of the cut, the weak material fractures without material behind it to support the stress. The higher the radial thrust forces are the farther from the edge the damage initiates. Therefore, reduced feed rates are recommended when machining near thin sections or edges. Machining should always be approached using an outside-in strategy and minimize the number of cuts which exit the workpiece whenever possible. Unsupported edge loss was most severe in CB110 followed by AAC. Cfoam was found to resist unsupported edge loss. This was in spite of being the weakest of the three tested materials.

From the study of cutting forces conducted during the feasibility investigation it was found that feed rates and material removal rates in excess of what the currently available test platform could provide were achievable. However, the achievable feed rate and material

removal rate was still limited by other factors such as the amount of damage the workpiece sustained during the cut. Recommendations of cutting conditions for each tool in each material were presented.

During the experimental optimization study, a more robust full factorial DOE was carried out studying cutting forces using carbide based fluted cutting tools. Cutting forces were modeled empirically through ANOVA for all three materials. In addition, studies of surface integrity were conducted to determine if any reduction in residual flexural strength had occurred due to machining.

The cutting force measurement equipment used during the feasibility investigation was not available for use for the experimental optimization study. A switch from a rotating type dynamometer to a plate dynamometer was made. Lower background noise levels aided measurements. But the lack of a cutter angle synchronization signal complicated analysis with a conversion from static coordinate Cartesian force to tangential and radial cutting forces.

Cutting forces were random in magnitude and shape. This was frequently combined with the low magnitude of the signal, which together made reliable measurement difficult. In order to quantify the forces, the average of several peak cutting force tooth profiles was taken for each of the cutting tests. Although the shape of the cutting forces was random in magnitude modeling of the average peak cutting forces based on ANOVA and regression modeling was shown to achieve acceptable average R^2 value of 0.92. Cutting force evolution when quantified in the manner demonstrated was shown to be largely linear with respect to cutting parameters. The regression models of each material were presented and compared.

Following the cutting force study an investigation into the effects of machining induced damage on surface integrity was conducted. Four point bend tests were conducted on machined

samples in order to measure changes in transverse rupture strength. Two sample sets were created from each material. One set was machined using roughing cutting conditions, which was shown to induce more severe levels of machining induced damage than typical finishing cutting conditions. This micro scale damage is documented in SEM studies and presented in Chapter 5 and Chapter 6. The measured transverse rupture strengths were subjected to a Weibull analysis which showed that the AAC and Cfoam were negligibly affected by the change in cutting conditions. However, it was discovered that CB1100 showed a 16% decrease in characteristic strength in samples machined using roughing cutting conditions. Reduced surface integrity is the result of a damage tolerance mechanism which was incapable of containing damage sufficiently enough to maintain the surface integrity successfully. The small pores in CB1100 combined with the brittleness of the solid ligament material were shown to be susceptible to machining induced micro-scale damage. Further evidence of this was found in the study of chip formation.

Chip formation was investigated to determine the nature of material removal and type of cutting/fracturing mechanism at work. Of the three materials, only CB1100 showed a variation in the size of the particles in the collected machined material. These results confirmed the results of the surface integrity study in two ways. The constant size of the particles found in the collected materials of AAC and Cfoam was evidence that the fracture is a function of the pore size and distribution in these materials and less dependent upon the cutting conditions. The second confirming result was the trend in the variation of the size of the particles during the machining of CB1100. The trend was clearly toward large fractured sections as forces increased. As the cutting force was increased, the small pores were increasingly incapable of controlling fracture, resulting in larger sections of fractured material. The common factor between the contrasting materials is the size of the pores. The larger pores of AAC and Cfoam were shown

to be more damage tolerant to machining induced micro-damage than those of CB1100 despite their lower strengths.

8.1 Conclusions

Based on the machinability investigation of porous and heterogeneous materials: AAC, CB1100 and Cfoam the following conclusions were made:

AAC:

- The low strength of AAC made handling and mounting of samples problematic. Damage and fracture were frequently observed. Low strength also contributed to occurrences of unsupported edge loss.
- It is recommended that AAC only be used on small scale tooling and in a non-structural way or as a sacrificial form of temporary support.
- Large variations in pore size and distribution lead to increased variations in cutting force.
- Dust created while machining AAC was shown to bond to diamond abrasive type cutting tools which increased radial thrust forces leading to damage and fracture of the workpiece. Diamond abrasive type cutting tools are not recommended for use.

CB1100:

- CB1100 is the strongest of the three materials tested. However, it is the least damage tolerant.
- The smaller pore size and brittle nature of the solid material in CB1100 proved limited in its ability to control damage on macro or micro scales.
- Cutting forces resulting from typical rough machining conditions were shown to induce micro-scale damage which reduced the surface integrity by up to 16% compared to typical finishing cutting conditions.

- Large cutting forces also cause unsupported edge loss and gouging/chipping of the machined surface, limiting the rate of material removal.
- As with AAC, dust created from CB1100 while machining using diamond abrasive type cutting tools bonded to the cutting tool and increased radial thrust forces and heat. Unsupported edge loss is exacerbated by the increased cutting force.

Cfoam:

- Cfoam was the second strongest of the materials tested but the lowest density.
- Cfoam is abrasive due to the high hardness of the carbon based solid ligaments. High hardness in combination with the thin cross section of ligaments and cell walls creates highly localized stress concentrations in cutting edges.
- The extremely abrasive texture of the Cfoam accelerated tool wear in HSS and PCD. Diamond abrasive type cutting tools are recommended and exhibited no measureable tool wear.
- Unlike AAC or CB1100 unsupported edge loss was minimal and Cfoam was found to be damage tolerant to large scale fracture as well as micro scale damage. Cfoam exhibited damage tolerance which was capable of maintaining machined surface integrity regardless of the machining conditions used.
- The carbon based dust produced while machining Cfoam is hazardous to electrical equipment and a possible health hazard. Additional waste handling procedures and safety measures should be made to limit exposure.

The analytical phase of the research included the mathematical modeling of cutting forces in a brittle porous material. A cutting force model used in metallic materials was adapted for use in brittle porous materials through the addition of a porous material coefficient which was

developed. A simulated DOE identical to that of the experimental optimization study was created using the proposed model and compared to the measured cutting forces. From the results of the developed model and comparison to measured cutting forces the following conclusions were made:

- The developed model including the porous cutting coefficient has been shown to produce cutting force profiles matching those measured experimentally both in shape and magnitude
- The evolution of predicted cutting forces over the range of cutting parameters has been shown to closely match measured forces. Dependency on cutting parameters and variation in response is consistent with measured forces.
- The developed dynamic cutting coefficient has been shown to allow the application of traditional metallic cutting force modeling approaches to brittle porous materials.
- Element count has a significant effect on accuracy. Element size should remain within a 20% deviation from the mean pore diameter.

8.2 Recommendations for future work

8.2.1 Equipment and testing

Future testing should be carried out on industry standard equipment. Studies of cutting forces using increase cutting velocities and feed rates should be conducted in order to determine behavior over a larger range of cutting conditions. A rotating type milling dynamometer with a rotational angle signal should be used if possible to simplify the study of tangential and radial cutting forces. Larger cutting tools than those tested here should also be investigated as well.

Although several attempts at quantifying the amount of damage induced by machining were made using surface profilometry, results were inconclusive. Damage could only be quantified through time consuming SEM studies. A method of identifying and quantifying damage induce during machining should be developed or identified.

Attempts to measure localized changes in strength using micro-hardness testing were also made. Testing proved too difficult and attempts at measurement were abandoned. It is recommended for future research to identify a method of measuring localized changes in strength near and below the machined surface.

Measurements of transverse rupture strength performed in this research utilized rubber cushions between the sample and rollers of the fixture. This ensured that the rollers did not dig into the material and that failure occurred consistently in the gage section of the sample. Without the use of a clip gauge or laser displacement sensor deflection of the sample could not be recorded. Only the maximum load was of concern during testing. No calculation of flexural modulus could be made for comparisons. Future works should involve the use of four point

bend fixtures having fully articulating rollers with flat contact surfaces and some form of deflection measurement.

8.2.2 Brittle porous cutting force model

The total time required to complete the simulation is high for three reasons: the amount of data is very large; the code's language is slow; and there iteration count is high. The first problem has been discussed previously. The model is developed and run using Matlab, which is a *compile as you go* environment. Use of a precompiled code would greatly increase the speed of the calculation. The final speed bump is the number of iterations that are required. Data is stored in a large multidimensional array. Accessing this array required many nested 'for loop' statements. Vectorized code greatly reduces the time required to access arrays.

In addition, a recording of the calculation steps could reduce the total calculation time could be greatly decreased while simultaneously eliminating the error in summing forces across time. At the start of the simulation, pore diameters across through the entire cutting path are pre-mapped. Pre-mapping the pores gives two advantages. First, the determination of the pore diameter does not occur at the send to lowest level of the nested for loop statement. Therefore, the time savings are magnified several orders. Second, with the pores pre-mapped the data point spacing can be constant for the whole simulation. This completely eliminates the error in correlating rotational angle and time. Further, this calculation is run approximately 4000 times per set of cutting conditions. When multiplied by 100 or more simulated cutting conditions these time savings can also become significant.

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Curriculum Vitae

Alexander Pinpin O'Connor

Education

PhD. March 2014

Mechanical Engineering, University of Washington, Seattle, WA.

Dissertation: *Machinability of Aerospace Tooling Materials for Composite Repair*

MSME – 2009

Mechanical Engineering, University of Washington, Seattle, WA.

Thesis: *Feasibility Study of Traditional Friction Stir Welding Tooling for Use in Polymers*

BSME – 2008

Mechanical Engineering, University of Washington, Seattle, WA.

Research Areas

- Machinability of porous heterogeneous materials for composite tooling.
- Machine tool structural dynamics
- Machining process dynamics
- Machine tool and cutter technologies
- Titanium and Aluminum machining
- NC programming technology

Professional Experience

Materials, Processing and Physics Engineer, 2013 - Present

Boeing Research and Technology, Machining Technology, Seattle, WA

Primary activities involve: The research and development and implementation of machining technologies to production applications. Provide machining technology support to internal and external suppliers worldwide.

Manufacturing Quality Consultant, 2012

NW Tech. – Seattle, WA

Test and evaluate imported motorcycles based upon their materials and manufacturing methods used. Identify weaknesses or poor manufacturing practices which may lead to safety or performance/longevity concerns.

Instructor, 2011

Department of Mechanical Engineering, University of Washington, Seattle, WA

- ME 409 – Introduction to computer aided manufacturing and numerical control

Teaching Assistant, 2009 – 2012

Department of Mechanical Engineering, University of Washington, Seattle, WA

- ME 599E – Machining and Surface Integrity of Advanced Composites
- ME 559 – Introduction to fracture mechanics
- ME 355 – Introduction to manufacturing processes
- ME 599 – Composite Tooling Course (Boeing Certification Course)

Lead Mechanical/Manufacturing Engineer, 2007 – 2009

AmplePower LLC. - Seattle, WA

Lead Engineer and project manager of DC marine and land based generators. Main responsibilities include: the design of harsh environment enclosures for offshore research buoys, remote telecommunication and radar installations. International clients include: Ratheon, The Boeing Company, and The Columbian Government.

Mechanical/Manufacturing Engineer, 2007

Bamboo Hardwoods – Seattle, WA

Parametric modeling of current product lines and drafting of custom applications. Procurement and installation of CNC router production equipment and modernization of production line.

Journal Publications

- P. Edwards, A. O'Connor, M. Ramulu. "Electron Beam Additive Manufacturing of Titanium Components: Properties and Performance." *ASME Journal of Manufacturing Science and Engineering*, Vol. 135(6).Nov 2013. pp. 61016-1 to 061016-7.
- A. O'Connor, J. Miller, M. Ramulu. "Evaluation of Substrates for Rapid Tooling Applications." *SAMPE Journal*, Vol.49(1). Jan, 2013. pp. 34-39.
- A. O'Connor. M. Ramulu. "The Effects of Machining Induced Damage on Flexural Strength of Low Density Carbon Foam" *ASME International Mechanical Engineering Congress and Exposition*, Houston Tx, 2012. Paper#IMECE2012-88124
- A. O'Connor, M. Ramulu. "Experimental Investigation of Porosity Effects On Machinability And Residual Strength in Brittle Materials." *ASME International Mechanical Engineering Congress and Exposition*, Montreal, Canada. Nov, 2014. Paper#IMECE2014-39304.

Submitted For Publication

- A. O'Connor. M. Ramulu. "Experimental Investigation of Abrasive Wear of High Speed Steel in Machining Carbon Foam." *Elsevier, Wear*
- A. O'Connor. M. Ramulu. "Machinability of Heterogeneous Materials for Composite Tooling." *Journal of Material Processing and Technology*
- A. O'Connor. M. Ramulu. "Experimental Investigation of Machining Induced Damage and Residual Flexural Strength in CB1100 Ceramic." *ASME Journal of Engineering Materials and Technology*
- A. O'Connor. M. Ramulu. "A Mechanistic Model for End Milling Cutting Forces in Porous Heterogeneous Materials." *ASME Journal of Manufacturing Science and Engineering*

Conference Presentations

- "Machinability of Brittle Porous Materials for Composite Manufacture." *International Conference on Computational and Experimental Engineering and Sciences*. April, 2013. Bellevue, WA

- “Machinability of Brittle Substrate Tooling Materials.” *ASM International, AeroMat*. April, 2013. Bellevue, WA
- “Machining of Porous Materials for Aerospace Component Manufacturing” *SME, Composite Manufacturing* 2011, Dayton Ohio, 2011
- “Feasibility Study of Traditional Friction Stir Welding Tooling for Use in Polymers.” *University of Washington Libraries Press*. Seattle, WA. 2009

Appendix: A. Dynamometer calibration

Calibration of the dynamometer was carried out through the simple means of applying a static, known load to the dynamometer and verifying the magnitude of the force recorded matched the known magnitude. The dynamometer can then be calibrated by adjusting the sensitivity coefficients of the systems. The factory set coefficients in this case were correct and did not need any additional tuning. The second procedure of calibration was to confirm the range of the dynamometer. The dynamometer has two separate operational ranges: course and fine. It is important to select the proper range for the forces the dynamometer will be experiencing in order to avoid damage to the dynamometer and loss of data. Because the cutting forces expected from all materials investigated were far below the limit of the dynamometer a simplified procedure for confirmation of the range was selected. A test cut consisting of a 12.70 [mm] depth of cut and full diameter radial depth of cut was performed utilizing a 12.70 [mm] endmill. The magnitude of the maximum force of this test cut was found to be toward the lower visible range of the heavy range of the dynamometer. A second cut was then performed utilizing the fine range. This cut yielded distinguishable behavior without causing saturation. Therefore, the fine range was used throughout all experiments.

1.) Tool Concentricity Verification

Before any cutting force measurements using PCD tooling could be attempted, tool geometry/concentricity had to be verified. Due to the fact that the PCD tooling insert holder had to be modified, a verification of the concentricity of the machined shank had to be performed. The reason for this is twofold. First, any lack of concentricity would result in an undesirably balanced tool leading to vibration which would cause noise and distortion in the data. Second, if the tool were unbalanced the chipload would not be equal between all the teeth. This would also

lead to unacceptable data. Fortunately the dynamometer itself is a useful tool for detecting any run out.

A simple peripheral cut was performed in an aluminum work piece. Aluminum was selected due simply to availability; but any metallic material would have sufficed. The radial depth of cut was selected so that only one tooth would be engaged in the cut at any one time. Therefore, if the measured forces for each tooth are similar, within an acceptable range, the chipload can be assumed to even. Therefore, by this method concentricity of the newly machined tool shank was confirmed.

Appendix: B. Dust enclosure and test setup fabrication

The first stage of the research involved the development and manufacture of the experimental setup. The dust enclosure/collection system, and sample platen holding fixture, shown in Figure B-1 as well as the dynamometer stator mount and clamp, described later, all required fabrication before experimentation could begin. The enclosure is intended to limit the amount of dust created during milling from entering any delicate areas of the milling machine. This dust also has the potential to be a significant health hazard in the case of carbon based materials. Carbon dust is also electrically conductive and as such, poses a threat to any exposed electrical equipment.

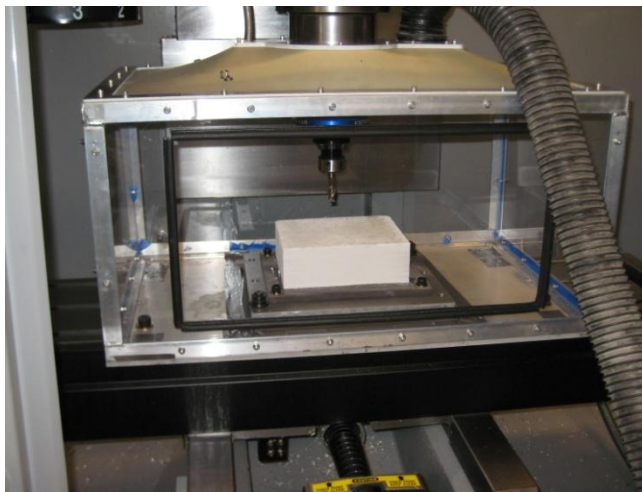


Figure B-1: Dust Enclosure and Sample Platen.

The dust enclosure consisted of an aluminum frame with Plexiglas panels. A flexible membrane was used for the top of the enclosure to allow for adequate mobility without the fear of access material coming in contact with any high speed rotating components.

Appendix: C. CB1100 surface roughness reports

1.) 4000 RPM

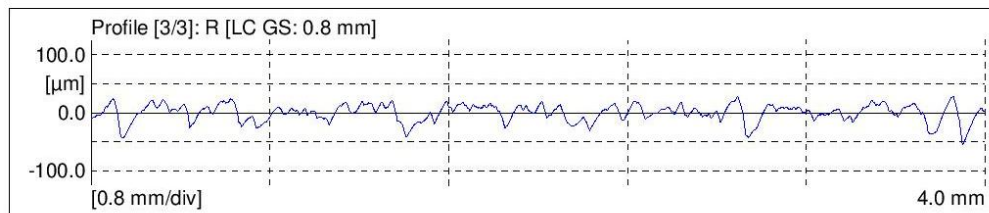
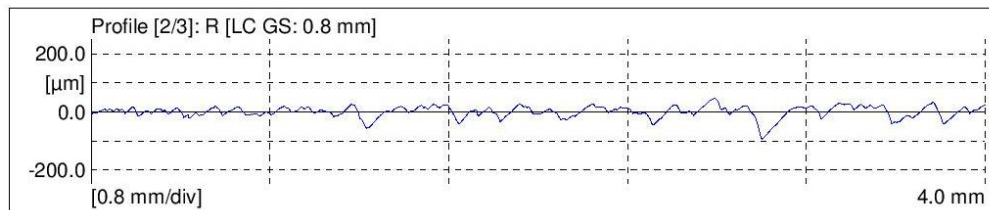
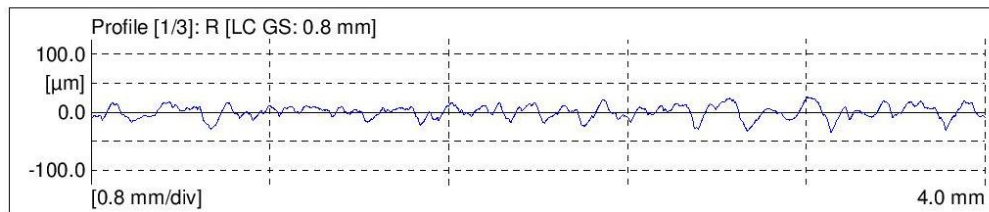
2.54m/min, peripherally milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:46 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:46 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	9.027	11.225	49.012	61.42	61.42	31.737	61.42	19.82	29.19	30.753	190.20
2:	14.501	19.620	82.019	139.55	139.55	52.302	139.55	30.60	51.42	38.548	200.11
3:	11.303	14.479	66.832	83.33	83.33	40.728	83.33	23.96	42.87	38.462	217.56
Xb:	11.610	15.108	65.955	94.77	94.77	41.589	94.77	24.79	41.16	35.921	202.62
S:	2.750	4.232	16.521	40.30	40.30	10.309	40.30	5.44	11.21	4.476	13.85
Max:	14.501	19.620	82.019	139.55	139.55	52.302	139.55	30.60	51.42	38.548	217.56
Min:	9.027	11.225	49.012	61.42	61.42	31.737	61.42	19.82	29.19	30.753	190.20
R:	5.474	8.394	33.007	78.14	78.14	20.565	78.14	10.78	22.23	7.795	27.36

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	46.25 μm	Rp1	17.29 μm
Rz2	34.72 μm	Rp2	11.29 μm
Rz3	45.28 μm	Rp3	21.17 μm
Rz4	57.40 μm	Rp4	23.80 μm
Rz5	61.42 μm	Rp5	25.57 μm
Rz sigma	10.61 μm	Rp sigma	5.70 μm
Rz min	34.72 μm	Rp min	11.29 μm
Rz max	61.42 μm	Rp max	25.57 μm
Rz mean	49.01 μm	Rp mean	19.82 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	30.45 μm	Rdc (0.00;5.00)	8.58 μm
R3z2	24.26 μm	Rdc (10.00;5.00)	-2.62 μm
R3z3	34.65 μm	Rdc (20.00;5.00)	-7.42 μm
R3z4	31.74 μm	Rdc (30.00;5.00)	-10.32 μm
R3z5	32.67 μm	Rdc (40.00;5.00)	-13.12 μm
R3z sigma	3.94 μm	Rdc (50.00;5.00)	-15.93 μm
R3z min	24.26 μm	Rdc (60.00;5.00)	-19.13 μm
R3z max	34.65 μm	Rdc (70.00;5.00)	-22.52 μm
R3z mean	30.75 μm	Rdc (80.00;5.00)	-25.78 μm
		Rdc (90.00;5.00)	-31.26 μm
		Rdc (100.00;5.00)	-52.84 μm

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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (8.58;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.65 % R Mr (-2.00;5.00) 8.76 % R Mr (-3.00;5.00) 10.61 % R Mr (-4.00;5.00) 11.97 % R Mr (-5.00;5.00) 13.73 % R Mr (-6.00;5.00) 16.29 % R Mr (-7.00;5.00) 19.05 % R Mr (-8.00;5.00) 21.70 % R Mr (-9.00;5.00) 25.07 % R Mr (-10.00;5.00) 28.83 % R Mr (-11.00;5.00) 32.16 % R Mr (-12.00;5.00) 36.23 % R Mr (-13.00;5.00) 39.69 % R Mr (-14.00;5.00) 43.38 % R Mr (-15.00;5.00) 47.11 % R Mr (-16.00;5.00) 50.14 % R Mr (-17.00;5.00) 53.10 % R Mr (-18.00;5.00) 56.45 % R Mr (-19.00;5.00) 59.62 % R Mr (-20.00;5.00) 62.43 % R Mr (-21.00;5.00) 65.66 % R Mr (-22.00;5.00) 68.35 % R Mr (-23.00;5.00) 71.31 % R Mr (-24.00;5.00) 74.30 % R Mr (-25.00;5.00) 77.85 % R Mr (-26.00;5.00) 80.49 % R Mr (-27.00;5.00) 82.39 % R Mr (-28.00;5.00) 84.46 % R Mr (-29.00;5.00) 86.00 % R Mr (-30.00;5.00) 87.74 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 43.39 µm Rz2 84.03 µm Rz3 67.78 µm Rz4 139.55 µm Rz5 75.35 µm Rz sigma 35.55 µm Rz min 43.39 µm Rz max 139.55 µm Rz mean 82.02 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 19.39 µm Rp2 27.62 µm Rp3 26.68 µm Rp4 45.88 µm Rp5 33.44 µm Rp sigma 9.89 µm Rp min 19.39 µm Rp max 45.88 µm Rp mean 30.60 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 31.53 µm R3z2 33.84 µm R3z3 44.22 µm R3z4 33.23 µm R3z5 49.93 µm R3z sigma 8.08 µm R3z min 31.53 µm R3z max 49.93 µm R3z mean 38.55 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:46 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 21.48 µm Rdc (10.00;5.00) -3.88 µm Rdc (20.00;5.00) -8.71 µm Rdc (30.00;5.00) -12.66 µm Rdc (40.00;5.00) -17.23 µm Rdc (50.00;5.00) -21.65 µm Rdc (60.00;5.00) -25.90 µm Rdc (70.00;5.00) -30.01 µm Rdc (80.00;5.00) -36.28 µm Rdc (90.00;5.00) -49.06 µm Rdc (100.00;5.00) -118.07 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (21.48;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.39 % R Mr (-2.00;5.00) 7.72 % R Mr (-3.00;5.00) 8.99 % R Mr (-4.00;5.00) 10.22 % R Mr (-5.00;5.00) 11.51 % R Mr (-6.00;5.00) 13.27 % R Mr (-7.00;5.00) 15.36 % R Mr (-8.00;5.00) 18.19 % R Mr (-9.00;5.00) 20.77 % R Mr (-10.00;5.00) 23.27 % R Mr (-11.00;5.00) 25.95 % R Mr (-12.00;5.00) 28.48 % R Mr (-13.00;5.00) 30.83 % R Mr (-14.00;5.00) 32.92 % R Mr (-15.00;5.00) 34.97 % R Mr (-16.00;5.00) 36.99 % R Mr (-17.00;5.00) 39.45 % R Mr (-18.00;5.00) 41.63 % R Mr (-19.00;5.00) 43.74 % R Mr (-20.00;5.00) 45.83 % R Mr (-21.00;5.00) 48.19 % R Mr (-22.00;5.00) 51.06 % R Mr (-23.00;5.00) 53.60 % R Mr (-24.00;5.00) 55.90 % R Mr (-25.00;5.00) 57.86 % R Mr (-26.00;5.00) 60.23 % R Mr (-27.00;5.00) 62.52 % R Mr (-28.00;5.00) 65.17 % R Mr (-29.00;5.00) 67.56 % R Mr (-30.00;5.00) 69.97 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 66.59 µm Rz2 64.17 µm Rz3 49.83 µm Rz4 70.25 µm Rz5 83.33 µm Rz sigma 12.04 µm Rz min 49.83 µm Rz max 83.33 µm Rz mean 66.83 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 24.16 µm Rp2 21.14 µm Rp3 18.90 µm Rp4 27.52 µm Rp5 28.07 µm Rp sigma 3.97 µm Rp min 18.90 µm Rp max 28.07 µm Rp mean 23.96 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:46 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	47.87 μm	Rdc (0.00;5.00)	9.39 μm
R3z2	39.30 μm	Rdc (10.00;5.00)	-2.67 μm
R3z3	39.78 μm	Rdc (20.00;5.00)	-7.03 μm
R3z4	29.15 μm	Rdc (30.00;5.00)	-10.25 μm
R3z5	36.21 μm	Rdc (40.00;5.00)	-13.13 μm
R3z sigma	6.76 μm	Rdc (50.00;5.00)	-16.44 μm
R3z min	29.15 μm	Rdc (60.00;5.00)	-20.02 μm
R3z max	47.87 μm	Rdc (70.00;5.00)	-24.11 μm
R3z mean	38.46 μm	Rdc (80.00;5.00)	-30.36 μm
		Rdc (90.00;5.00)	-39.34 μm
		Rdc (100.00;5.00)	-73.94 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:46 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (9.39;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.67 %
R Mr (-2.00;5.00)	8.49 %
R Mr (-3.00;5.00)	10.57 %
R Mr (-4.00;5.00)	12.52 %
R Mr (-5.00;5.00)	14.61 %
R Mr (-6.00;5.00)	17.30 %
R Mr (-7.00;5.00)	19.92 %
R Mr (-8.00;5.00)	22.11 %
R Mr (-9.00;5.00)	25.56 %
R Mr (-10.00;5.00)	29.18 %
R Mr (-11.00;5.00)	32.49 %
R Mr (-12.00;5.00)	35.66 %
R Mr (-13.00;5.00)	39.58 %
R Mr (-14.00;5.00)	42.15 %
R Mr (-15.00;5.00)	45.17 %
R Mr (-16.00;5.00)	48.48 %
R Mr (-17.00;5.00)	51.58 %
R Mr (-18.00;5.00)	54.36 %
R Mr (-19.00;5.00)	57.39 %
R Mr (-20.00;5.00)	59.97 %
R Mr (-21.00;5.00)	62.35 %
R Mr (-22.00;5.00)	64.86 %
R Mr (-23.00;5.00)	67.47 %
R Mr (-24.00;5.00)	69.81 %
R Mr (-25.00;5.00)	71.34 %
R Mr (-26.00;5.00)	73.30 %
R Mr (-27.00;5.00)	75.16 %
R Mr (-28.00;5.00)	76.77 %
R Mr (-29.00;5.00)	78.30 %
R Mr (-30.00;5.00)	79.61 %

No Quick&Easy

6

2.54m/min, peripherally milled, transverse direction:



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement

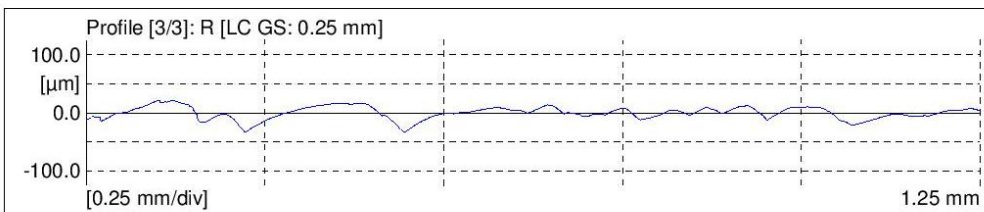
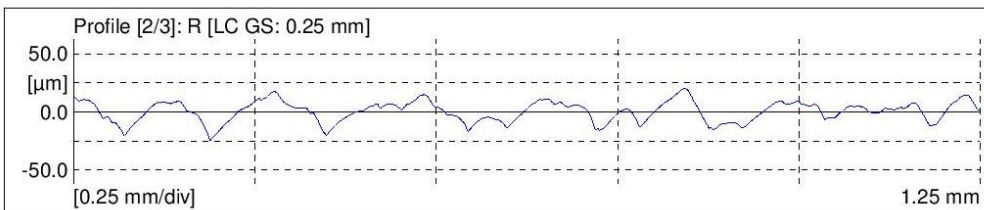
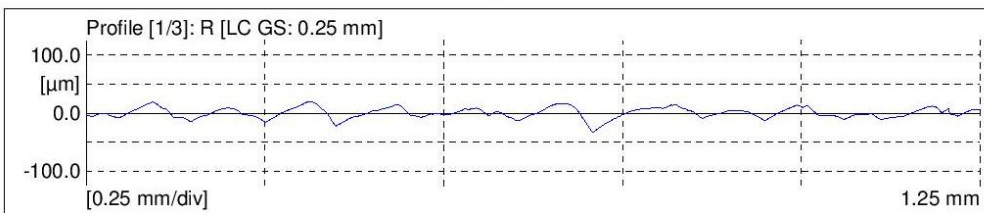


08/31/12, 11:11 AM

Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.10 mm/s
Points: 10500 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:11 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm ...
1:	7.199	8.971	35.370	50.29	50.29	26.766	52.49	16.26	19.11	---	116.90 ...
2:	7.320	8.748	32.838	37.57	37.57	28.001	44.84	15.16	17.68	---	157.14 ...
3:	8.444	10.769	36.345	55.19	55.19	29.445	55.31	14.94	21.41	---	163.43 ...
Xb:	7.654	9.496	34.851	47.68	47.68	28.070	50.88	15.45	19.40	145.82	
S:	0.686	1.108	1.810	9.09	9.09	1.341	5.42	0.71	1.88	25.25	
Max:	8.444	10.769	36.345	55.19	55.19	29.445	55.31	16.26	21.41	163.43	
Min:	7.199	8.748	32.838	37.57	37.57	26.766	44.84	14.94	17.68	116.90	
R:	1.244	2.022	3.507	17.62	17.62	2.679	10.47	1.32	3.73	46.53	

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	34.48 µm	Rp1	18.70 µm
Rz2	41.11 µm	Rp2	19.05 µm
Rz3	50.29 µm	Rp3	16.85 µm
Rz4	28.02 µm	Rp4	14.36 µm
Rz5	22.96 µm	Rp5	12.32 µm
Rz sigma	10.77 µm	Rp sigma	2.88 µm
Rz min	22.96 µm	Rp min	12.32 µm
Rz max	50.29 µm	Rp max	19.05 µm
Rz mean	35.37 µm	Rp mean	16.26 µm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	---	Rdc (0.00;5.00)	4.66 µm
R3z2	---	Rdc (10.00;5.00)	-2.70 µm
R3z3	---	Rdc (20.00;5.00)	-6.30 µm
R3z4	---	Rdc (30.00;5.00)	-9.07 µm
R3z5	---	Rdc (40.00;5.00)	-11.77 µm
R3z sigma	---	Rdc (50.00;5.00)	-15.08 µm
R3z min	---	Rdc (60.00;5.00)	-17.00 µm
R3z max	---	Rdc (70.00;5.00)	-18.99 µm
R3z mean	---	Rdc (80.00;5.00)	-21.29 µm
		Rdc (90.00;5.00)	-24.63 µm
		Rdc (100.00;5.00)	-47.82 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:11 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (4.66;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.78 % R Mr (-2.00;5.00) 8.52 % R Mr (-3.00;5.00) 10.68 % R Mr (-4.00;5.00) 12.88 % R Mr (-5.00;5.00) 15.35 % R Mr (-6.00;5.00) 18.54 % R Mr (-7.00;5.00) 23.12 % R Mr (-8.00;5.00) 26.35 % R Mr (-9.00;5.00) 29.79 % R Mr (-10.00;5.00) 33.52 % R Mr (-11.00;5.00) 37.48 % R Mr (-12.00;5.00) 40.73 % R Mr (-13.00;5.00) 43.62 % R Mr (-14.00;5.00) 46.57 % R Mr (-15.00;5.00) 49.67 % R Mr (-16.00;5.00) 53.93 % R Mr (-17.00;5.00) 60.00 % R Mr (-18.00;5.00) 65.00 % R Mr (-19.00;5.00) 70.03 % R Mr (-20.00;5.00) 74.94 % R Mr (-21.00;5.00) 79.13 % R Mr (-22.00;5.00) 82.92 % R Mr (-23.00;5.00) 86.48 % R Mr (-24.00;5.00) 88.61 % R Mr (-25.00;5.00) 90.92 % R Mr (-26.00;5.00) 92.16 % R Mr (-27.00;5.00) 93.27 % R Mr (-28.00;5.00) 94.69 % R Mr (-29.00;5.00) 95.56 % R Mr (-30.00;5.00) 96.08 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 37.03 µm Rz2 37.57 µm Rz3 28.09 µm Rz4 35.33 µm Rz5 26.17 µm Rz sigma 5.32 µm Rz min 26.17 µm Rz max 37.57 µm Rz mean 32.84 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 12.42 µm Rp2 17.54 µm Rp3 11.24 µm Rp4 20.23 µm Rp5 14.34 µm Rp sigma 3.70 µm Rp min 11.24 µm Rp max 20.23 µm Rp mean 15.16 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:11 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 6.85 µm Rdc (10.00;5.00) -2.98 µm Rdc (20.00;5.00) -5.67 µm Rdc (30.00;5.00) -7.52 µm Rdc (40.00;5.00) -9.45 µm Rdc (50.00;5.00) -11.44 µm Rdc (60.00;5.00) -14.42 µm Rdc (70.00;5.00) -18.13 µm Rdc (80.00;5.00) -21.78 µm Rdc (90.00;5.00) -25.55 µm Rdc (100.00;5.00) -37.98 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (6.85;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.01 % R Mr (-2.00;5.00) 7.33 % R Mr (-3.00;5.00) 10.08 % R Mr (-4.00;5.00) 13.26 % R Mr (-5.00;5.00) 16.79 % R Mr (-6.00;5.00) 21.53 % R Mr (-7.00;5.00) 27.25 % R Mr (-8.00;5.00) 32.37 % R Mr (-9.00;5.00) 37.61 % R Mr (-10.00;5.00) 43.06 % R Mr (-11.00;5.00) 48.11 % R Mr (-12.00;5.00) 51.93 % R Mr (-13.00;5.00) 55.24 % R Mr (-14.00;5.00) 58.42 % R Mr (-15.00;5.00) 61.86 % R Mr (-16.00;5.00) 64.47 % R Mr (-17.00;5.00) 66.82 % R Mr (-18.00;5.00) 69.26 % R Mr (-19.00;5.00) 73.44 % R Mr (-20.00;5.00) 76.20 % R Mr (-21.00;5.00) 78.48 % R Mr (-22.00;5.00) 80.48 % R Mr (-23.00;5.00) 83.49 % R Mr (-24.00;5.00) 86.30 % R Mr (-25.00;5.00) 88.88 % R Mr (-26.00;5.00) 90.93 % R Mr (-27.00;5.00) 92.81 % R Mr (-28.00;5.00) 94.76 % R Mr (-29.00;5.00) 96.19 % R Mr (-30.00;5.00) 97.07 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 55.19 µm Rz2 50.18 µm Rz3 19.80 µm Rz4 24.97 µm Rz5 31.58 µm Rz sigma 15.59 µm Rz min 19.80 µm Rz max 55.19 µm Rz mean 36.35 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 21.92 µm Rp2 16.79 µm Rp3 13.69 µm Rp4 12.07 µm Rp5 10.20 µm Rp sigma 4.59 µm Rp min 10.20 µm Rp max 21.92 µm Rp mean 14.94 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:11 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (5.61;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	7.08 %
R Mr (-2.00;5.00)	8.68 %
R Mr (-3.00;5.00)	10.01 %
R Mr (-4.00;5.00)	11.07 %
R Mr (-5.00;5.00)	12.90 %
R Mr (-6.00;5.00)	14.67 %
R Mr (-7.00;5.00)	18.56 %
R Mr (-8.00;5.00)	21.95 %
R Mr (-9.00;5.00)	25.16 %
R Mr (-10.00;5.00)	28.55 %
R Mr (-11.00;5.00)	31.62 %
R Mr (-12.00;5.00)	37.31 %
R Mr (-13.00;5.00)	40.94 %
R Mr (-14.00;5.00)	43.76 %
R Mr (-15.00;5.00)	46.62 %
R Mr (-16.00;5.00)	50.22 %
R Mr (-17.00;5.00)	54.22 %
R Mr (-18.00;5.00)	58.38 %
R Mr (-19.00;5.00)	63.14 %
R Mr (-20.00;5.00)	66.57 %
R Mr (-21.00;5.00)	69.33 %
R Mr (-22.00;5.00)	74.55 %
R Mr (-23.00;5.00)	77.13 %
R Mr (-24.00;5.00)	79.02 %
R Mr (-25.00;5.00)	80.89 %
R Mr (-26.00;5.00)	82.42 %
R Mr (-27.00;5.00)	84.41 %
R Mr (-28.00;5.00)	86.01 %
R Mr (-29.00;5.00)	87.58 %
R Mr (-30.00;5.00)	88.86 %

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:11 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 5.61 μm
R3z2	Rdc (10.00;5.00) -2.98 μm
R3z3	Rdc (20.00;5.00) -7.35 μm
R3z4	Rdc (30.00;5.00) -10.48 μm
R3z5	Rdc (40.00;5.00) -12.68 μm
R3z sigma	Rdc (50.00;5.00) -15.98 μm
R3z min	Rdc (60.00;5.00) -18.33 μm
R3z max	Rdc (70.00;5.00) -21.16 μm
R3z mean	Rdc (80.00;5.00) -24.48 μm
	Rdc (90.00;5.00) -31.03 μm
	Rdc (100.00;5.00) -49.70 μm

No Quick&Easy

5

2.54m/min, face milled, longitudinal direction:



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement

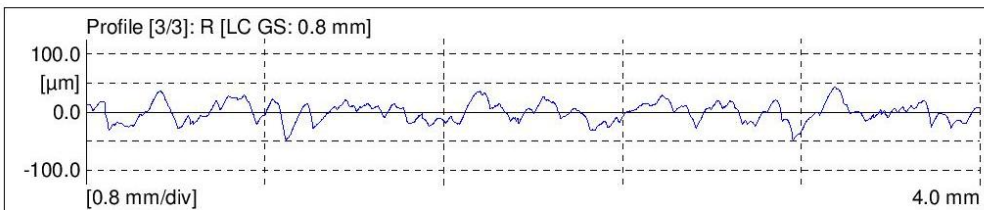
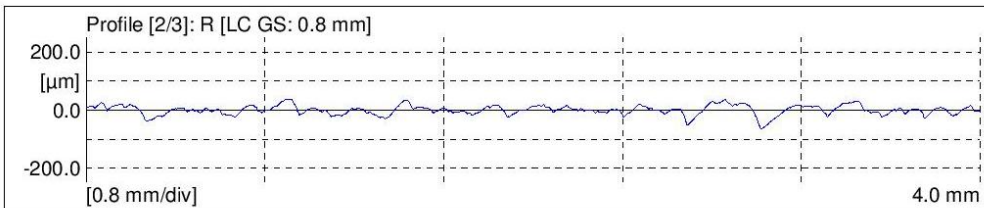
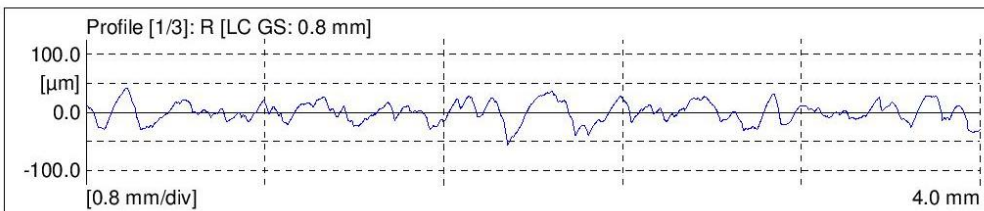


08/31/12, 10:34 AM

Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:34 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (14.55;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.21 % R Mr (-2.00;5.00) 7.13 % R Mr (-3.00;5.00) 8.16 % R Mr (-4.00;5.00) 9.35 % R Mr (-5.00;5.00) 10.63 % R Mr (-6.00;5.00) 12.10 % R Mr (-7.00;5.00) 13.33 % R Mr (-8.00;5.00) 14.42 % R Mr (-9.00;5.00) 15.96 % R Mr (-10.00;5.00) 17.39 % R Mr (-11.00;5.00) 18.88 % R Mr (-12.00;5.00) 20.58 % R Mr (-13.00;5.00) 22.18 % R Mr (-14.00;5.00) 23.50 % R Mr (-15.00;5.00) 24.82 % R Mr (-16.00;5.00) 26.78 % R Mr (-17.00;5.00) 28.85 % R Mr (-18.00;5.00) 30.91 % R Mr (-19.00;5.00) 32.77 % R Mr (-20.00;5.00) 34.53 % R Mr (-21.00;5.00) 36.46 % R Mr (-22.00;5.00) 39.02 % R Mr (-23.00;5.00) 41.12 % R Mr (-24.00;5.00) 43.34 % R Mr (-25.00;5.00) 45.65 % R Mr (-26.00;5.00) 48.03 % R Mr (-27.00;5.00) 50.26 % R Mr (-28.00;5.00) 52.71 % R Mr (-29.00;5.00) 54.88 % R Mr (-30.00;5.00) 57.11 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 61.77 µm Rz2 69.56 µm Rz3 42.89 µm Rz4 100.28 µm Rz5 59.92 µm Rz sigma 21.05 µm Rz min 42.89 µm Rz max 100.28 µm Rz mean 66.88 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 25.62 µm Rp2 38.66 µm Rp3 18.74 µm Rp4 36.07 µm Rp5 31.32 µm Rp sigma 8.05 µm Rp min 18.74 µm Rp max 38.66 µm Rp mean 30.08 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 27.89 µm R3z2 27.26 µm R3z3 27.45 µm R3z4 47.67 µm R3z5 32.28 µm R3z sigma 8.72 µm R3z min 27.26 µm R3z max 47.67 µm R3z mean 32.51 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:34 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 13.53 µm Rdc (10.00;5.00) -5.94 µm Rdc (20.00;5.00) -11.67 µm Rdc (30.00;5.00) -16.87 µm Rdc (40.00;5.00) -21.01 µm Rdc (50.00;5.00) -24.22 µm Rdc (60.00;5.00) -27.61 µm Rdc (70.00;5.00) -31.77 µm Rdc (80.00;5.00) -36.88 µm Rdc (90.00;5.00) -45.10 µm Rdc (100.00;5.00) -89.34 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (13.53;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.76 % R Mr (-2.00;5.00) 6.71 % R Mr (-3.00;5.00) 7.98 % R Mr (-4.00;5.00) 8.66 % R Mr (-5.00;5.00) 9.33 % R Mr (-6.00;5.00) 10.04 % R Mr (-7.00;5.00) 11.06 % R Mr (-8.00;5.00) 12.47 % R Mr (-9.00;5.00) 13.99 % R Mr (-10.00;5.00) 15.88 % R Mr (-11.00;5.00) 18.32 % R Mr (-12.00;5.00) 20.74 % R Mr (-13.00;5.00) 22.74 % R Mr (-14.00;5.00) 24.33 % R Mr (-15.00;5.00) 26.18 % R Mr (-16.00;5.00) 28.25 % R Mr (-17.00;5.00) 30.29 % R Mr (-18.00;5.00) 32.33 % R Mr (-19.00;5.00) 34.77 % R Mr (-20.00;5.00) 37.35 % R Mr (-21.00;5.00) 39.96 % R Mr (-22.00;5.00) 42.71 % R Mr (-23.00;5.00) 46.24 % R Mr (-24.00;5.00) 49.19 % R Mr (-25.00;5.00) 52.09 % R Mr (-26.00;5.00) 55.57 % R Mr (-27.00;5.00) 58.34 % R Mr (-28.00;5.00) 61.10 % R Mr (-29.00;5.00) 63.70 % R Mr (-30.00;5.00) 65.92 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 67.30 µm Rz2 69.46 µm Rz3 68.08 µm Rz4 78.42 µm Rz5 75.93 µm Rz sigma 5.01 µm Rz min 67.30 µm Rz max 78.42 µm Rz mean 71.84 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 35.72 µm Rp2 22.14 µm Rp3 36.04 µm Rp4 28.90 µm Rp5 43.08 µm Rp sigma 7.95 µm Rp min 22.14 µm Rp max 43.08 µm Rp mean 33.18 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:34 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	54.53 μm	Rdc (0.00;5.00)	16.71 μm
R3z2	39.41 μm	Rdc (10.00;5.00)	-6.21 μm
R3z3	34.71 μm	Rdc (20.00;5.00)	-12.88 μm
R3z4	43.97 μm	Rdc (30.00;5.00)	-17.49 μm
R3z5	28.76 μm	Rdc (40.00;5.00)	-21.19 μm
R3z sigma	9.76 μm	Rdc (50.00;5.00)	-26.21 μm
R3z min	28.76 μm	Rdc (60.00;5.00)	-31.38 μm
R3z max	54.53 μm	Rdc (70.00;5.00)	-37.07 μm
R3z mean	40.27 μm	Rdc (80.00;5.00)	-42.60 μm
		Rdc (90.00;5.00)	-47.60 μm
		Rdc (100.00;5.00)	-75.89 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:34 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	54.53 μm	Rdc (0.00;5.00)	16.71 μm
R3z2	39.41 μm	Rdc (10.00;5.00)	-6.21 μm
R3z3	34.71 μm	Rdc (20.00;5.00)	-12.88 μm
R3z4	43.97 μm	Rdc (30.00;5.00)	-17.49 μm
R3z5	28.76 μm	Rdc (40.00;5.00)	-21.19 μm
R3z sigma	9.76 μm	Rdc (50.00;5.00)	-26.21 μm
R3z min	28.76 μm	Rdc (60.00;5.00)	-31.38 μm
R3z max	54.53 μm	Rdc (70.00;5.00)	-37.07 μm
R3z mean	40.27 μm	Rdc (80.00;5.00)	-42.60 μm
		Rdc (90.00;5.00)	-47.60 μm
		Rdc (100.00;5.00)	-75.89 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:34 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (16.71;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.68 %
R Mr (-2.00;5.00)	6.48 %
R Mr (-3.00;5.00)	7.27 %
R Mr (-4.00;5.00)	8.01 %
R Mr (-5.00;5.00)	8.95 %
R Mr (-6.00;5.00)	9.76 %
R Mr (-7.00;5.00)	10.86 %
R Mr (-8.00;5.00)	12.21 %
R Mr (-9.00;5.00)	13.90 %
R Mr (-10.00;5.00)	15.33 %
R Mr (-11.00;5.00)	16.73 %
R Mr (-12.00;5.00)	18.36 %
R Mr (-13.00;5.00)	20.23 %
R Mr (-14.00;5.00)	22.25 %
R Mr (-15.00;5.00)	24.14 %
R Mr (-16.00;5.00)	26.35 %
R Mr (-17.00;5.00)	28.91 %
R Mr (-18.00;5.00)	31.14 %
R Mr (-19.00;5.00)	33.65 %
R Mr (-20.00;5.00)	36.72 %
R Mr (-21.00;5.00)	39.57 %
R Mr (-22.00;5.00)	41.69 %
R Mr (-23.00;5.00)	43.45 %
R Mr (-24.00;5.00)	45.44 %
R Mr (-25.00;5.00)	47.26 %
R Mr (-26.00;5.00)	49.28 %
R Mr (-27.00;5.00)	51.69 %
R Mr (-28.00;5.00)	53.74 %
R Mr (-29.00;5.00)	55.86 %
R Mr (-30.00;5.00)	57.41 %

No Quick&Easy

6

2.54m/min, face milled, transverse direction:



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement

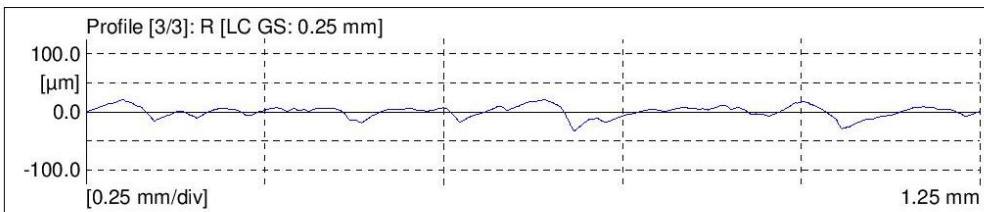
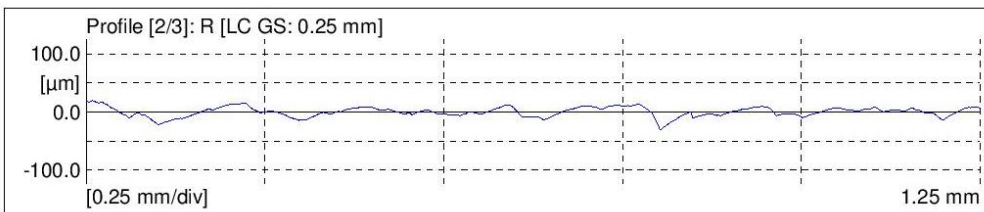
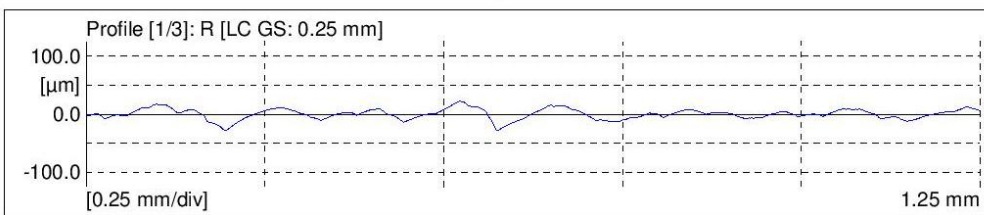


08/31/12, 10:57 AM

Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μ m
VB: ± 250 μ m
Vt: 0.10 mm/s
Points: 10500 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:57 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	6.935	8.938	32.502	50.67	50.67	23.404	50.67	13.93	18.58	4.753	141.88
2:	6.583	8.273	31.436	43.62	43.62	25.675	50.06	12.49	18.95	-.-	176.08
3:	7.780	9.897	37.346	53.61	53.61	27.364	53.61	16.49	20.86	-.-	161.42
Xb:	7.099	9.036	33.762	49.30	49.30	25.481	51.44	14.30	19.46	4.753	159.79
S:	0.615	0.816	3.150	5.13	5.13	1.987	1.90	2.03	1.22	0.000	17.16
Max:	7.780	9.897	37.346	53.61	53.61	27.364	53.61	16.49	20.86	4.753	176.08
Min:	6.583	8.273	31.436	43.62	43.62	23.404	50.06	12.49	18.58	4.753	141.88
R:	1.196	1.623	5.910	9.99	9.99	3.961	3.55	4.00	2.28	0.000	34.21

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	45.39 μm	Rp1	16.95 μm
Rz2	24.54 μm	Rp2	10.92 μm
Rz3	50.67 μm	Rp3	22.22 μm
Rz4	17.84 μm	Rp4	7.47 μm
Rz5	24.08 μm	Rp5	12.08 μm
Rz sigma	14.54 μm	Rp sigma	5.74 μm
Rz min	17.84 μm	Rp min	7.47 μm
Rz max	50.67 μm	Rp max	22.22 μm
Rz mean	32.50 μm	Rp mean	13.93 μm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	4.53 μm	Rdc (0.00;5.00)	8.15 μm
R3z2	5.21 μm	Rdc (10.00;5.00)	-3.22 μm
R3z3	2.85 μm	Rdc (20.00;5.00)	-6.60 μm
R3z4	7.08 μm	Rdc (30.00;5.00)	-9.24 μm
R3z5	4.09 μm	Rdc (40.00;5.00)	-11.64 μm
R3z sigma	1.56 μm	Rdc (50.00;5.00)	-13.54 μm
R3z min	2.85 μm	Rdc (60.00;5.00)	-15.47 μm
R3z max	7.08 μm	Rdc (70.00;5.00)	-18.03 μm
R3z mean	4.75 μm	Rdc (80.00;5.00)	-20.82 μm
		Rdc (90.00;5.00)	-25.20 μm
		Rdc (100.00;5.00)	-42.52 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:57 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (8.15;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 7.14 % R Mr (-2.00;5.00) 8.01 % R Mr (-3.00;5.00) 9.49 % R Mr (-4.00;5.00) 12.06 % R Mr (-5.00;5.00) 14.30 % R Mr (-6.00;5.00) 18.11 % R Mr (-7.00;5.00) 22.70 % R Mr (-8.00;5.00) 25.87 % R Mr (-9.00;5.00) 28.83 % R Mr (-10.00;5.00) 32.32 % R Mr (-11.00;5.00) 36.48 % R Mr (-12.00;5.00) 41.51 % R Mr (-13.00;5.00) 46.83 % R Mr (-14.00;5.00) 52.38 % R Mr (-15.00;5.00) 57.55 % R Mr (-16.00;5.00) 62.37 % R Mr (-17.00;5.00) 66.17 % R Mr (-18.00;5.00) 69.96 % R Mr (-19.00;5.00) 72.91 % R Mr (-20.00;5.00) 76.78 % R Mr (-21.00;5.00) 80.94 % R Mr (-22.00;5.00) 83.70 % R Mr (-23.00;5.00) 85.38 % R Mr (-24.00;5.00) 87.40 % R Mr (-25.00;5.00) 89.59 % R Mr (-26.00;5.00) 91.53 % R Mr (-27.00;5.00) 92.91 % R Mr (-28.00;5.00) 94.48 % R Mr (-29.00;5.00) 94.99 % R Mr (-30.00;5.00) 95.44 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 41.46 µm Rz2 23.09 µm Rz3 26.03 µm Rz4 43.62 µm Rz5 22.98 µm Rz sigma 10.24 µm Rz min 22.98 µm Rz max 43.62 µm Rz mean 31.44 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 19.50 µm Rp2 8.71 µm Rp3 12.42 µm Rp4 13.07 µm Rp5 8.73 µm Rp sigma 4.41 µm Rp min 8.71 µm Rp max 19.50 µm Rp mean 12.49 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:57 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 7.11 µm Rdc (10.00;5.00) -2.20 µm Rdc (20.00;5.00) -5.07 µm Rdc (30.00;5.00) -7.70 µm Rdc (40.00;5.00) -9.59 µm Rdc (50.00;5.00) -11.72 µm Rdc (60.00;5.00) -14.23 µm Rdc (70.00;5.00) -16.09 µm Rdc (80.00;5.00) -18.53 µm Rdc (90.00;5.00) -23.00 µm Rdc (100.00;5.00) -42.94 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (7.11;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.75 % R Mr (-2.00;5.00) 9.51 % R Mr (-3.00;5.00) 12.02 % R Mr (-4.00;5.00) 15.76 % R Mr (-5.00;5.00) 19.75 % R Mr (-6.00;5.00) 23.53 % R Mr (-7.00;5.00) 27.22 % R Mr (-8.00;5.00) 31.84 % R Mr (-9.00;5.00) 37.23 % R Mr (-10.00;5.00) 42.01 % R Mr (-11.00;5.00) 45.90 % R Mr (-12.00;5.00) 50.92 % R Mr (-13.00;5.00) 54.53 % R Mr (-14.00;5.00) 58.78 % R Mr (-15.00;5.00) 63.35 % R Mr (-16.00;5.00) 69.57 % R Mr (-17.00;5.00) 73.87 % R Mr (-18.00;5.00) 78.12 % R Mr (-19.00;5.00) 81.14 % R Mr (-20.00;5.00) 82.99 % R Mr (-21.00;5.00) 85.88 % R Mr (-22.00;5.00) 88.07 % R Mr (-23.00;5.00) 90.00 % R Mr (-24.00;5.00) 91.90 % R Mr (-25.00;5.00) 93.11 % R Mr (-26.00;5.00) 94.68 % R Mr (-27.00;5.00) 95.88 % R Mr (-28.00;5.00) 96.33 % R Mr (-29.00;5.00) 96.80 % R Mr (-30.00;5.00) 97.40 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 36.59 µm Rz2 25.67 µm Rz3 53.61 µm Rz4 24.47 µm Rz5 46.39 µm Rz sigma 12.74 µm Rz min 24.47 µm Rz max 53.61 µm Rz mean 37.35 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 20.58 µm Rp2 6.92 µm Rp3 20.68 µm Rp4 16.84 µm Rp5 17.44 µm Rp sigma 5.63 µm Rp min 6.92 µm Rp max 20.68 µm Rp mean 16.49 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:57 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 4.29 µm
R3z2	Rdc (10.00;5.00) -5.05 µm
R3z3	Rdc (20.00;5.00) -9.52 µm
R3z4	Rdc (30.00;5.00) -11.01 µm
R3z5	Rdc (40.00;5.00) -12.41 µm
R3z sigma	Rdc (50.00;5.00) -14.02 µm
R3z min	Rdc (60.00;5.00) -16.27 µm
R3z max	Rdc (70.00;5.00) -20.23 µm
R3z mean	Rdc (80.00;5.00) -23.81 µm
	Rdc (90.00;5.00) -30.06 µm
	Rdc (100.00;5.00) -49.32 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:57 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (4.29;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.17 %
R Mr (-2.00;5.00)	7.41 %
R Mr (-3.00;5.00)	8.30 %
R Mr (-4.00;5.00)	9.10 %
R Mr (-5.00;5.00)	9.96 %
R Mr (-6.00;5.00)	11.50 %
R Mr (-7.00;5.00)	12.68 %
R Mr (-8.00;5.00)	15.38 %
R Mr (-9.00;5.00)	18.11 %
R Mr (-10.00;5.00)	22.52 %
R Mr (-11.00;5.00)	29.96 %
R Mr (-12.00;5.00)	36.34 %
R Mr (-13.00;5.00)	44.95 %
R Mr (-14.00;5.00)	49.88 %
R Mr (-15.00;5.00)	55.53 %
R Mr (-16.00;5.00)	59.19 %
R Mr (-17.00;5.00)	61.85 %
R Mr (-18.00;5.00)	64.28 %
R Mr (-19.00;5.00)	66.55 %
R Mr (-20.00;5.00)	69.13 %
R Mr (-21.00;5.00)	72.45 %
R Mr (-22.00;5.00)	74.82 %
R Mr (-23.00;5.00)	78.01 %
R Mr (-24.00;5.00)	80.65 %
R Mr (-25.00;5.00)	82.45 %
R Mr (-26.00;5.00)	83.76 %
R Mr (-27.00;5.00)	85.07 %
R Mr (-28.00;5.00)	86.39 %
R Mr (-29.00;5.00)	88.20 %
R Mr (-30.00;5.00)	89.88 %

No Quick&Easy

6

5.08 m/min, peripherally milled, transverse direction:



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement

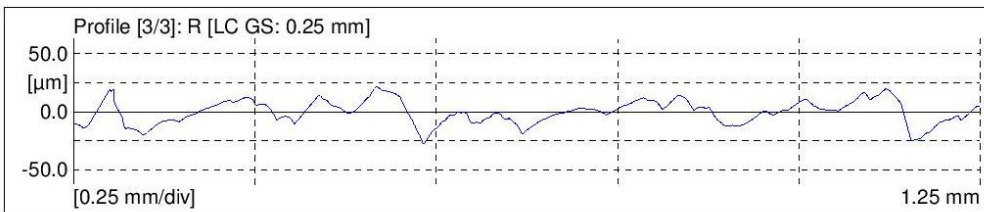
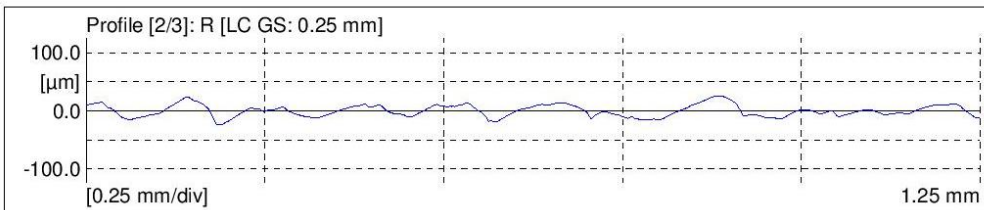
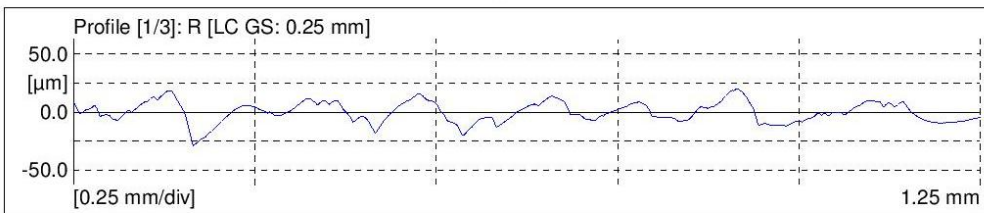


08/31/12, 11:16 AM

Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.10 mm/s
Points: 10500 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:16 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm ...
1:	7.201	8.789	33.219	47.33	47.33	26.659	48.65	15.45	17.77	---	164.75 ...
2:	8.434	10.149	34.107	48.29	48.29	28.634	50.35	17.58	16.53	---	175.83 ...
3:	8.042	9.939	36.235	48.89	48.89	35.800	48.89	15.32	20.92	---	241.80 ...
Xb:	7.892	9.625	34.521	48.17	48.17	30.364	49.29	16.12	18.41	194.13	
S:	0.630	0.732	1.550	0.78	0.78	4.810	0.92	1.27	2.26	41.66	
Max:	8.434	10.149	36.235	48.89	48.89	35.800	50.35	17.58	20.92	241.80	
Min:	7.201	8.789	33.219	47.33	47.33	26.659	48.65	15.32	16.53	164.75	
R:	1.233	1.360	3.016	1.55	1.55	9.141	1.70	2.26	4.39	77.05	

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	47.33 µm	Rp1	18.42 µm
Rz2	33.79 µm	Rp2	15.57 µm
Rz3	33.91 µm	Rp3	13.61 µm
Rz4	31.79 µm	Rp4	19.74 µm
Rz5	19.28 µm	Rp5	9.90 µm
Rz sigma	9.96 µm	Rp sigma	3.92 µm
Rz min	19.28 µm	Rp min	9.90 µm
Rz max	47.33 µm	Rp max	19.74 µm
Rz mean	33.22 µm	Rp mean	15.45 µm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	---	Rdc (0.00;5.00)	6.27 µm
R3z2	---	Rdc (10.00;5.00)	-3.02 µm
R3z3	---	Rdc (20.00;5.00)	-5.66 µm
R3z4	---	Rdc (30.00;5.00)	-8.19 µm
R3z5	---	Rdc (40.00;5.00)	-10.93 µm
R3z sigma	---	Rdc (50.00;5.00)	-14.04 µm
R3z min	---	Rdc (60.00;5.00)	-16.39 µm
R3z max	---	Rdc (70.00;5.00)	-18.74 µm
R3z mean	---	Rdc (80.00;5.00)	-21.24 µm
		Rdc (90.00;5.00)	-24.16 µm
		Rdc (100.00;5.00)	-42.38 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:16 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (6.27;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.49 % R Mr (-2.00;5.00) 8.25 % R Mr (-3.00;5.00) 9.94 % R Mr (-4.00;5.00) 13.59 % R Mr (-5.00;5.00) 17.54 % R Mr (-6.00;5.00) 21.32 % R Mr (-7.00;5.00) 25.05 % R Mr (-8.00;5.00) 29.20 % R Mr (-9.00;5.00) 33.20 % R Mr (-10.00;5.00) 37.12 % R Mr (-11.00;5.00) 40.18 % R Mr (-12.00;5.00) 42.86 % R Mr (-13.00;5.00) 46.00 % R Mr (-14.00;5.00) 49.71 % R Mr (-15.00;5.00) 53.89 % R Mr (-16.00;5.00) 58.12 % R Mr (-17.00;5.00) 62.21 % R Mr (-18.00;5.00) 65.34 % R Mr (-19.00;5.00) 70.95 % R Mr (-20.00;5.00) 74.92 % R Mr (-21.00;5.00) 79.20 % R Mr (-22.00;5.00) 83.57 % R Mr (-23.00;5.00) 87.82 % R Mr (-24.00;5.00) 89.66 % R Mr (-25.00;5.00) 92.46 % R Mr (-26.00;5.00) 94.15 % R Mr (-27.00;5.00) 94.88 % R Mr (-28.00;5.00) 95.40 % R Mr (-29.00;5.00) 95.88 % R Mr (-30.00;5.00) 96.40 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 48.29 µm Rz2 23.14 µm Rz3 33.73 µm Rz4 41.93 µm Rz5 23.44 µm Rz sigma 11.14 µm Rz min 23.14 µm Rz max 48.29 µm Rz mean 34.11 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 24.00 µm Rp2 11.35 µm Rp3 14.33 µm Rp4 26.06 µm Rp5 12.14 µm Rp sigma 6.93 µm Rp min 11.35 µm Rp max 26.06 µm Rp mean 17.58 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:16 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 9.42 µm Rdc (10.00;5.00) -3.94 µm Rdc (20.00;5.00) -7.14 µm Rdc (30.00;5.00) -10.32 µm Rdc (40.00;5.00) -14.41 µm Rdc (50.00;5.00) -17.38 µm Rdc (60.00;5.00) -20.51 µm Rdc (70.00;5.00) -22.87 µm Rdc (80.00;5.00) -26.04 µm Rdc (90.00;5.00) -29.26 µm Rdc (100.00;5.00) -40.93 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (9.42;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.75 % R Mr (-2.00;5.00) 6.41 % R Mr (-3.00;5.00) 8.06 % R Mr (-4.00;5.00) 10.18 % R Mr (-5.00;5.00) 12.22 % R Mr (-6.00;5.00) 15.31 % R Mr (-7.00;5.00) 19.46 % R Mr (-8.00;5.00) 23.09 % R Mr (-9.00;5.00) 26.29 % R Mr (-10.00;5.00) 29.13 % R Mr (-11.00;5.00) 31.37 % R Mr (-12.00;5.00) 33.83 % R Mr (-13.00;5.00) 36.39 % R Mr (-14.00;5.00) 38.48 % R Mr (-15.00;5.00) 42.72 % R Mr (-16.00;5.00) 45.72 % R Mr (-17.00;5.00) 48.77 % R Mr (-18.00;5.00) 52.12 % R Mr (-19.00;5.00) 54.92 % R Mr (-20.00;5.00) 57.89 % R Mr (-21.00;5.00) 61.83 % R Mr (-22.00;5.00) 65.36 % R Mr (-23.00;5.00) 70.43 % R Mr (-24.00;5.00) 74.28 % R Mr (-25.00;5.00) 77.12 % R Mr (-26.00;5.00) 79.82 % R Mr (-27.00;5.00) 82.59 % R Mr (-28.00;5.00) 86.28 % R Mr (-29.00;5.00) 89.28 % R Mr (-30.00;5.00) 91.47 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 38.73 µm Rz2 48.89 µm Rz3 22.00 µm Rz4 26.76 µm Rz5 44.80 µm Rz sigma 11.53 µm Rz min 22.00 µm Rz max 48.89 µm Rz mean 36.24 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 18.88 µm Rp2 21.14 µm Rp3 2.94 µm Rp4 14.11 µm Rp5 19.52 µm Rp sigma 7.40 µm Rp min 2.94 µm Rp max 21.14 µm Rp mean 15.32 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:16 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 5.49 μm
R3z2	Rdc (10.00;5.00) -3.46 μm
R3z3	Rdc (20.00;5.00) -6.97 μm
R3z4	Rdc (30.00;5.00) -10.67 μm
R3z5	Rdc (40.00;5.00) -13.30 μm
R3z sigma	Rdc (50.00;5.00) -15.48 μm
R3z min	Rdc (60.00;5.00) -18.15 μm
R3z max	Rdc (70.00;5.00) -21.75 μm
R3z mean	Rdc (80.00;5.00) -24.86 μm
	Rdc (90.00;5.00) -29.31 μm
	Rdc (100.00;5.00) -43.40 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:16 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (5.49;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.84 %
R Mr (-2.00;5.00)	7.12 %
R Mr (-3.00;5.00)	8.99 %
R Mr (-4.00;5.00)	11.34 %
R Mr (-5.00;5.00)	13.64 %
R Mr (-6.00;5.00)	16.50 %
R Mr (-7.00;5.00)	20.00 %
R Mr (-8.00;5.00)	22.79 %
R Mr (-9.00;5.00)	25.00 %
R Mr (-10.00;5.00)	27.86 %
R Mr (-11.00;5.00)	31.17 %
R Mr (-12.00;5.00)	34.82 %
R Mr (-13.00;5.00)	38.68 %
R Mr (-14.00;5.00)	43.19 %
R Mr (-15.00;5.00)	48.28 %
R Mr (-16.00;5.00)	51.70 %
R Mr (-17.00;5.00)	56.07 %
R Mr (-18.00;5.00)	59.64 %
R Mr (-19.00;5.00)	62.71 %
R Mr (-20.00;5.00)	65.42 %
R Mr (-21.00;5.00)	67.82 %
R Mr (-22.00;5.00)	70.86 %
R Mr (-23.00;5.00)	74.60 %
R Mr (-24.00;5.00)	78.06 %
R Mr (-25.00;5.00)	80.53 %
R Mr (-26.00;5.00)	83.05 %
R Mr (-27.00;5.00)	84.98 %
R Mr (-28.00;5.00)	87.76 %
R Mr (-29.00;5.00)	89.54 %
R Mr (-30.00;5.00)	91.17 %

No Quick&Easy

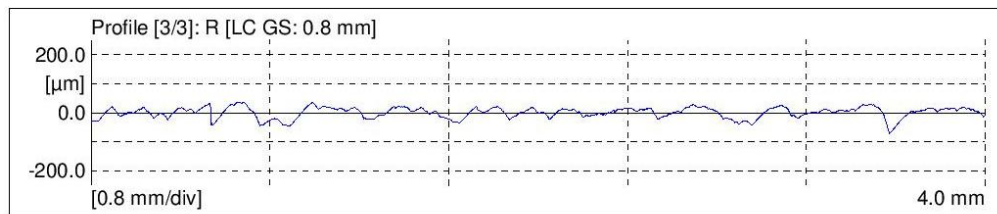
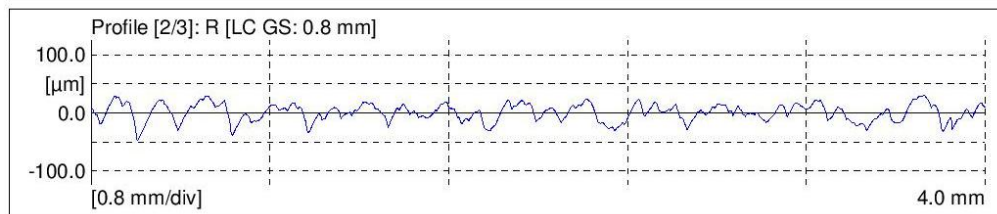
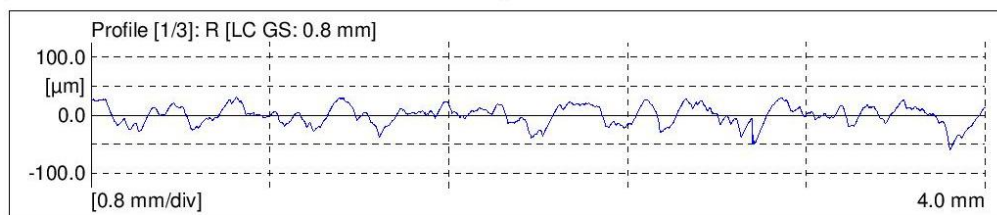
6

5.08 m/min, peripherally milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 5.60 mm [N=5] Ls: 2.5 μ m VB: $\pm$ 250 μ m Vt: 0.50 mm/s Points: 33600 [3]
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No Quick&Easy

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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	13.557	16.766	70.828	86.28	86.28	49.656	90.48	27.58	43.25	42.377	338.27
2:	11.928	14.518	60.177	76.77	76.77	39.928	77.37	25.12	35.05	38.280	204.47
3:	14.727	18.388	77.898	100.08	100.08	54.631	108.59	29.72	48.18	34.753	280.23
Xb:	13.404	16.557	69.634	87.71	87.71	48.071	92.15	27.48	42.16	38.470	274.33
S:	1.406	1.944	8.920	11.72	11.72	7.478	15.68	2.30	6.63	3.816	67.09
Max:	14.727	18.388	77.898	100.08	100.08	54.631	108.59	29.72	48.18	42.377	338.27
Min:	11.928	14.518	60.177	76.77	76.77	39.928	77.37	25.12	35.05	34.753	204.47
R:	2.799	3.870	17.720	23.30	23.30	14.703	31.22	4.60	13.13	7.625	133.80

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	57.93 μm	Rp1	30.46 μm
Rz2	67.22 μm	Rp2	29.41 μm
Rz3	62.11 μm	Rp3	22.03 μm
Rz4	80.60 μm	Rp4	29.75 μm
Rz5	86.28 μm	Rp5	26.25 μm
Rz sigma	12.14 μm	Rp sigma	3.50 μm
Rz min	57.93 μm	Rp min	22.03 μm
Rz max	86.28 μm	Rp max	30.46 μm
Rz mean	70.83 μm	Rp mean	27.58 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	51.71 μm	Rdc (0.00;5.00)	5.71 μm
R3z2	32.78 μm	Rdc (10.00;5.00)	-4.08 μm
R3z3	40.62 μm	Rdc (20.00;5.00)	-10.06 μm
R3z4	56.60 μm	Rdc (30.00;5.00)	-14.88 μm
R3z5	30.19 μm	Rdc (40.00;5.00)	-20.23 μm
R3z sigma	11.54 μm	Rdc (50.00;5.00)	-23.60 μm
R3z min	30.19 μm	Rdc (60.00;5.00)	-28.39 μm
R3z max	56.60 μm	Rdc (70.00;5.00)	-33.87 μm
R3z mean	42.38 μm	Rdc (80.00;5.00)	-39.99 μm
		Rdc (90.00;5.00)	-47.15 μm
		Rdc (100.00;5.00)	-84.78 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (5.71;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.39 % R Mr (-2.00;5.00) 7.62 % R Mr (-3.00;5.00) 8.92 % R Mr (-4.00;5.00) 9.89 % R Mr (-5.00;5.00) 11.39 % R Mr (-6.00;5.00) 13.12 % R Mr (-7.00;5.00) 14.98 % R Mr (-8.00;5.00) 16.95 % R Mr (-9.00;5.00) 18.26 % R Mr (-10.00;5.00) 19.90 % R Mr (-11.00;5.00) 22.06 % R Mr (-12.00;5.00) 24.19 % R Mr (-13.00;5.00) 26.20 % R Mr (-14.00;5.00) 28.19 % R Mr (-15.00;5.00) 30.21 % R Mr (-16.00;5.00) 31.82 % R Mr (-17.00;5.00) 33.42 % R Mr (-18.00;5.00) 35.48 % R Mr (-19.00;5.00) 37.55 % R Mr (-20.00;5.00) 39.55 % R Mr (-21.00;5.00) 42.09 % R Mr (-22.00;5.00) 45.07 % R Mr (-23.00;5.00) 48.40 % R Mr (-24.00;5.00) 51.01 % R Mr (-25.00;5.00) 53.45 % R Mr (-26.00;5.00) 55.65 % R Mr (-27.00;5.00) 57.36 % R Mr (-28.00;5.00) 59.21 % R Mr (-29.00;5.00) 61.45 % R Mr (-30.00;5.00) 63.49 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 76.77 µm Rz2 53.68 µm Rz3 55.09 µm Rz4 52.96 µm Rz5 62.38 µm Rz sigma 10.00 µm Rz min 52.96 µm Rz max 76.77 µm Rz mean 60.18 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 29.43 µm Rp2 19.16 µm Rp3 23.92 µm Rp4 23.10 µm Rp5 30.02 µm Rp sigma 4.57 µm Rp min 19.16 µm Rp max 30.02 µm Rp mean 25.12 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 52.16 µm R3z2 29.04 µm R3z3 39.67 µm R3z4 23.83 µm R3z5 46.68 µm R3z sigma 11.82 µm R3z min 23.83 µm R3z max 52.16 µm R3z mean 38.28 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 8.44 µm Rdc (10.00;5.00) -3.68 µm Rdc (20.00;5.00) -8.16 µm Rdc (30.00;5.00) -12.32 µm Rdc (40.00;5.00) -15.77 µm Rdc (50.00;5.00) -19.78 µm Rdc (60.00;5.00) -24.08 µm Rdc (70.00;5.00) -28.91 µm Rdc (80.00;5.00) -34.23 µm Rdc (90.00;5.00) -41.15 µm Rdc (100.00;5.00) -68.92 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (8.44;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.55 % R Mr (-2.00;5.00) 7.70 % R Mr (-3.00;5.00) 9.10 % R Mr (-4.00;5.00) 10.42 % R Mr (-5.00;5.00) 12.19 % R Mr (-6.00;5.00) 14.30 % R Mr (-7.00;5.00) 16.76 % R Mr (-8.00;5.00) 19.48 % R Mr (-9.00;5.00) 22.24 % R Mr (-10.00;5.00) 24.78 % R Mr (-11.00;5.00) 26.95 % R Mr (-12.00;5.00) 29.30 % R Mr (-13.00;5.00) 31.88 % R Mr (-14.00;5.00) 34.61 % R Mr (-15.00;5.00) 37.39 % R Mr (-16.00;5.00) 40.48 % R Mr (-17.00;5.00) 42.99 % R Mr (-18.00;5.00) 45.80 % R Mr (-19.00;5.00) 48.19 % R Mr (-20.00;5.00) 50.45 % R Mr (-21.00;5.00) 52.78 % R Mr (-22.00;5.00) 54.96 % R Mr (-23.00;5.00) 57.34 % R Mr (-24.00;5.00) 59.71 % R Mr (-25.00;5.00) 62.45 % R Mr (-26.00;5.00) 64.65 % R Mr (-27.00;5.00) 66.60 % R Mr (-28.00;5.00) 68.38 % R Mr (-29.00;5.00) 70.19 % R Mr (-30.00;5.00) 72.58 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 82.15 µm Rz2 79.04 µm Rz3 58.07 µm Rz4 70.15 µm Rz5 100.08 µm Rz sigma 15.53 µm Rz min 58.07 µm Rz max 100.08 µm Rz mean 77.90 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 36.81 µm Rp2 34.46 µm Rp3 21.13 µm Rp4 27.91 µm Rp5 28.29 µm Rp sigma 6.16 µm Rp min 21.13 µm Rp max 36.81 µm Rp mean 29.72 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	50.61 μm	Rdc (0.00;5.00)	11.77 μm
R3z2	29.89 μm	Rdc (10.00;5.00)	-5.59 μm
R3z3	41.26 μm	Rdc (20.00;5.00)	-9.75 μm
R3z4	39.59 μm	Rdc (30.00;5.00)	-13.39 μm
R3z5	12.41 μm	Rdc (40.00;5.00)	-16.96 μm
R3z sigma	14.49 μm	Rdc (50.00;5.00)	-20.85 μm
R3z min	12.41 μm	Rdc (60.00;5.00)	-25.09 μm
R3z max	50.61 μm	Rdc (70.00;5.00)	-32.28 μm
R3z mean	34.75 μm	Rdc (80.00;5.00)	-40.63 μm
		Rdc (90.00;5.00)	-52.66 μm
		Rdc (100.00;5.00)	-96.82 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:49 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (11.77;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.54 %
R Mr (-2.00;5.00)	6.15 %
R Mr (-3.00;5.00)	6.86 %
R Mr (-4.00;5.00)	7.91 %
R Mr (-5.00;5.00)	9.19 %
R Mr (-6.00;5.00)	10.69 %
R Mr (-7.00;5.00)	12.80 %
R Mr (-8.00;5.00)	15.13 %
R Mr (-9.00;5.00)	17.49 %
R Mr (-10.00;5.00)	20.65 %
R Mr (-11.00;5.00)	23.76 %
R Mr (-12.00;5.00)	26.11 %
R Mr (-13.00;5.00)	28.77 %
R Mr (-14.00;5.00)	31.91 %
R Mr (-15.00;5.00)	34.98 %
R Mr (-16.00;5.00)	37.40 %
R Mr (-17.00;5.00)	40.13 %
R Mr (-18.00;5.00)	42.63 %
R Mr (-19.00;5.00)	45.48 %
R Mr (-20.00;5.00)	47.87 %
R Mr (-21.00;5.00)	50.34 %
R Mr (-22.00;5.00)	52.46 %
R Mr (-23.00;5.00)	54.89 %
R Mr (-24.00;5.00)	57.57 %
R Mr (-25.00;5.00)	59.84 %
R Mr (-26.00;5.00)	61.63 %
R Mr (-27.00;5.00)	63.09 %
R Mr (-28.00;5.00)	64.29 %
R Mr (-29.00;5.00)	65.72 %
R Mr (-30.00;5.00)	67.01 %

No Quick&Easy

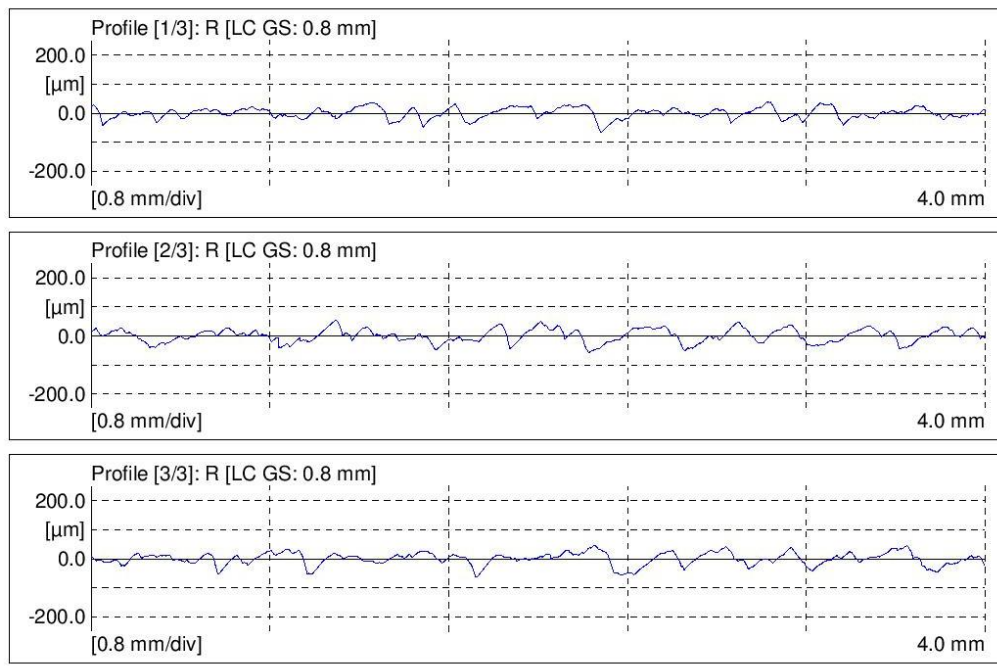
6

5.08 m/min, face milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/31/12, 10:37 AM
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 5.60 mm [N=5] Ls: 2.5 µm VB: ±250 µm Vt: 0.50 mm/s Points: 33600 [3]
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:37 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	14.602	18.175	80.174	98.71	98.71	51.384	105.77	33.51	46.66	41.096	242.47
2:	18.612	22.553	90.964	108.32	108.32	66.153	113.81	42.65	48.32	41.076	327.80
3:	16.597	21.390	92.285	109.34	109.34	59.528	109.34	38.09	54.20	36.870	267.64
Xb:	16.603	20.706	87.808	105.46	105.46	59.022	109.64	38.08	49.72	39.681	279.30
S:	2.005	2.268	6.644	5.87	5.87	7.397	4.03	4.57	3.96	2.434	43.85
Max:	18.612	22.553	92.285	109.34	109.34	66.153	113.81	42.65	54.20	41.096	327.80
Min:	14.602	18.175	80.174	98.71	98.71	51.384	105.77	33.51	46.66	36.870	242.47
R:	4.010	4.378	12.111	10.63	10.63	14.769	8.04	9.13	7.53	4.226	85.33

Profile [1/3]: R [LC GS: 0.8 mm]			Profile [1/3]: R [LC GS: 0.8 mm]		
Rz1	69.47	μm	Rp1	27.20	μm
Rz2	84.97	μm	Rp2	36.65	μm
Rz3	98.71	μm	Rp3	30.95	μm
Rz4	72.41	μm	Rp4	38.00	μm
Rz5	75.31	μm	Rp5	34.76	μm
Rz sigma	11.88	μm	Rp sigma	4.42	μm
Rz min	69.47	μm	Rp min	27.20	μm
Rz max	98.71	μm	Rp max	38.00	μm
Rz mean	80.17	μm	Rp mean	33.51	μm

Profile [1/3]: R [LC GS: 0.8 mm]			Profile [1/3]: R [LC GS: 0.8 mm]		
R3z1	35.89	μm	Rdc (0.00;5.00)	10.55	μm
R3z2	40.81	μm	Rdc (10.00;5.00)	-4.40	μm
R3z3	57.39	μm	Rdc (20.00;5.00)	-12.36	μm
R3z4	43.53	μm	Rdc (30.00;5.00)	-17.88	μm
R3z5	27.86	μm	Rdc (40.00;5.00)	-22.31	μm
R3z sigma	10.88	μm	Rdc (50.00;5.00)	-26.73	μm
R3z min	27.86	μm	Rdc (60.00;5.00)	-32.19	μm
R3z max	57.39	μm	Rdc (70.00;5.00)	-37.06	μm
R3z mean	41.10	μm	Rdc (80.00;5.00)	-42.94	μm
			Rdc (90.00;5.00)	-51.79	μm
			Rdc (100.00;5.00)	-95.22	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:37 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (10.55;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.93 % R Mr (-2.00;5.00) 6.89 % R Mr (-3.00;5.00) 8.18 % R Mr (-4.00;5.00) 9.53 % R Mr (-5.00;5.00) 11.02 % R Mr (-6.00;5.00) 13.11 % R Mr (-7.00;5.00) 14.44 % R Mr (-8.00;5.00) 15.46 % R Mr (-9.00;5.00) 16.56 % R Mr (-10.00;5.00) 17.58 % R Mr (-11.00;5.00) 18.45 % R Mr (-12.00;5.00) 19.56 % R Mr (-13.00;5.00) 21.11 % R Mr (-14.00;5.00) 22.34 % R Mr (-15.00;5.00) 24.02 % R Mr (-16.00;5.00) 25.73 % R Mr (-17.00;5.00) 27.81 % R Mr (-18.00;5.00) 30.29 % R Mr (-19.00;5.00) 32.63 % R Mr (-20.00;5.00) 34.70 % R Mr (-21.00;5.00) 36.81 % R Mr (-22.00;5.00) 39.24 % R Mr (-23.00;5.00) 41.85 % R Mr (-24.00;5.00) 44.16 % R Mr (-25.00;5.00) 46.42 % R Mr (-26.00;5.00) 48.68 % R Mr (-27.00;5.00) 50.39 % R Mr (-28.00;5.00) 51.93 % R Mr (-29.00;5.00) 53.60 % R Mr (-30.00;5.00) 55.31 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 68.26 µm Rz2 101.75 µm Rz3 108.32 µm Rz4 97.93 µm Rz5 78.56 µm Rz sigma 16.85 µm Rz min 68.26 µm Rz max 108.32 µm Rz mean 90.96 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 28.41 µm Rp2 54.60 µm Rp3 49.11 µm Rp4 47.31 µm Rp5 33.79 µm Rp sigma 11.04 µm Rp min 28.41 µm Rp max 54.60 µm Rp mean 42.65 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 27.12 µm R3z2 46.03 µm R3z3 55.23 µm R3z4 47.95 µm R3z5 29.06 µm R3z sigma 12.36 µm R3z min 27.12 µm R3z max 55.23 µm R3z mean 41.08 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:37 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 20.82 µm Rdc (10.00;5.00) -4.98 µm Rdc (20.00;5.00) -12.23 µm Rdc (30.00;5.00) -18.78 µm Rdc (40.00;5.00) -26.94 µm Rdc (50.00;5.00) -32.68 µm Rdc (60.00;5.00) -39.04 µm Rdc (70.00;5.00) -46.26 µm Rdc (80.00;5.00) -53.01 µm Rdc (90.00;5.00) -65.68 µm Rdc (100.00;5.00) -93.00 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (20.82;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.87 % R Mr (-2.00;5.00) 6.63 % R Mr (-3.00;5.00) 7.60 % R Mr (-4.00;5.00) 8.70 % R Mr (-5.00;5.00) 10.01 % R Mr (-6.00;5.00) 11.23 % R Mr (-7.00;5.00) 12.86 % R Mr (-8.00;5.00) 14.86 % R Mr (-9.00;5.00) 16.44 % R Mr (-10.00;5.00) 17.67 % R Mr (-11.00;5.00) 18.64 % R Mr (-12.00;5.00) 19.63 % R Mr (-13.00;5.00) 21.22 % R Mr (-14.00;5.00) 22.85 % R Mr (-15.00;5.00) 24.11 % R Mr (-16.00;5.00) 25.46 % R Mr (-17.00;5.00) 27.02 % R Mr (-18.00;5.00) 28.86 % R Mr (-19.00;5.00) 30.20 % R Mr (-20.00;5.00) 31.50 % R Mr (-21.00;5.00) 32.65 % R Mr (-22.00;5.00) 33.74 % R Mr (-23.00;5.00) 34.99 % R Mr (-24.00;5.00) 36.22 % R Mr (-25.00;5.00) 37.51 % R Mr (-26.00;5.00) 38.74 % R Mr (-27.00;5.00) 40.06 % R Mr (-28.00;5.00) 41.42 % R Mr (-29.00;5.00) 43.45 % R Mr (-30.00;5.00) 45.41 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 79.90 µm Rz2 85.88 µm Rz3 109.34 µm Rz4 95.85 µm Rz5 90.46 µm Rz sigma 11.20 µm Rz min 79.90 µm Rz max 109.34 µm Rz mean 92.28 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 26.53 µm Rp2 32.81 µm Rp3 45.87 µm Rp4 40.93 µm Rp5 44.31 µm Rp sigma 8.20 µm Rp min 26.53 µm Rp max 45.87 µm Rp mean 38.09 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:37 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	36.83 μm	Rdc (0.00;5.00)	14.80 μm
R3z2	42.79 μm	Rdc (10.00;5.00)	-5.89 μm
R3z3	24.50 μm	Rdc (20.00;5.00)	-14.33 μm
R3z4	42.98 μm	Rdc (30.00;5.00)	-20.25 μm
R3z5	37.25 μm	Rdc (40.00;5.00)	-24.48 μm
R3z sigma	7.51 μm	Rdc (50.00;5.00)	-28.54 μm
R3z min	24.50 μm	Rdc (60.00;5.00)	-34.20 μm
R3z max	42.98 μm	Rdc (70.00;5.00)	-39.46 μm
R3z mean	36.87 μm	Rdc (80.00;5.00)	-46.13 μm
		Rdc (90.00;5.00)	-63.20 μm
		Rdc (100.00;5.00)	-94.54 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:37 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (14.80;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.51 %
R Mr (-2.00;5.00)	5.98 %
R Mr (-3.00;5.00)	6.69 %
R Mr (-4.00;5.00)	7.68 %
R Mr (-5.00;5.00)	8.81 %
R Mr (-6.00;5.00)	10.12 %
R Mr (-7.00;5.00)	11.36 %
R Mr (-8.00;5.00)	12.73 %
R Mr (-9.00;5.00)	13.60 %
R Mr (-10.00;5.00)	14.67 %
R Mr (-11.00;5.00)	15.57 %
R Mr (-12.00;5.00)	16.97 %
R Mr (-13.00;5.00)	18.24 %
R Mr (-14.00;5.00)	19.53 %
R Mr (-15.00;5.00)	20.74 %
R Mr (-16.00;5.00)	22.05 %
R Mr (-17.00;5.00)	23.66 %
R Mr (-18.00;5.00)	25.30 %
R Mr (-19.00;5.00)	27.53 %
R Mr (-20.00;5.00)	29.45 %
R Mr (-21.00;5.00)	31.85 %
R Mr (-22.00;5.00)	33.69 %
R Mr (-23.00;5.00)	36.05 %
R Mr (-24.00;5.00)	38.61 %
R Mr (-25.00;5.00)	41.63 %
R Mr (-26.00;5.00)	44.12 %
R Mr (-27.00;5.00)	46.98 %
R Mr (-28.00;5.00)	49.02 %
R Mr (-29.00;5.00)	50.68 %
R Mr (-30.00;5.00)	52.36 %

No Quick&Easy

6

10.16 m/min, peripherally milled, longitudinal direction:



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement

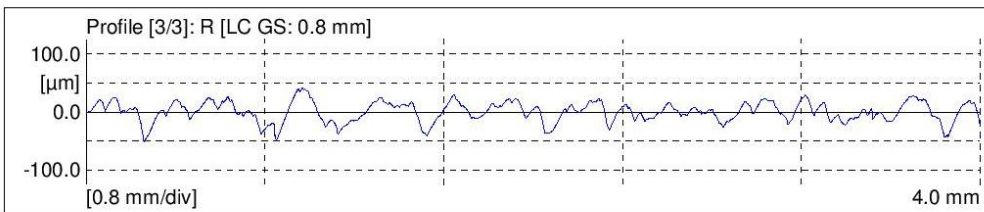
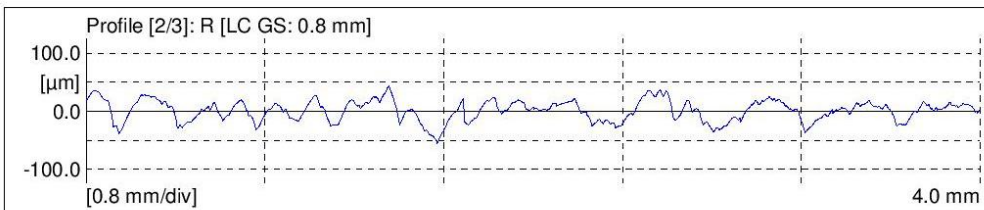
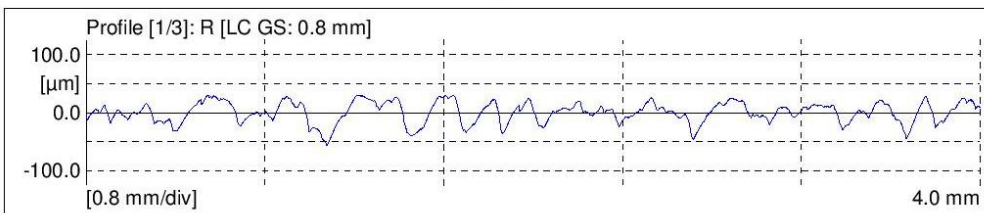


08/31/12, 10:53 AM

Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]



No Quick&Easy

1

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:53 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	14.150	17.594	72.396	88.05	88.05	49.832	88.05	28.53	43.87	44.249	254.40
2:	14.503	17.675	71.593	98.36	98.36	52.152	98.36	31.57	40.02	42.841	293.67
3:	13.572	16.897	71.640	90.97	90.97	46.099	93.52	29.92	41.72	39.755	235.90
Xb:	14.075	17.389	71.876	92.46	92.46	49.361	93.31	30.01	41.87	42.282	261.32
S:	0.470	0.428	0.451	5.31	5.31	3.054	5.16	1.53	1.93	2.299	29.50
Max:	14.503	17.675	72.396	98.36	98.36	52.152	98.36	31.57	43.87	44.249	293.67
Min:	13.572	16.897	71.593	88.05	88.05	46.099	88.05	28.53	40.02	39.755	235.90
R:	0.931	0.778	0.803	10.31	10.31	6.053	10.31	3.05	3.85	4.494	57.77

Profile [1/3]: R [LC GS: 0.8 mm]			Profile [1/3]: R [LC GS: 0.8 mm]		
Rz1	61.17	μm	Rp1	29.32	μm
Rz2	88.05	μm	Rp2	30.18	μm
Rz3	66.38	μm	Rp3	29.38	μm
Rz4	72.06	μm	Rp4	25.43	μm
Rz5	74.31	μm	Rp5	28.31	μm
Rz sigma	10.14	μm	Rp sigma	1.85	μm
Rz min	61.17	μm	Rp min	25.43	μm
Rz max	88.05	μm	Rp max	30.18	μm
Rz mean	72.40	μm	Rp mean	28.53	μm

Profile [1/3]: R [LC GS: 0.8 mm]			Profile [1/3]: R [LC GS: 0.8 mm]		
R3z1	35.44	μm	Rdc (0.00;5.00)	4.77	μm
R3z2	60.49	μm	Rdc (10.00;5.00)	-3.15	μm
R3z3	49.34	μm	Rdc (20.00;5.00)	-9.19	μm
R3z4	28.37	μm	Rdc (30.00;5.00)	-14.91	μm
R3z5	47.61	μm	Rdc (40.00;5.00)	-19.38	μm
R3z sigma	12.56	μm	Rdc (50.00;5.00)	-23.78	μm
R3z min	28.37	μm	Rdc (60.00;5.00)	-28.11	μm
R3z max	60.49	μm	Rdc (70.00;5.00)	-32.73	μm
R3z mean	44.25	μm	Rdc (80.00;5.00)	-39.98	μm
			Rdc (90.00;5.00)	-50.89	μm
			Rdc (100.00;5.00)	-83.28	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:53 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (4.77;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.53 % R Mr (-2.00;5.00) 8.34 % R Mr (-3.00;5.00) 9.82 % R Mr (-4.00;5.00) 11.60 % R Mr (-5.00;5.00) 13.55 % R Mr (-6.00;5.00) 15.81 % R Mr (-7.00;5.00) 17.10 % R Mr (-8.00;5.00) 18.59 % R Mr (-9.00;5.00) 19.78 % R Mr (-10.00;5.00) 21.08 % R Mr (-11.00;5.00) 22.56 % R Mr (-12.00;5.00) 24.34 % R Mr (-13.00;5.00) 26.47 % R Mr (-14.00;5.00) 28.36 % R Mr (-15.00;5.00) 30.12 % R Mr (-16.00;5.00) 32.61 % R Mr (-17.00;5.00) 35.20 % R Mr (-18.00;5.00) 37.33 % R Mr (-19.00;5.00) 39.16 % R Mr (-20.00;5.00) 41.33 % R Mr (-21.00;5.00) 43.86 % R Mr (-22.00;5.00) 46.16 % R Mr (-23.00;5.00) 47.99 % R Mr (-24.00;5.00) 50.50 % R Mr (-25.00;5.00) 53.11 % R Mr (-26.00;5.00) 55.75 % R Mr (-27.00;5.00) 57.99 % R Mr (-28.00;5.00) 59.79 % R Mr (-29.00;5.00) 61.75 % R Mr (-30.00;5.00) 63.78 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 74.37 µm Rz2 98.36 µm Rz3 56.54 µm Rz4 72.46 µm Rz5 56.23 µm Rz sigma 17.23 µm Rz min 56.23 µm Rz max 98.36 µm Rz mean 71.59 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 35.57 µm Rp2 43.13 µm Rp3 23.97 µm Rp4 36.27 µm Rp5 18.93 µm Rp sigma 9.87 µm Rp min 18.93 µm Rp max 43.13 µm Rp mean 31.57 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 48.42 µm R3z2 47.79 µm R3z3 46.31 µm R3z4 51.32 µm R3z5 20.38 µm R3z sigma 12.69 µm R3z min 20.38 µm R3z max 51.32 µm R3z mean 42.84 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:53 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 15.91 µm Rdc (10.00;5.00) -5.21 µm Rdc (20.00;5.00) -11.32 µm Rdc (30.00;5.00) -15.73 µm Rdc (40.00;5.00) -20.02 µm Rdc (50.00;5.00) -24.09 µm Rdc (60.00;5.00) -28.19 µm Rdc (70.00;5.00) -35.56 µm Rdc (80.00;5.00) -43.26 µm Rdc (90.00;5.00) -51.26 µm Rdc (100.00;5.00) -82.45 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (15.91;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.19 % R Mr (-2.00;5.00) 7.09 % R Mr (-3.00;5.00) 8.15 % R Mr (-4.00;5.00) 9.11 % R Mr (-5.00;5.00) 9.83 % R Mr (-6.00;5.00) 10.79 % R Mr (-7.00;5.00) 11.81 % R Mr (-8.00;5.00) 13.36 % R Mr (-9.00;5.00) 15.39 % R Mr (-10.00;5.00) 17.41 % R Mr (-11.00;5.00) 19.42 % R Mr (-12.00;5.00) 21.32 % R Mr (-13.00;5.00) 23.69 % R Mr (-14.00;5.00) 25.90 % R Mr (-15.00;5.00) 28.42 % R Mr (-16.00;5.00) 30.65 % R Mr (-17.00;5.00) 32.99 % R Mr (-18.00;5.00) 35.56 % R Mr (-19.00;5.00) 37.97 % R Mr (-20.00;5.00) 39.96 % R Mr (-21.00;5.00) 41.96 % R Mr (-22.00;5.00) 43.61 % R Mr (-23.00;5.00) 46.25 % R Mr (-24.00;5.00) 49.64 % R Mr (-25.00;5.00) 52.88 % R Mr (-26.00;5.00) 55.64 % R Mr (-27.00;5.00) 57.74 % R Mr (-28.00;5.00) 59.63 % R Mr (-29.00;5.00) 61.51 % R Mr (-30.00;5.00) 62.98 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 78.02 µm Rz2 90.97 µm Rz3 66.41 µm Rz4 50.06 µm Rz5 72.75 µm Rz sigma 15.07 µm Rz min 50.06 µm Rz max 90.97 µm Rz mean 71.64 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 26.00 µm Rp2 41.51 µm Rp3 29.59 µm Rp4 23.35 µm Rp5 29.15 µm Rp sigma 6.96 µm Rp min 23.35 µm Rp max 41.51 µm Rp mean 29.92 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:53 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	37.77 µm	Rdc (0.00;5.00)	17.58 µm
R3z2	55.99 µm	Rdc (10.00;5.00)	-3.34 µm
R3z3	33.85 µm	Rdc (20.00;5.00)	-8.40 µm
R3z4	32.99 µm	Rdc (30.00;5.00)	-13.54 µm
R3z5	38.18 µm	Rdc (40.00;5.00)	-18.21 µm
R3z sigma	9.36 µm	Rdc (50.00;5.00)	-22.42 µm
R3z min	32.99 µm	Rdc (60.00;5.00)	-26.82 µm
R3z max	55.99 µm	Rdc (70.00;5.00)	-31.70 µm
R3z mean	39.76 µm	Rdc (80.00;5.00)	-37.49 µm
		Rdc (90.00;5.00)	-46.65 µm
		Rdc (100.00;5.00)	-75.95 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:53 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (17.58;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.00 %
R Mr (-2.00;5.00)	7.22 %
R Mr (-3.00;5.00)	9.32 %
R Mr (-4.00;5.00)	11.14 %
R Mr (-5.00;5.00)	13.64 %
R Mr (-6.00;5.00)	15.17 %
R Mr (-7.00;5.00)	17.27 %
R Mr (-8.00;5.00)	19.13 %
R Mr (-9.00;5.00)	21.26 %
R Mr (-10.00;5.00)	23.07 %
R Mr (-11.00;5.00)	24.60 %
R Mr (-12.00;5.00)	26.90 %
R Mr (-13.00;5.00)	28.89 %
R Mr (-14.00;5.00)	30.88 %
R Mr (-15.00;5.00)	33.14 %
R Mr (-16.00;5.00)	35.47 %
R Mr (-17.00;5.00)	37.61 %
R Mr (-18.00;5.00)	39.63 %
R Mr (-19.00;5.00)	41.54 %
R Mr (-20.00;5.00)	43.91 %
R Mr (-21.00;5.00)	46.19 %
R Mr (-22.00;5.00)	48.72 %
R Mr (-23.00;5.00)	51.34 %
R Mr (-24.00;5.00)	53.41 %
R Mr (-25.00;5.00)	55.28 %
R Mr (-26.00;5.00)	58.12 %
R Mr (-27.00;5.00)	60.47 %
R Mr (-28.00;5.00)	62.84 %
R Mr (-29.00;5.00)	64.80 %
R Mr (-30.00;5.00)	66.73 %

No Quick&Easy

6

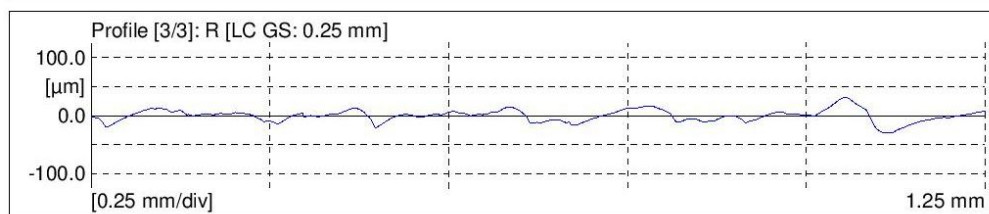
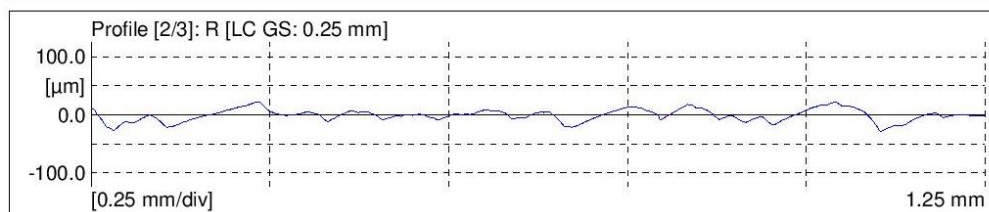
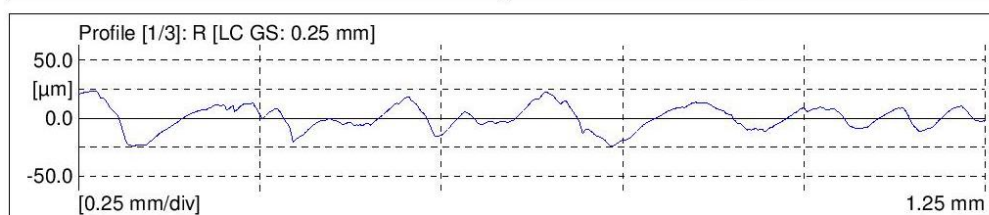
10.16 m/min, peripherally milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μ m
VB: ± 250 μ m
Vt: 0.10 mm/s
Points: 10500 [3]



No Quick&Easy

1

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	8.748	10.636	37.560	47.47	47.47	27.399	47.65	17.65	19.91	---	148.64 ...
2:	7.943	10.298	37.693	51.00	51.00	27.109	51.44	16.39	21.31	---	135.50 ...
3:	7.731	10.245	37.483	61.35	61.35	31.124	61.35	17.47	20.01	---	234.20 ...
Xb:	8.141	10.393	37.579	53.27	53.27	28.544	53.48	17.17	20.41	172.78	
S:	0.537	0.212	0.106	7.22	7.22	2.239	7.07	0.68	0.78	53.59	
Max:	8.748	10.636	37.693	61.35	61.35	31.124	61.35	17.65	21.31	234.20	
Min:	7.731	10.245	37.483	47.47	47.47	27.109	47.65	16.39	19.91	135.50	
R:	1.017	0.391	0.210	13.89	13.89	4.016	13.70	1.26	1.40	98.70	

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
Rz1	47.47	μm	Rp1	23.50	μm
Rz2	38.97	μm	Rp2	18.53	μm
Rz3	46.74	μm	Rp3	22.58	μm
Rz4	33.04	μm	Rp4	13.50	μm
Rz5	21.59	μm	Rp5	10.14	μm
Rz sigma	10.72	μm	Rp sigma	5.76	μm
Rz min	21.59	μm	Rp min	10.14	μm
Rz max	47.47	μm	Rp max	23.50	μm
Rz mean	37.56	μm	Rp mean	17.65	μm

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
R3z1	---	μm	Rdc (0.00;5.00)	6.52	μm
R3z2	---	μm	Rdc (10.00;5.00)	-4.10	μm
R3z3	---	μm	Rdc (20.00;5.00)	-7.83	μm
R3z4	---	μm	Rdc (30.00;5.00)	-9.97	μm
R3z5	---	μm	Rdc (40.00;5.00)	-12.84	μm
R3z sigma	---	μm	Rdc (50.00;5.00)	-16.73	μm
R3z min	---	μm	Rdc (60.00;5.00)	-19.82	μm
R3z max	---	μm	Rdc (70.00;5.00)	-22.21	μm
R3z mean	---	μm	Rdc (80.00;5.00)	-25.91	μm
			Rdc (90.00;5.00)	-31.53	μm
			Rdc (100.00;5.00)	-41.14	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (6.52;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.16 % R Mr (-2.00;5.00) 6.88 % R Mr (-3.00;5.00) 7.74 % R Mr (-4.00;5.00) 9.75 % R Mr (-5.00;5.00) 12.91 % R Mr (-6.00;5.00) 14.91 % R Mr (-7.00;5.00) 17.11 % R Mr (-8.00;5.00) 20.62 % R Mr (-9.00;5.00) 25.17 % R Mr (-10.00;5.00) 30.27 % R Mr (-11.00;5.00) 34.24 % R Mr (-12.00;5.00) 37.48 % R Mr (-13.00;5.00) 40.39 % R Mr (-14.00;5.00) 43.27 % R Mr (-15.00;5.00) 45.93 % R Mr (-16.00;5.00) 48.42 % R Mr (-17.00;5.00) 50.66 % R Mr (-18.00;5.00) 53.25 % R Mr (-19.00;5.00) 56.69 % R Mr (-20.00;5.00) 60.81 % R Mr (-21.00;5.00) 65.27 % R Mr (-22.00;5.00) 69.13 % R Mr (-23.00;5.00) 72.97 % R Mr (-24.00;5.00) 75.37 % R Mr (-25.00;5.00) 77.28 % R Mr (-26.00;5.00) 80.30 % R Mr (-27.00;5.00) 83.69 % R Mr (-28.00;5.00) 85.91 % R Mr (-29.00;5.00) 87.65 % R Mr (-30.00;5.00) 88.69 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 49.66 µm Rz2 18.43 µm Rz3 34.31 µm Rz4 35.06 µm Rz5 51.00 µm Rz sigma 13.32 µm Rz min 18.43 µm Rz max 51.00 µm Rz mean 37.69 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 22.53 µm Rp2 6.82 µm Rp3 12.75 µm Rp4 17.75 µm Rp5 22.08 µm Rp sigma 6.65 µm Rp min 6.82 µm Rp max 22.53 µm Rp mean 16.39 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 6.35 µm Rdc (10.00;5.00) -3.32 µm Rdc (20.00;5.00) -9.29 µm Rdc (30.00;5.00) -12.20 µm Rdc (40.00;5.00) -15.06 µm Rdc (50.00;5.00) -16.74 µm Rdc (60.00;5.00) -18.70 µm Rdc (70.00;5.00) -21.49 µm Rdc (80.00;5.00) -24.92 µm Rdc (90.00;5.00) -31.93 µm Rdc (100.00;5.00) -45.09 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (6.35;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.38 % R Mr (-2.00;5.00) 7.56 % R Mr (-3.00;5.00) 9.11 % R Mr (-4.00;5.00) 11.18 % R Mr (-5.00;5.00) 13.32 % R Mr (-6.00;5.00) 14.75 % R Mr (-7.00;5.00) 15.87 % R Mr (-8.00;5.00) 17.57 % R Mr (-9.00;5.00) 19.35 % R Mr (-10.00;5.00) 22.54 % R Mr (-11.00;5.00) 25.25 % R Mr (-12.00;5.00) 29.32 % R Mr (-13.00;5.00) 32.42 % R Mr (-14.00;5.00) 35.69 % R Mr (-15.00;5.00) 39.59 % R Mr (-16.00;5.00) 44.72 % R Mr (-17.00;5.00) 51.70 % R Mr (-18.00;5.00) 56.34 % R Mr (-19.00;5.00) 61.07 % R Mr (-20.00;5.00) 64.45 % R Mr (-21.00;5.00) 68.26 % R Mr (-22.00;5.00) 72.09 % R Mr (-23.00;5.00) 74.88 % R Mr (-24.00;5.00) 77.60 % R Mr (-25.00;5.00) 80.29 % R Mr (-26.00;5.00) 81.73 % R Mr (-27.00;5.00) 83.12 % R Mr (-28.00;5.00) 84.74 % R Mr (-29.00;5.00) 86.53 % R Mr (-30.00;5.00) 88.28 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 31.85 µm Rz2 33.74 µm Rz3 31.21 µm Rz4 29.26 µm Rz5 61.35 µm Rz sigma 13.44 µm Rz min 29.26 µm Rz max 61.35 µm Rz mean 37.48 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 12.14 µm Rp2 12.38 µm Rp3 14.34 µm Rp4 16.70 µm Rp5 31.79 µm Rp sigma 8.21 µm Rp min 12.14 µm Rp max 31.79 µm Rp mean 17.47 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 17.14 µm
R3z2	Rdc (10.00;5.00) -2.67 µm
R3z3	Rdc (20.00;5.00) -7.81 µm
R3z4	Rdc (30.00;5.00) -10.91 µm
R3z5	Rdc (40.00;5.00) -12.45 µm
R3z sigma	Rdc (50.00;5.00) -14.05 µm
R3z min	Rdc (60.00;5.00) -16.21 µm
R3z max	Rdc (70.00;5.00) -19.78 µm
R3z mean	Rdc (80.00;5.00) -23.69 µm
	Rdc (90.00;5.00) -27.05 µm
	Rdc (100.00;5.00) -44.22 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:25 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (17.14;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.58 %
R Mr (-2.00;5.00)	7.98 %
R Mr (-3.00;5.00)	11.74 %
R Mr (-4.00;5.00)	13.61 %
R Mr (-5.00;5.00)	14.94 %
R Mr (-6.00;5.00)	16.45 %
R Mr (-7.00;5.00)	17.95 %
R Mr (-8.00;5.00)	20.54 %
R Mr (-9.00;5.00)	23.71 %
R Mr (-10.00;5.00)	26.70 %
R Mr (-11.00;5.00)	30.40 %
R Mr (-12.00;5.00)	36.19 %
R Mr (-13.00;5.00)	44.14 %
R Mr (-14.00;5.00)	49.70 %
R Mr (-15.00;5.00)	54.63 %
R Mr (-16.00;5.00)	59.29 %
R Mr (-17.00;5.00)	62.57 %
R Mr (-18.00;5.00)	65.70 %
R Mr (-19.00;5.00)	68.58 %
R Mr (-20.00;5.00)	70.72 %
R Mr (-21.00;5.00)	73.06 %
R Mr (-22.00;5.00)	75.02 %
R Mr (-23.00;5.00)	78.13 %
R Mr (-24.00;5.00)	80.85 %
R Mr (-25.00;5.00)	84.04 %
R Mr (-26.00;5.00)	86.75 %
R Mr (-27.00;5.00)	89.70 %
R Mr (-28.00;5.00)	91.32 %
R Mr (-29.00;5.00)	92.32 %
R Mr (-30.00;5.00)	93.26 %

No Quick&Easy

6

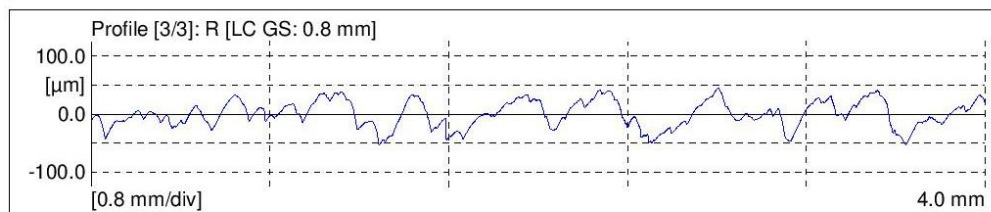
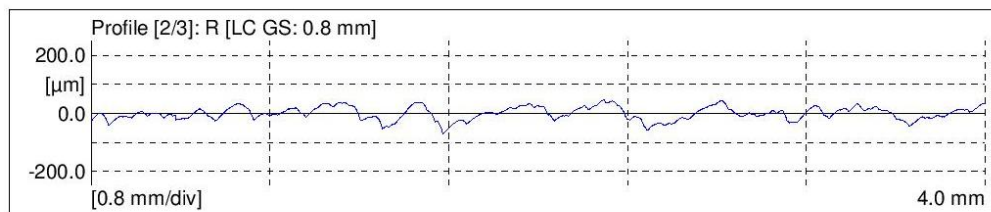
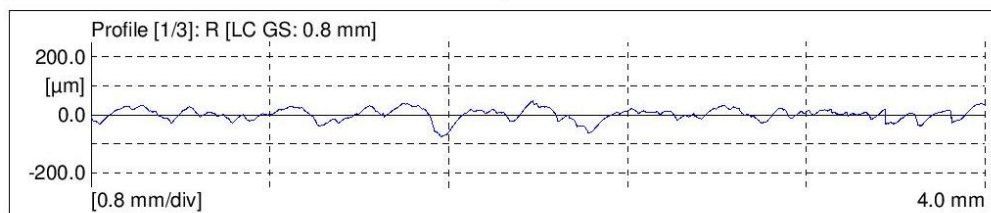
10.16 m/min, face milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μ m
VB: $\pm$ 250 μ m
Vt: 0.50 mm/s
Points: 33600 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	16.447	21.125	86.350	115.02	115.02	54.198	124.20	38.00	48.35	46.814	318.46
2:	18.179	22.269	92.970	109.49	109.49	60.360	117.33	39.83	53.14	37.129	308.36
3:	18.582	22.486	88.509	94.66	94.66	56.677	98.31	39.59	48.91	47.094	310.55
Xb:	17.736	21.960	89.276	106.39	106.39	57.078	113.28	39.14	50.13	43.679	312.46
S:	1.134	0.731	3.376	10.53	10.53	3.101	13.41	1.00	2.62	5.674	5.31
Max:	18.582	22.486	92.970	115.02	115.02	60.360	124.20	39.83	53.14	47.094	318.46
Min:	16.447	21.125	86.350	94.66	94.66	54.198	98.31	38.00	48.35	37.129	308.36
R:	2.135	1.361	6.620	20.35	20.35	6.162	25.89	1.83	4.79	9.965	10.09

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	65.57 μm	Rp1	32.83 μm
Rz2	115.02 μm	Rp2	38.87 μm
Rz3	112.17 μm	Rp3	48.05 μm
Rz4	61.86 μm	Rp4	32.16 μm
Rz5	77.14 μm	Rp5	38.11 μm
Rz sigma	25.52 μm	Rp sigma	6.37 μm
Rz min	61.86 μm	Rp min	32.16 μm
Rz max	115.02 μm	Rp max	48.05 μm
Rz mean	86.35 μm	Rp mean	38.00 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	55.67 μm	Rdc (0.00;5.00)	18.01 μm
R3z2	57.80 μm	Rdc (10.00;5.00)	-3.88 μm
R3z3	39.93 μm	Rdc (20.00;5.00)	-11.99 μm
R3z4	37.24 μm	Rdc (30.00;5.00)	-17.72 μm
R3z5	43.43 μm	Rdc (40.00;5.00)	-22.59 μm
R3z sigma	9.35 μm	Rdc (50.00;5.00)	-26.93 μm
R3z min	37.24 μm	Rdc (60.00;5.00)	-31.42 μm
R3z max	57.80 μm	Rdc (70.00;5.00)	-38.03 μm
R3z mean	46.81 μm	Rdc (80.00;5.00)	-46.25 μm
		Rdc (90.00;5.00)	-56.68 μm
		Rdc (100.00;5.00)	-106.20 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (18.01;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.26 % R Mr (-2.00;5.00) 7.30 % R Mr (-3.00;5.00) 8.79 % R Mr (-4.00;5.00) 10.12 % R Mr (-5.00;5.00) 11.20 % R Mr (-6.00;5.00) 12.55 % R Mr (-7.00;5.00) 13.83 % R Mr (-8.00;5.00) 15.08 % R Mr (-9.00;5.00) 16.20 % R Mr (-10.00;5.00) 17.51 % R Mr (-11.00;5.00) 18.64 % R Mr (-12.00;5.00) 20.01 % R Mr (-13.00;5.00) 21.61 % R Mr (-14.00;5.00) 23.21 % R Mr (-15.00;5.00) 24.82 % R Mr (-16.00;5.00) 26.59 % R Mr (-17.00;5.00) 28.72 % R Mr (-18.00;5.00) 30.41 % R Mr (-19.00;5.00) 32.30 % R Mr (-20.00;5.00) 34.30 % R Mr (-21.00;5.00) 36.15 % R Mr (-22.00;5.00) 38.37 % R Mr (-23.00;5.00) 41.08 % R Mr (-24.00;5.00) 43.61 % R Mr (-25.00;5.00) 45.82 % R Mr (-26.00;5.00) 47.49 % R Mr (-27.00;5.00) 50.22 % R Mr (-28.00;5.00) 52.47 % R Mr (-29.00;5.00) 54.81 % R Mr (-30.00;5.00) 57.18 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 76.26 µm Rz2 109.49 µm Rz3 96.83 µm Rz4 102.80 µm Rz5 79.47 µm Rz sigma 14.54 µm Rz min 76.26 µm Rz max 109.49 µm Rz mean 92.97 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 34.43 µm Rp2 38.59 µm Rp3 46.42 µm Rp4 44.52 µm Rp5 35.21 µm Rp sigma 5.42 µm Rp min 34.43 µm Rp max 46.42 µm Rp mean 39.83 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 32.40 µm R3z2 59.42 µm R3z3 31.89 µm R3z4 43.16 µm R3z5 18.78 µm R3z sigma 15.17 µm R3z min 18.78 µm R3z max 59.42 µm R3z mean 37.13 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 11.53 µm Rdc (10.00;5.00) -5.88 µm Rdc (20.00;5.00) -14.43 µm Rdc (30.00;5.00) -22.07 µm Rdc (40.00;5.00) -29.26 µm Rdc (50.00;5.00) -35.69 µm Rdc (60.00;5.00) -41.98 µm Rdc (70.00;5.00) -46.93 µm Rdc (80.00;5.00) -53.80 µm Rdc (90.00;5.00) -64.99 µm Rdc (100.00;5.00) -105.80 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (11.53;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.91 % R Mr (-2.00;5.00) 6.67 % R Mr (-3.00;5.00) 7.50 % R Mr (-4.00;5.00) 8.49 % R Mr (-5.00;5.00) 9.44 % R Mr (-6.00;5.00) 10.09 % R Mr (-7.00;5.00) 10.88 % R Mr (-8.00;5.00) 11.95 % R Mr (-9.00;5.00) 13.87 % R Mr (-10.00;5.00) 14.97 % R Mr (-11.00;5.00) 16.21 % R Mr (-12.00;5.00) 17.42 % R Mr (-13.00;5.00) 18.60 % R Mr (-14.00;5.00) 19.54 % R Mr (-15.00;5.00) 20.51 % R Mr (-16.00;5.00) 21.45 % R Mr (-17.00;5.00) 22.58 % R Mr (-18.00;5.00) 24.07 % R Mr (-19.00;5.00) 25.73 % R Mr (-20.00;5.00) 27.07 % R Mr (-21.00;5.00) 28.54 % R Mr (-22.00;5.00) 29.82 % R Mr (-23.00;5.00) 31.73 % R Mr (-24.00;5.00) 33.38 % R Mr (-25.00;5.00) 34.95 % R Mr (-26.00;5.00) 36.25 % R Mr (-27.00;5.00) 37.36 % R Mr (-28.00;5.00) 38.31 % R Mr (-29.00;5.00) 39.57 % R Mr (-30.00;5.00) 40.86 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 76.20 µm Rz2 92.43 µm Rz3 84.92 µm Rz4 94.66 µm Rz5 94.33 µm Rz sigma 7.93 µm Rz min 76.20 µm Rz max 94.66 µm Rz mean 88.51 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 33.06 µm Rp2 38.42 µm Rp3 41.60 µm Rp4 44.30 µm Rp5 40.58 µm Rp sigma 4.22 µm Rp min 33.06 µm Rp max 44.30 µm Rp mean 39.59 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	36.03 μm	Rdc (0.00;5.00)	9.81 μm
R3z2	65.08 μm	Rdc (10.00;5.00)	-4.51 μm
R3z3	50.97 μm	Rdc (20.00;5.00)	-12.09 μm
R3z4	41.81 μm	Rdc (30.00;5.00)	-20.52 μm
R3z5	41.57 μm	Rdc (40.00;5.00)	-29.22 μm
R3z sigma	11.39 μm	Rdc (50.00;5.00)	-36.10 μm
R3z min	36.03 μm	Rdc (60.00;5.00)	-41.12 μm
R3z max	65.08 μm	Rdc (70.00;5.00)	-46.81 μm
R3z mean	47.09 μm	Rdc (80.00;5.00)	-53.87 μm
		Rdc (90.00;5.00)	-66.99 μm
		Rdc (100.00;5.00)	-88.50 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 10:42 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (9.81;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.77 %
R Mr (-2.00;5.00)	6.88 %
R Mr (-3.00;5.00)	7.88 %
R Mr (-4.00;5.00)	9.31 %
R Mr (-5.00;5.00)	10.73 %
R Mr (-6.00;5.00)	11.94 %
R Mr (-7.00;5.00)	13.30 %
R Mr (-8.00;5.00)	14.32 %
R Mr (-9.00;5.00)	15.64 %
R Mr (-10.00;5.00)	17.25 %
R Mr (-11.00;5.00)	18.79 %
R Mr (-12.00;5.00)	19.91 %
R Mr (-13.00;5.00)	20.92 %
R Mr (-14.00;5.00)	22.10 %
R Mr (-15.00;5.00)	23.43 %
R Mr (-16.00;5.00)	24.54 %
R Mr (-17.00;5.00)	25.58 %
R Mr (-18.00;5.00)	26.84 %
R Mr (-19.00;5.00)	27.86 %
R Mr (-20.00;5.00)	29.41 %
R Mr (-21.00;5.00)	30.57 %
R Mr (-22.00;5.00)	31.86 %
R Mr (-23.00;5.00)	32.97 %
R Mr (-24.00;5.00)	34.15 %
R Mr (-25.00;5.00)	35.38 %
R Mr (-26.00;5.00)	36.55 %
R Mr (-27.00;5.00)	37.67 %
R Mr (-28.00;5.00)	38.67 %
R Mr (-29.00;5.00)	39.72 %
R Mr (-30.00;5.00)	40.83 %

No Quick&Easy

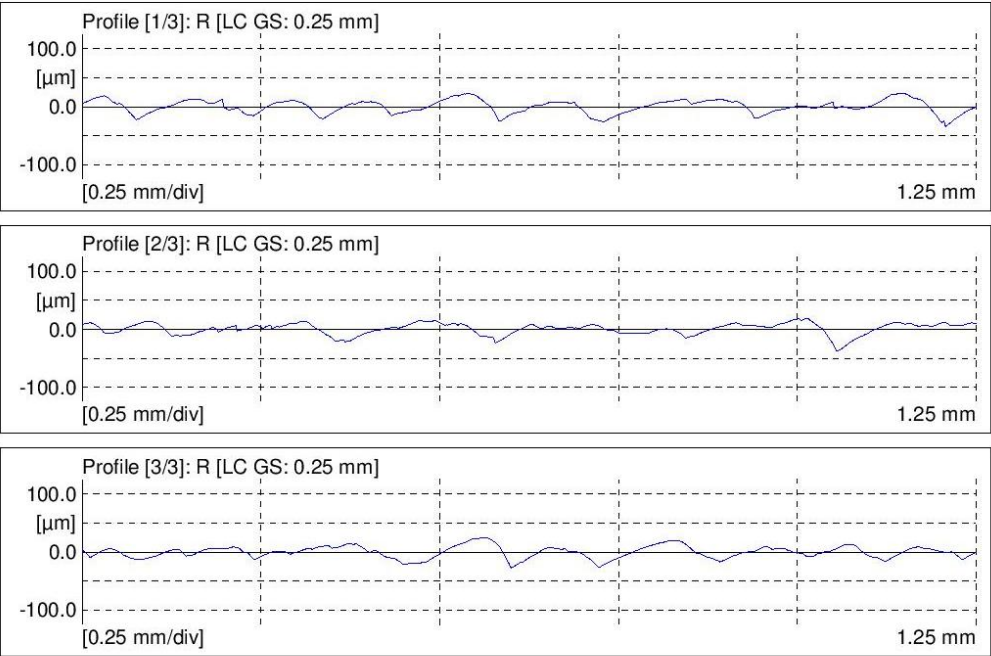
6

10.16 m/min, face milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/31/12, 11:06 AM
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 1.75 mm [N=5] Ls: 2.5 μ m VB: $\pm$ 250 μ m Vt: 0.10 mm/s Points: 10500 [3]
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:06 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	9.475	11.588	42.027	57.64	57.64	33.990	57.64	17.47	24.56	---	151.83 ...
2:	7.966	9.930	37.554	56.85	56.85	29.246	56.85	15.41	22.14	---	210.30 ...
3:	8.150	10.273	35.236	51.77	51.77	26.458	51.77	16.15	19.08	---	124.67 ...
Xb:	8.530	10.597	38.272	55.42	55.42	29.898	55.42	16.34	21.93	162.27	
S:	0.823	0.875	3.452	3.19	3.19	3.808	3.19	1.04	2.74	43.76	
Max:	9.475	11.588	42.027	57.64	57.64	33.990	57.64	17.47	24.56	210.30	
Min:	7.966	9.930	35.236	51.77	51.77	26.458	51.77	15.41	19.08	124.67	
R:	1.509	1.658	6.791	5.87	5.87	7.532	5.87	2.06	5.47	85.63	

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	40.75 μm	Rp1	18.59 μm
Rz2	31.38 μm	Rp2	10.58 μm
Rz3	48.30 μm	Rp3	22.38 μm
Rz4	32.05 μm	Rp4	12.51 μm
Rz5	57.64 μm	Rp5	23.28 μm
Rz sigma	11.15 μm	Rp sigma	5.73 μm
Rz min	31.38 μm	Rp min	10.58 μm
Rz max	57.64 μm	Rp max	23.28 μm
Rz mean	42.03 μm	Rp mean	17.47 μm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	---	Rdc (0.00;5.00)	4.84 μm
R3z2	---	Rdc (10.00;5.00)	-5.47 μm
R3z3	---	Rdc (20.00;5.00)	-8.59 μm
R3z4	---	Rdc (30.00;5.00)	-10.93 μm
R3z5	---	Rdc (40.00;5.00)	-13.35 μm
R3z sigma	---	Rdc (50.00;5.00)	-17.43 μm
R3z min	---	Rdc (60.00;5.00)	-20.54 μm
R3z max	---	Rdc (70.00;5.00)	-23.95 μm
R3z mean	---	Rdc (80.00;5.00)	-28.71 μm
		Rdc (90.00;5.00)	-34.99 μm
		Rdc (100.00;5.00)	-52.80 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:06 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (4.84;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.02 % R Mr (-2.00;5.00) 6.76 % R Mr (-3.00;5.00) 7.52 % R Mr (-4.00;5.00) 8.52 % R Mr (-5.00;5.00) 9.30 % R Mr (-6.00;5.00) 11.43 % R Mr (-7.00;5.00) 14.95 % R Mr (-8.00;5.00) 17.71 % R Mr (-9.00;5.00) 21.07 % R Mr (-10.00;5.00) 24.46 % R Mr (-11.00;5.00) 30.26 % R Mr (-12.00;5.00) 35.06 % R Mr (-13.00;5.00) 38.74 % R Mr (-14.00;5.00) 42.23 % R Mr (-15.00;5.00) 44.40 % R Mr (-16.00;5.00) 46.27 % R Mr (-17.00;5.00) 48.92 % R Mr (-18.00;5.00) 51.64 % R Mr (-19.00;5.00) 55.18 % R Mr (-20.00;5.00) 58.22 % R Mr (-21.00;5.00) 61.94 % R Mr (-22.00;5.00) 65.38 % R Mr (-23.00;5.00) 68.01 % R Mr (-24.00;5.00) 70.16 % R Mr (-25.00;5.00) 72.82 % R Mr (-26.00;5.00) 74.79 % R Mr (-27.00;5.00) 76.67 % R Mr (-28.00;5.00) 78.59 % R Mr (-29.00;5.00) 80.55 % R Mr (-30.00;5.00) 82.36 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 26.06 µm Rz2 36.75 µm Rz3 34.88 µm Rz4 33.23 µm Rz5 56.85 µm Rz sigma 11.52 µm Rz min 26.06 µm Rz max 56.85 µm Rz mean 37.55 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 13.95 µm Rp2 15.11 µm Rp3 11.44 µm Rp4 17.62 µm Rp5 18.92 µm Rp sigma 2.96 µm Rp min 11.44 µm Rp max 18.92 µm Rp mean 15.41 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:06 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 5.33 µm Rdc (10.00;5.00) -2.28 µm Rdc (20.00;5.00) -4.52 µm Rdc (30.00;5.00) -6.68 µm Rdc (40.00;5.00) -8.51 µm Rdc (50.00;5.00) -10.89 µm Rdc (60.00;5.00) -12.99 µm Rdc (70.00;5.00) -16.51 µm Rdc (80.00;5.00) -20.75 µm Rdc (90.00;5.00) -26.11 µm Rdc (100.00;5.00) -51.52 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (5.33;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 7.20 % R Mr (-2.00;5.00) 9.32 % R Mr (-3.00;5.00) 13.21 % R Mr (-4.00;5.00) 17.89 % R Mr (-5.00;5.00) 21.88 % R Mr (-6.00;5.00) 25.50 % R Mr (-7.00;5.00) 31.78 % R Mr (-8.00;5.00) 37.23 % R Mr (-9.00;5.00) 42.18 % R Mr (-10.00;5.00) 46.19 % R Mr (-11.00;5.00) 51.09 % R Mr (-12.00;5.00) 56.23 % R Mr (-13.00;5.00) 60.07 % R Mr (-14.00;5.00) 62.95 % R Mr (-15.00;5.00) 66.55 % R Mr (-16.00;5.00) 68.98 % R Mr (-17.00;5.00) 71.00 % R Mr (-18.00;5.00) 72.86 % R Mr (-19.00;5.00) 74.78 % R Mr (-20.00;5.00) 77.09 % R Mr (-21.00;5.00) 81.62 % R Mr (-22.00;5.00) 83.21 % R Mr (-23.00;5.00) 84.18 % R Mr (-24.00;5.00) 85.95 % R Mr (-25.00;5.00) 88.07 % R Mr (-26.00;5.00) 89.71 % R Mr (-27.00;5.00) 91.40 % R Mr (-28.00;5.00) 92.33 % R Mr (-29.00;5.00) 93.07 % R Mr (-30.00;5.00) 93.73 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 21.54 µm Rz2 36.27 µm Rz3 51.77 µm Rz4 37.18 µm Rz5 29.42 µm Rz sigma 11.18 µm Rz min 21.54 µm Rz max 51.77 µm Rz mean 35.24 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 8.63 µm Rp2 14.71 µm Rp3 24.65 µm Rp4 20.04 µm Rp5 12.73 µm Rp sigma 6.28 µm Rp min 8.63 µm Rp max 24.65 µm Rp mean 16.15 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:06 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 7.33 µm
R3z2	Rdc (10.00;5.00) -4.97 µm
R3z3	Rdc (20.00;5.00) -9.91 µm
R3z4	Rdc (30.00;5.00) -11.96 µm
R3z5	Rdc (40.00;5.00) -14.69 µm
R3z sigma	Rdc (50.00;5.00) -17.07 µm
R3z min	Rdc (60.00;5.00) -19.58 µm
R3z max	Rdc (70.00;5.00) -23.02 µm
R3z mean	Rdc (80.00;5.00) -26.70 µm
	Rdc (90.00;5.00) -31.07 µm
	Rdc (100.00;5.00) -44.44 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/31/12, 11:06 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (7.33;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.80 %
R Mr (-2.00;5.00)	6.50 %
R Mr (-3.00;5.00)	7.39 %
R Mr (-4.00;5.00)	8.50 %
R Mr (-5.00;5.00)	10.24 %
R Mr (-6.00;5.00)	11.92 %
R Mr (-7.00;5.00)	13.38 %
R Mr (-8.00;5.00)	14.66 %
R Mr (-9.00;5.00)	17.40 %
R Mr (-10.00;5.00)	20.34 %
R Mr (-11.00;5.00)	24.66 %
R Mr (-12.00;5.00)	30.15 %
R Mr (-13.00;5.00)	34.62 %
R Mr (-14.00;5.00)	37.82 %
R Mr (-15.00;5.00)	40.92 %
R Mr (-16.00;5.00)	44.90 %
R Mr (-17.00;5.00)	49.49 %
R Mr (-18.00;5.00)	54.64 %
R Mr (-19.00;5.00)	58.26 %
R Mr (-20.00;5.00)	61.75 %
R Mr (-21.00;5.00)	64.75 %
R Mr (-22.00;5.00)	67.16 %
R Mr (-23.00;5.00)	69.95 %
R Mr (-24.00;5.00)	72.71 %
R Mr (-25.00;5.00)	75.35 %
R Mr (-26.00;5.00)	78.12 %
R Mr (-27.00;5.00)	80.80 %
R Mr (-28.00;5.00)	83.34 %
R Mr (-29.00;5.00)	85.55 %
R Mr (-30.00;5.00)	88.59 %

No Quick&Easy

6

2.) 6000 rpm

2.54 m/min, peripherally milled, longitudinal direction:

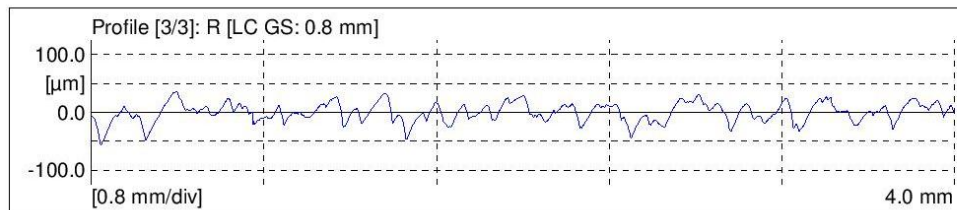
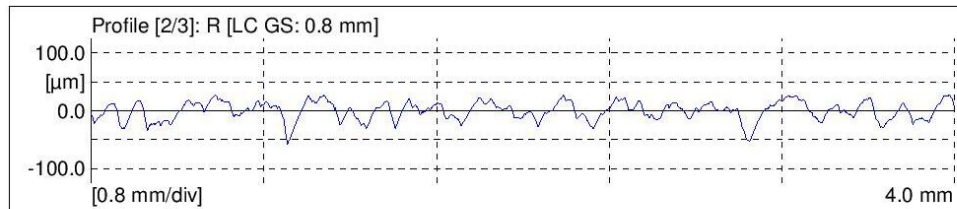
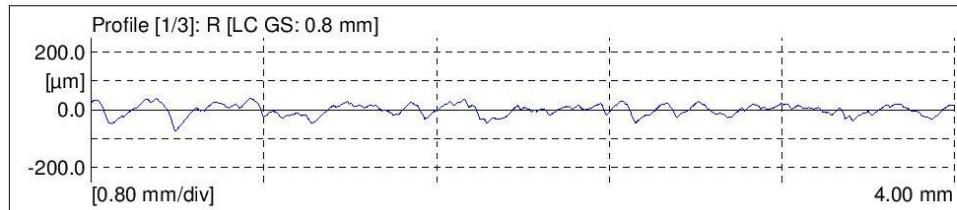
 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [9.2 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]

	Ra μm	Rz μm	Rt μm	Rp μm
1:	16.196	81.043	113.59	31.29
2:	12.701	67.204	85.48	26.13
3:	13.013	72.818	93.68	31.07
Xb:	13.970	73.689	97.58	29.50
S:	1.934	6.961	14.45	2.92
Max:	16.196	81.043	113.59	31.29
Min:	12.701	67.204	85.48	26.13
R:	3.495	13.839	28.11	5.16

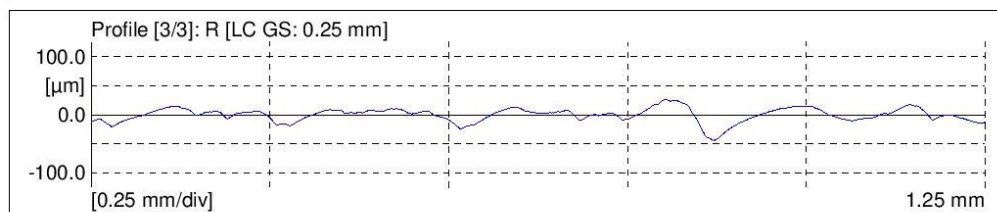
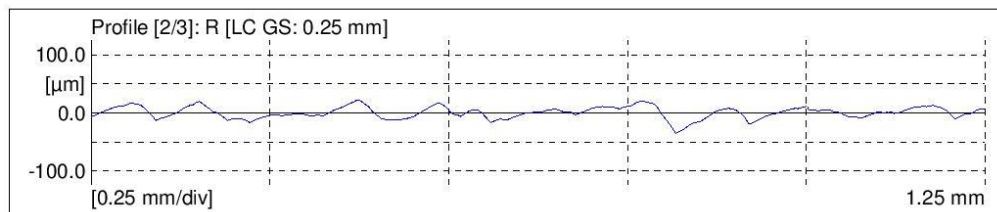
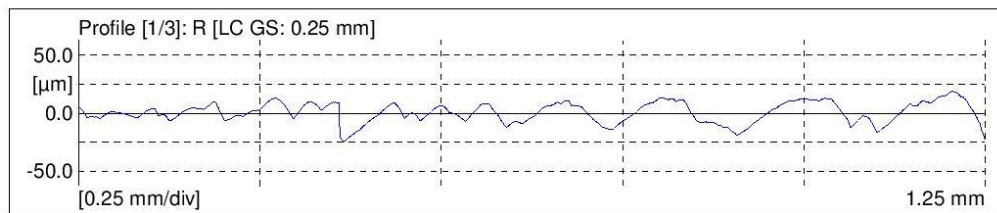


2.54 m/min, face milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/30/12, 10:25 AM
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 1.75 mm [N=5] Ls: 2.5 μ m VB: $\pm$ 250 μ m Vt: 0.10 mm/s Points: 10500 [3]
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:25 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm ...
1:	6.972	8.476	30.545	41.29	41.29	20.632	43.31	13.18	17.37	---	103.90 ...
2:	7.929	9.938	35.108	55.43	55.43	27.983	57.02	17.08	18.03	---	135.17 ...
3:	8.949	11.789	41.176	70.61	70.61	31.757	70.61	16.25	24.92	---	172.75 ...
Xb:	7.950	10.068	35.609	55.78	55.78	26.790	56.98	15.50	20.10	137.27	
S:	0.988	1.660	5.333	14.66	14.66	5.658	13.65	2.06	4.18	34.47	
Max:	8.949	11.789	41.176	70.61	70.61	31.757	70.61	17.08	24.92	172.75	
Min:	6.972	8.476	30.545	41.29	41.29	20.632	43.31	13.18	17.37	103.90	
R:	1.977	3.312	10.631	29.32	29.32	11.125	27.31	3.90	7.55	68.85	

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	16.26 µm	Rp1	9.71 µm
Rz2	37.33 µm	Rp2	12.91 µm
Rz3	25.32 µm	Rp3	10.98 µm
Rz4	32.52 µm	Rp4	13.40 µm
Rz5	41.29 µm	Rp5	18.88 µm
Rz sigma	9.96 µm	Rp sigma	3.52 µm
Rz min	16.26 µm	Rp min	9.71 µm
Rz max	41.29 µm	Rp max	18.88 µm
Rz mean	30.54 µm	Rp mean	13.18 µm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	---	Rdc (0.00;5.00)	6.40 µm
R3z2	---	Rdc (10.00;5.00)	-1.20 µm
R3z3	---	Rdc (20.00;5.00)	-3.83 µm
R3z4	---	Rdc (30.00;5.00)	-6.38 µm
R3z5	---	Rdc (40.00;5.00)	-9.01 µm
R3z sigma	---	Rdc (50.00;5.00)	-11.90 µm
R3z min	---	Rdc (60.00;5.00)	-14.25 µm
R3z max	---	Rdc (70.00;5.00)	-16.10 µm
R3z mean	---	Rdc (80.00;5.00)	-19.20 µm
		Rdc (90.00;5.00)	-23.81 µm
		Rdc (100.00;5.00)	-36.91 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:25 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (6.40;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 9.39 % R Mr (-2.00;5.00) 12.74 % R Mr (-3.00;5.00) 15.80 % R Mr (-4.00;5.00) 20.47 % R Mr (-5.00;5.00) 24.38 % R Mr (-6.00;5.00) 27.67 % R Mr (-7.00;5.00) 32.45 % R Mr (-8.00;5.00) 35.32 % R Mr (-9.00;5.00) 39.93 % R Mr (-10.00;5.00) 43.70 % R Mr (-11.00;5.00) 47.06 % R Mr (-12.00;5.00) 50.40 % R Mr (-13.00;5.00) 54.93 % R Mr (-14.00;5.00) 58.95 % R Mr (-15.00;5.00) 63.99 % R Mr (-16.00;5.00) 69.51 % R Mr (-17.00;5.00) 73.46 % R Mr (-18.00;5.00) 76.31 % R Mr (-19.00;5.00) 79.46 % R Mr (-20.00;5.00) 81.93 % R Mr (-21.00;5.00) 85.38 % R Mr (-22.00;5.00) 87.37 % R Mr (-23.00;5.00) 88.89 % R Mr (-24.00;5.00) 90.35 % R Mr (-25.00;5.00) 92.45 % R Mr (-26.00;5.00) 93.80 % R Mr (-27.00;5.00) 95.23 % R Mr (-28.00;5.00) 96.04 % R Mr (-29.00;5.00) 96.84 % R Mr (-30.00;5.00) 97.62 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 36.04 µm Rz2 34.20 µm Rz3 27.16 µm Rz4 55.43 µm Rz5 22.70 µm Rz sigma 12.57 µm Rz min 22.70 µm Rz max 55.43 µm Rz mean 35.11 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 19.45 µm Rp2 21.90 µm Rp3 11.00 µm Rp4 20.31 µm Rp5 12.74 µm Rp sigma 4.87 µm Rp min 11.00 µm Rp max 21.90 µm Rp mean 17.08 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:25 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 5.64 µm Rdc (10.00;5.00) -3.58 µm Rdc (20.00;5.00) -6.66 µm Rdc (30.00;5.00) -10.29 µm Rdc (40.00;5.00) -12.78 µm Rdc (50.00;5.00) -15.38 µm Rdc (60.00;5.00) -18.14 µm Rdc (70.00;5.00) -20.60 µm Rdc (80.00;5.00) -24.01 µm Rdc (90.00;5.00) -28.10 µm Rdc (100.00;5.00) -51.38 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (5.64;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.45 % R Mr (-2.00;5.00) 7.82 % R Mr (-3.00;5.00) 8.96 % R Mr (-4.00;5.00) 10.87 % R Mr (-5.00;5.00) 13.46 % R Mr (-6.00;5.00) 18.30 % R Mr (-7.00;5.00) 20.73 % R Mr (-8.00;5.00) 22.84 % R Mr (-9.00;5.00) 25.83 % R Mr (-10.00;5.00) 28.92 % R Mr (-11.00;5.00) 33.04 % R Mr (-12.00;5.00) 37.27 % R Mr (-13.00;5.00) 40.61 % R Mr (-14.00;5.00) 43.21 % R Mr (-15.00;5.00) 48.33 % R Mr (-16.00;5.00) 52.77 % R Mr (-17.00;5.00) 55.84 % R Mr (-18.00;5.00) 59.36 % R Mr (-19.00;5.00) 63.15 % R Mr (-20.00;5.00) 67.50 % R Mr (-21.00;5.00) 71.53 % R Mr (-22.00;5.00) 74.87 % R Mr (-23.00;5.00) 77.54 % R Mr (-24.00;5.00) 79.93 % R Mr (-25.00;5.00) 82.10 % R Mr (-26.00;5.00) 84.15 % R Mr (-27.00;5.00) 86.69 % R Mr (-28.00;5.00) 89.73 % R Mr (-29.00;5.00) 92.61 % R Mr (-30.00;5.00) 93.65 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 35.59 µm Rz2 29.58 µm Rz3 38.43 µm Rz4 70.61 µm Rz5 31.67 µm Rz sigma 16.81 µm Rz min 29.58 µm Rz max 70.61 µm Rz mean 41.18 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 14.27 µm Rp2 10.28 µm Rp3 13.31 µm Rp4 26.19 µm Rp5 17.23 µm Rp sigma 6.08 µm Rp min 10.28 µm Rp max 26.19 µm Rp mean 16.25 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:25 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 11.02 µm
R3z2	Rdc (10.00;5.00) -1.98 µm
R3z3	Rdc (20.00;5.00) -6.78 µm
R3z4	Rdc (30.00;5.00) -9.43 µm
R3z5	Rdc (40.00;5.00) -11.58 µm
R3z sigma	Rdc (50.00;5.00) -13.35 µm
R3z min	Rdc (60.00;5.00) -16.57 µm
R3z max	Rdc (70.00;5.00) -20.45 µm
R3z mean	Rdc (80.00;5.00) -24.04 µm
	Rdc (90.00;5.00) -30.81 µm
	Rdc (100.00;5.00) -59.60 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:25 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (11.02;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	7.72 %
R Mr (-2.00;5.00)	10.06 %
R Mr (-3.00;5.00)	11.76 %
R Mr (-4.00;5.00)	13.45 %
R Mr (-5.00;5.00)	15.39 %
R Mr (-6.00;5.00)	18.41 %
R Mr (-7.00;5.00)	20.49 %
R Mr (-8.00;5.00)	24.00 %
R Mr (-9.00;5.00)	27.69 %
R Mr (-10.00;5.00)	32.85 %
R Mr (-11.00;5.00)	37.40 %
R Mr (-12.00;5.00)	42.99 %
R Mr (-13.00;5.00)	48.42 %
R Mr (-14.00;5.00)	52.07 %
R Mr (-15.00;5.00)	54.61 %
R Mr (-16.00;5.00)	57.59 %
R Mr (-17.00;5.00)	61.54 %
R Mr (-18.00;5.00)	64.36 %
R Mr (-19.00;5.00)	66.59 %
R Mr (-20.00;5.00)	68.93 %
R Mr (-21.00;5.00)	71.42 %
R Mr (-22.00;5.00)	74.67 %
R Mr (-23.00;5.00)	77.46 %
R Mr (-24.00;5.00)	79.86 %
R Mr (-25.00;5.00)	82.22 %
R Mr (-26.00;5.00)	84.30 %
R Mr (-27.00;5.00)	85.49 %
R Mr (-28.00;5.00)	86.62 %
R Mr (-29.00;5.00)	87.84 %
R Mr (-30.00;5.00)	89.31 %

No Quick&Easy

6

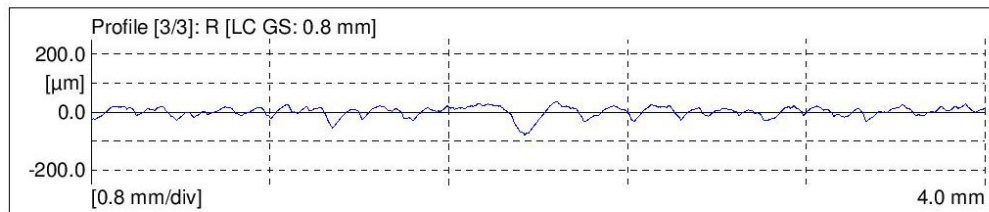
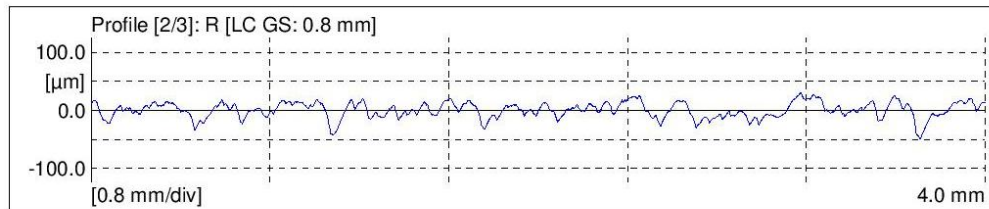
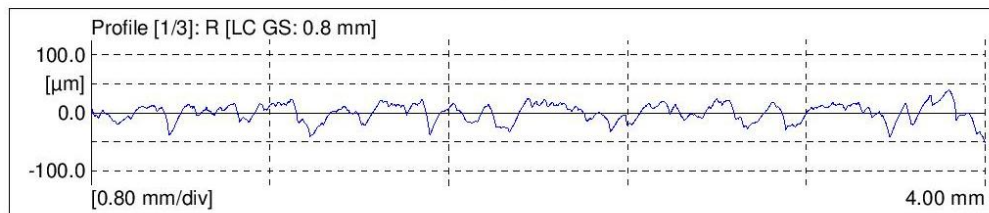
2.54 m/min, peripherally milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 100ipm edge long.prf	 08/30/12, 11:39 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 100ipm edge long.prf	 08/30/12, 11:39 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	12.408	15.075	63.667	90.06	90.06	43.082	90.06	25.10	38.57	36.005	269.73 ...
2:	10.738	13.444	61.007	75.85	75.85	36.801	79.73	23.23	37.78	35.760	232.53 ...
3:	13.839	17.968	72.821	114.81	114.81	46.897	114.81	26.77	46.06	37.710	218.15 ...
Xb:	12.328	15.496	65.832	93.57	93.57	42.260	94.87	25.03	40.80	36.492	240.14
S:	1.552	2.292	6.198	19.71	19.71	5.098	18.03	1.77	4.57	1.062	26.62
Max:	13.839	17.968	72.821	114.81	114.81	46.897	114.81	26.77	46.06	37.710	269.73
Min:	10.738	13.444	61.007	75.85	75.85	36.801	79.73	23.23	37.78	35.760	218.15
R:	3.101	4.525	11.815	38.96	38.96	10.096	35.08	3.54	8.28	1.950	51.58

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	54.19 μm	Rp1	15.55 μm
Rz2	63.87 μm	Rp2	22.99 μm
Rz3	56.83 μm	Rp3	23.83 μm
Rz4	53.39 μm	Rp4	24.10 μm
Rz5	90.06 μm	Rp5	39.03 μm
Rz sigma	15.32 μm	Rp sigma	8.55 μm
Rz min	53.39 μm	Rp min	15.55 μm
Rz max	90.06 μm	Rp max	39.03 μm
Rz mean	63.67 μm	Rp mean	25.10 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	31.53 μm	Rdc (0.00;5.00)	19.29 μm
R3z2	43.77 μm	Rdc (10.00;5.00)	-3.17 μm
R3z3	40.86 μm	Rdc (20.00;5.00)	-6.34 μm
R3z4	33.27 μm	Rdc (30.00;5.00)	-9.61 μm
R3z5	30.59 μm	Rdc (40.00;5.00)	-13.18 μm
R3z sigma	5.93 μm	Rdc (50.00;5.00)	-17.45 μm
R3z min	30.59 μm	Rdc (60.00;5.00)	-22.24 μm
R3z max	43.77 μm	Rdc (70.00;5.00)	-27.17 μm
R3z mean	36.01 μm	Rdc (80.00;5.00)	-33.53 μm
		Rdc (90.00;5.00)	-40.80 μm
		Rdc (100.00;5.00)	-70.77 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 100ipm edge long.prf	 08/30/12, 11:39 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (19.29;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.51 % R Mr (-2.00;5.00) 7.92 % R Mr (-3.00;5.00) 9.62 % R Mr (-4.00;5.00) 11.76 % R Mr (-5.00;5.00) 14.96 % R Mr (-6.00;5.00) 18.74 % R Mr (-7.00;5.00) 22.06 % R Mr (-8.00;5.00) 25.10 % R Mr (-9.00;5.00) 27.72 % R Mr (-10.00;5.00) 31.42 % R Mr (-11.00;5.00) 34.74 % R Mr (-12.00;5.00) 37.36 % R Mr (-13.00;5.00) 39.52 % R Mr (-14.00;5.00) 42.20 % R Mr (-15.00;5.00) 44.49 % R Mr (-16.00;5.00) 47.08 % R Mr (-17.00;5.00) 48.99 % R Mr (-18.00;5.00) 51.24 % R Mr (-19.00;5.00) 53.10 % R Mr (-20.00;5.00) 55.04 % R Mr (-21.00;5.00) 57.16 % R Mr (-22.00;5.00) 59.47 % R Mr (-23.00;5.00) 61.45 % R Mr (-24.00;5.00) 63.91 % R Mr (-25.00;5.00) 66.20 % R Mr (-26.00;5.00) 67.85 % R Mr (-27.00;5.00) 69.73 % R Mr (-28.00;5.00) 71.20 % R Mr (-29.00;5.00) 73.00 % R Mr (-30.00;5.00) 74.76 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 52.28 µm Rz2 62.17 µm Rz3 53.58 µm Rz4 61.15 µm Rz5 75.85 µm Rz sigma 9.40 µm Rz min 52.28 µm Rz max 75.85 µm Rz mean 61.01 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 18.08 µm Rp2 20.59 µm Rp3 20.62 µm Rp4 30.36 µm Rp5 26.48 µm Rp sigma 5.04 µm Rp min 18.08 µm Rp max 30.36 µm Rp mean 23.23 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 38.16 µm R3z2 33.05 µm R3z3 34.67 µm R3z4 42.14 µm R3z5 30.77 µm R3z sigma 4.47 µm R3z min 30.77 µm R3z max 42.14 µm R3z mean 35.76 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 100ipm edge long.prf	 08/30/12, 11:39 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 10.57 µm Rdc (10.00;5.00) -3.59 µm Rdc (20.00;5.00) -7.35 µm Rdc (30.00;5.00) -11.21 µm Rdc (40.00;5.00) -15.26 µm Rdc (50.00;5.00) -19.19 µm Rdc (60.00;5.00) -22.35 µm Rdc (70.00;5.00) -26.29 µm Rdc (80.00;5.00) -30.31 µm Rdc (90.00;5.00) -36.97 µm Rdc (100.00;5.00) -69.16 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (10.57;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.20 % R Mr (-2.00;5.00) 7.08 % R Mr (-3.00;5.00) 8.90 % R Mr (-4.00;5.00) 10.85 % R Mr (-5.00;5.00) 13.29 % R Mr (-6.00;5.00) 15.81 % R Mr (-7.00;5.00) 18.99 % R Mr (-8.00;5.00) 21.66 % R Mr (-9.00;5.00) 24.20 % R Mr (-10.00;5.00) 26.24 % R Mr (-11.00;5.00) 29.49 % R Mr (-12.00;5.00) 32.12 % R Mr (-13.00;5.00) 34.87 % R Mr (-14.00;5.00) 37.42 % R Mr (-15.00;5.00) 39.46 % R Mr (-16.00;5.00) 41.78 % R Mr (-17.00;5.00) 44.20 % R Mr (-18.00;5.00) 46.66 % R Mr (-19.00;5.00) 49.54 % R Mr (-20.00;5.00) 52.25 % R Mr (-21.00;5.00) 55.40 % R Mr (-22.00;5.00) 58.93 % R Mr (-23.00;5.00) 62.06 % R Mr (-24.00;5.00) 64.58 % R Mr (-25.00;5.00) 66.67 % R Mr (-26.00;5.00) 69.05 % R Mr (-27.00;5.00) 71.71 % R Mr (-28.00;5.00) 74.86 % R Mr (-29.00;5.00) 77.53 % R Mr (-30.00;5.00) 79.55 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 50.45 µm Rz2 79.92 µm Rz3 114.81 µm Rz4 57.32 µm Rz5 61.61 µm Rz sigma 25.88 µm Rz min 50.45 µm Rz max 114.81 µm Rz mean 72.82 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 20.26 µm Rp2 24.93 µm Rp3 35.87 µm Rp4 25.02 µm Rp5 27.74 µm Rp sigma 5.76 µm Rp min 20.26 µm Rp max 35.87 µm Rp mean 26.77 µm

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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	35.61 µm	Rdc (0.00;5.00)	13.99 µm
R3z2	47.96 µm	Rdc (10.00;5.00)	-2.91 µm
R3z3	19.24 µm	Rdc (20.00;5.00)	-6.63 µm
R3z4	49.50 µm	Rdc (30.00;5.00)	-10.07 µm
R3z5	36.24 µm	Rdc (40.00;5.00)	-13.76 µm
R3z sigma	12.16 µm	Rdc (50.00;5.00)	-17.62 µm
R3z min	19.24 µm	Rdc (60.00;5.00)	-22.22 µm
R3z max	49.50 µm	Rdc (70.00;5.00)	-27.76 µm
R3z mean	37.71 µm	Rdc (80.00;5.00)	-34.36 µm
		Rdc (90.00;5.00)	-44.32 µm
		Rdc (100.00;5.00)	-100.82 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 100ipm edge long.prf	 08/30/12, 11:39 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (13.99;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.26 %
R Mr (-2.00;5.00)	8.27 %
R Mr (-3.00;5.00)	10.24 %
R Mr (-4.00;5.00)	13.06 %
R Mr (-5.00;5.00)	15.93 %
R Mr (-6.00;5.00)	18.33 %
R Mr (-7.00;5.00)	21.08 %
R Mr (-8.00;5.00)	24.03 %
R Mr (-9.00;5.00)	27.15 %
R Mr (-10.00;5.00)	29.81 %
R Mr (-11.00;5.00)	32.73 %
R Mr (-12.00;5.00)	35.06 %
R Mr (-13.00;5.00)	37.86 %
R Mr (-14.00;5.00)	40.74 %
R Mr (-15.00;5.00)	43.58 %
R Mr (-16.00;5.00)	46.17 %
R Mr (-17.00;5.00)	48.55 %
R Mr (-18.00;5.00)	50.96 %
R Mr (-19.00;5.00)	53.00 %
R Mr (-20.00;5.00)	54.86 %
R Mr (-21.00;5.00)	56.80 %
R Mr (-22.00;5.00)	59.40 %
R Mr (-23.00;5.00)	61.69 %
R Mr (-24.00;5.00)	63.53 %
R Mr (-25.00;5.00)	65.49 %
R Mr (-26.00;5.00)	67.57 %
R Mr (-27.00;5.00)	68.92 %
R Mr (-28.00;5.00)	70.39 %
R Mr (-29.00;5.00)	71.90 %
R Mr (-30.00;5.00)	73.44 %

No Quick&Easy

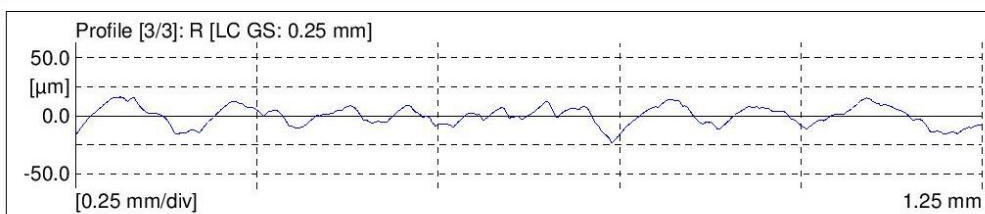
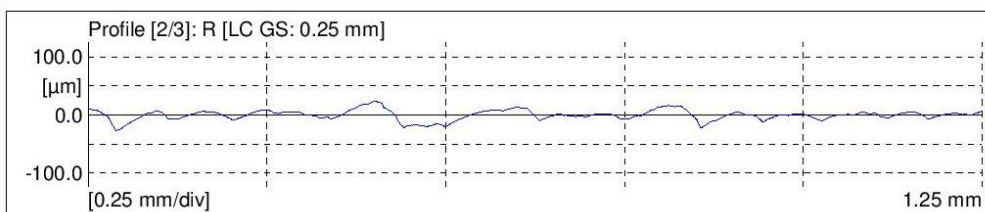
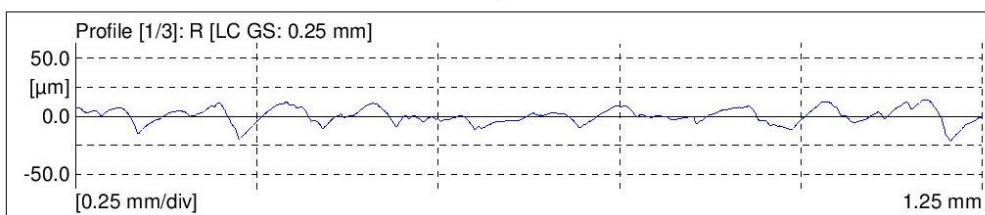
6

2.54 m/min, peripherally milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:37 AM
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Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 1.75 mm [N=5] Ls: 2.5 μ m VB: $\pm$ 250 μ m Vt: 0.10 mm/s Points: 10500 [3]
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:37 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	5.246	6.638	26.167	35.58	35.58	19.320	35.58	11.13	15.04	---	139.36 ...
2:	6.429	8.722	34.335	45.83	45.83	21.501	50.29	13.92	20.41	---	128.72 ...
3:	6.813	8.244	30.027	36.08	36.08	21.022	39.52	13.35	16.68	---	147.93 ...
Xb:	6.163	7.868	30.176	39.16	39.16	20.614	41.80	12.80	17.37	138.67	
S:	0.817	1.092	4.086	5.78	5.78	1.146	7.61	1.48	2.76	9.62	
Max:	6.813	8.722	34.335	45.83	45.83	21.501	50.29	13.92	20.41	147.93	
Min:	5.246	6.638	26.167	35.58	35.58	19.320	35.58	11.13	15.04	128.72	
R:	1.567	2.085	8.169	10.24	10.24	2.182	14.71	2.79	5.38	19.21	

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
Rz1	31.39 μm	Rp1	11.42 μm
Rz2	22.71 μm	Rp2	12.16 μm
Rz3	20.50 μm	Rp3	8.89 μm
Rz4	20.65 μm	Rp4	8.98 μm
Rz5	35.58 μm	Rp5	14.20 μm
Rz sigma	6.90 μm	Rp sigma	2.25 μm
Rz min	20.50 μm	Rp min	8.89 μm
Rz max	35.58 μm	Rp max	14.20 μm
Rz mean	26.17 μm	Rp mean	11.13 μm

Profile [1/3]: R [LC GS: 0.25 mm]		Profile [1/3]: R [LC GS: 0.25 mm]	
R3z1	---	Rdc (0.00;5.00)	3.57 μm
R3z2	---	Rdc (10.00;5.00)	-1.99 μm
R3z3	---	Rdc (20.00;5.00)	-4.14 μm
R3z4	---	Rdc (30.00;5.00)	-6.91 μm
R3z5	---	Rdc (40.00;5.00)	-8.94 μm
R3z sigma	---	Rdc (50.00;5.00)	-10.45 μm
R3z min	---	Rdc (60.00;5.00)	-11.92 μm
R3z max	---	Rdc (70.00;5.00)	-13.75 μm
R3z mean	---	Rdc (80.00;5.00)	-15.34 μm
		Rdc (90.00;5.00)	-19.26 μm
		Rdc (100.00;5.00)	-32.02 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:37 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (3.57;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 7.57 % R Mr (-2.00;5.00) 10.03 % R Mr (-3.00;5.00) 14.32 % R Mr (-4.00;5.00) 19.49 % R Mr (-5.00;5.00) 22.99 % R Mr (-6.00;5.00) 26.17 % R Mr (-7.00;5.00) 30.33 % R Mr (-8.00;5.00) 35.15 % R Mr (-9.00;5.00) 40.16 % R Mr (-10.00;5.00) 46.11 % R Mr (-11.00;5.00) 54.20 % R Mr (-12.00;5.00) 60.56 % R Mr (-13.00;5.00) 66.01 % R Mr (-14.00;5.00) 71.11 % R Mr (-15.00;5.00) 78.33 % R Mr (-16.00;5.00) 81.86 % R Mr (-17.00;5.00) 84.74 % R Mr (-18.00;5.00) 86.72 % R Mr (-19.00;5.00) 89.34 % R Mr (-20.00;5.00) 91.79 % R Mr (-21.00;5.00) 94.04 % R Mr (-22.00;5.00) 95.48 % R Mr (-23.00;5.00) 96.40 % R Mr (-24.00;5.00) 96.88 % R Mr (-25.00;5.00) 97.36 % R Mr (-26.00;5.00) 97.92 % R Mr (-27.00;5.00) 98.28 % R Mr (-28.00;5.00) 98.67 % R Mr (-29.00;5.00) 99.04 % R Mr (-30.00;5.00) 99.40 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 36.71 µm Rz2 45.83 µm Rz3 33.58 µm Rz4 38.78 µm Rz5 16.78 µm Rz sigma 10.79 µm Rz min 16.78 µm Rz max 45.83 µm Rz mean 34.34 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 10.00 µm Rp2 23.57 µm Rp3 13.59 µm Rp4 16.07 µm Rp5 6.40 µm Rp sigma 6.52 µm Rp min 6.40 µm Rp max 23.57 µm Rp mean 13.92 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:37 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 9.39 µm Rdc (10.00;5.00) -4.48 µm Rdc (20.00;5.00) -8.83 µm Rdc (30.00;5.00) -10.55 µm Rdc (40.00;5.00) -12.43 µm Rdc (50.00;5.00) -13.83 µm Rdc (60.00;5.00) -15.43 µm Rdc (70.00;5.00) -17.57 µm Rdc (80.00;5.00) -20.35 µm Rdc (90.00;5.00) -25.97 µm Rdc (100.00;5.00) -40.90 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (9.39;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.02 % R Mr (-2.00;5.00) 6.96 % R Mr (-3.00;5.00) 8.35 % R Mr (-4.00;5.00) 9.23 % R Mr (-5.00;5.00) 10.65 % R Mr (-6.00;5.00) 13.17 % R Mr (-7.00;5.00) 15.77 % R Mr (-8.00;5.00) 17.93 % R Mr (-9.00;5.00) 20.86 % R Mr (-10.00;5.00) 27.07 % R Mr (-11.00;5.00) 31.82 % R Mr (-12.00;5.00) 36.98 % R Mr (-13.00;5.00) 43.43 % R Mr (-14.00;5.00) 51.12 % R Mr (-15.00;5.00) 57.53 % R Mr (-16.00;5.00) 62.77 % R Mr (-17.00;5.00) 67.84 % R Mr (-18.00;5.00) 71.32 % R Mr (-19.00;5.00) 75.53 % R Mr (-20.00;5.00) 78.46 % R Mr (-21.00;5.00) 82.73 % R Mr (-22.00;5.00) 85.32 % R Mr (-23.00;5.00) 86.85 % R Mr (-24.00;5.00) 88.12 % R Mr (-25.00;5.00) 89.17 % R Mr (-26.00;5.00) 90.03 % R Mr (-27.00;5.00) 90.48 % R Mr (-28.00;5.00) 90.90 % R Mr (-29.00;5.00) 91.32 % R Mr (-30.00;5.00) 92.20 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 32.86 µm Rz2 19.63 µm Rz3 36.08 µm Rz4 30.39 µm Rz5 31.19 µm Rz sigma 6.21 µm Rz min 19.63 µm Rz max 36.08 µm Rz mean 30.03 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 16.04 µm Rp2 8.98 µm Rp3 12.59 µm Rp4 13.91 µm Rp5 15.24 µm Rp sigma 2.78 µm Rp min 8.98 µm Rp max 16.04 µm Rp mean 13.35 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:37 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 3.09 μm
R3z2	Rdc (10.00;5.00) -2.56 μm
R3z3	Rdc (20.00;5.00) -5.78 μm
R3z4	Rdc (30.00;5.00) -7.94 μm
R3z5	Rdc (40.00;5.00) -10.17 μm
R3z sigma	Rdc (50.00;5.00) -12.00 μm
R3z min	Rdc (60.00;5.00) -14.55 μm
R3z max	Rdc (70.00;5.00) -17.60 μm
R3z mean	Rdc (80.00;5.00) -20.73 μm
	Rdc (90.00;5.00) -24.83 μm
	Rdc (100.00;5.00) -36.43 μm

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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (3.09;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	7.24 %
R Mr (-2.00;5.00)	8.79 %
R Mr (-3.00;5.00)	10.72 %
R Mr (-4.00;5.00)	12.56 %
R Mr (-5.00;5.00)	15.96 %
R Mr (-6.00;5.00)	21.26 %
R Mr (-7.00;5.00)	26.26 %
R Mr (-8.00;5.00)	30.32 %
R Mr (-9.00;5.00)	34.93 %
R Mr (-10.00;5.00)	39.38 %
R Mr (-11.00;5.00)	43.60 %
R Mr (-12.00;5.00)	49.99 %
R Mr (-13.00;5.00)	53.94 %
R Mr (-14.00;5.00)	57.98 %
R Mr (-15.00;5.00)	61.27 %
R Mr (-16.00;5.00)	64.09 %
R Mr (-17.00;5.00)	68.16 %
R Mr (-18.00;5.00)	71.11 %
R Mr (-19.00;5.00)	74.90 %
R Mr (-20.00;5.00)	77.86 %
R Mr (-21.00;5.00)	80.85 %
R Mr (-22.00;5.00)	83.96 %
R Mr (-23.00;5.00)	86.19 %
R Mr (-24.00;5.00)	88.75 %
R Mr (-25.00;5.00)	90.33 %
R Mr (-26.00;5.00)	91.43 %
R Mr (-27.00;5.00)	93.83 %
R Mr (-28.00;5.00)	96.34 %
R Mr (-29.00;5.00)	98.24 %
R Mr (-30.00;5.00)	98.60 %

No Quick&Easy

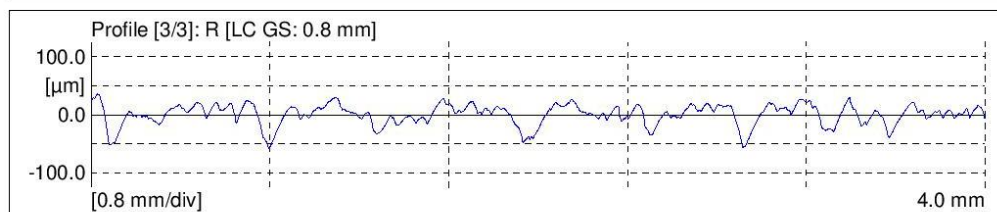
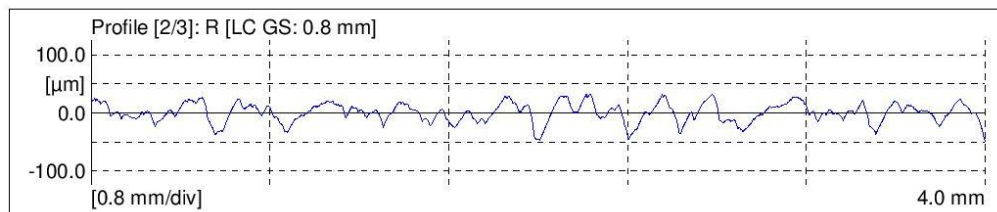
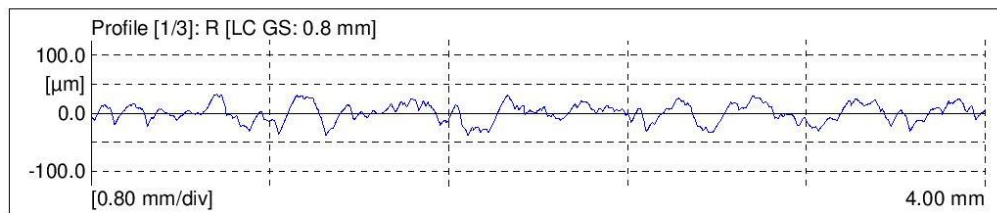
6

5.08 m/min, peripherally milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board	Lt: 5.60 mm [N=5]
Drive Unit: GD 25	Ls: 2.5 μ m
Pick-up: MFW-250 [8.0 %]	VB: $\pm$ 250 μ m
	Vt: 0.50 mm/s
	Points: 33600 [3]



 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	12.652	15.489	64.502	69.81	69.81	43.506	72.01	29.76	34.74	43.830	265.71
2:	12.801	16.115	69.359	79.26	79.26	47.261	81.47	27.06	42.30	42.385	265.85
3:	13.501	17.600	81.824	95.11	95.11	50.142	95.11	29.73	52.09	32.382	254.54
Xb:	12.985	16.402	71.895	81.40	81.40	46.970	82.86	28.85	43.04	39.532	262.03
S:	0.453	1.084	8.935	12.78	12.78	3.328	11.62	1.55	8.70	6.234	6.49
Max:	13.501	17.600	81.824	95.11	95.11	50.142	95.11	29.76	52.09	43.830	265.85
Min:	12.652	15.489	64.502	69.81	69.81	43.506	72.01	27.06	34.74	32.382	254.54
R:	0.848	2.111	17.323	25.30	25.30	6.637	23.11	2.70	17.35	11.448	11.31

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	63.91 μm	Rp1	32.64 μm
Rz2	69.81 μm	Rp2	30.45 μm
Rz3	69.36 μm	Rp3	30.50 μm
Rz4	63.05 μm	Rp4	30.21 μm
Rz5	56.37 μm	Rp5	25.03 μm
Rz sigma	5.49 μm	Rp sigma	2.82 μm
Rz min	56.37 μm	Rp min	25.03 μm
Rz max	69.81 μm	Rp max	32.64 μm
Rz mean	64.50 μm	Rp mean	29.76 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	35.08 μm	Rdc (0.00;5.00)	7.74 μm
R3z2	41.39 μm	Rdc (10.00;5.00)	-4.96 μm
R3z3	48.48 μm	Rdc (20.00;5.00)	-10.85 μm
R3z4	49.32 μm	Rdc (30.00;5.00)	-15.69 μm
R3z5	44.88 μm	Rdc (40.00;5.00)	-19.41 μm
R3z sigma	5.82 μm	Rdc (50.00;5.00)	-23.57 μm
R3z min	35.08 μm	Rdc (60.00;5.00)	-27.36 μm
R3z max	49.32 μm	Rdc (70.00;5.00)	-32.60 μm
R3z mean	43.83 μm	Rdc (80.00;5.00)	-37.80 μm
		Rdc (90.00;5.00)	-47.91 μm
		Rdc (100.00;5.00)	-64.26 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (7.74;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.08 % R Mr (-2.00;5.00) 6.75 % R Mr (-3.00;5.00) 7.61 % R Mr (-4.00;5.00) 8.65 % R Mr (-5.00;5.00) 10.07 % R Mr (-6.00;5.00) 11.53 % R Mr (-7.00;5.00) 13.32 % R Mr (-8.00;5.00) 15.11 % R Mr (-9.00;5.00) 16.83 % R Mr (-10.00;5.00) 18.67 % R Mr (-11.00;5.00) 20.32 % R Mr (-12.00;5.00) 22.38 % R Mr (-13.00;5.00) 24.60 % R Mr (-14.00;5.00) 26.61 % R Mr (-15.00;5.00) 28.51 % R Mr (-16.00;5.00) 30.77 % R Mr (-17.00;5.00) 33.22 % R Mr (-18.00;5.00) 36.26 % R Mr (-19.00;5.00) 39.08 % R Mr (-20.00;5.00) 41.37 % R Mr (-21.00;5.00) 44.07 % R Mr (-22.00;5.00) 46.42 % R Mr (-23.00;5.00) 48.85 % R Mr (-24.00;5.00) 50.92 % R Mr (-25.00;5.00) 53.36 % R Mr (-26.00;5.00) 56.26 % R Mr (-27.00;5.00) 58.98 % R Mr (-28.00;5.00) 61.46 % R Mr (-29.00;5.00) 63.21 % R Mr (-30.00;5.00) 65.47 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 63.11 µm Rz2 54.26 µm Rz3 79.26 µm Rz4 78.13 µm Rz5 72.03 µm Rz sigma 10.60 µm Rz min 54.26 µm Rz max 79.26 µm Rz mean 69.36 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 26.33 µm Rp2 20.93 µm Rp3 32.82 µm Rp4 31.84 µm Rp5 23.38 µm Rp sigma 5.19 µm Rp min 20.93 µm Rp max 32.82 µm Rp mean 27.06 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 34.82 µm R3z2 33.98 µm R3z3 48.46 µm R3z4 60.30 µm R3z5 34.36 µm R3z sigma 11.73 µm R3z min 33.98 µm R3z max 60.30 µm R3z mean 42.38 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 7.46 µm Rdc (10.00;5.00) -4.73 µm Rdc (20.00;5.00) -10.66 µm Rdc (30.00;5.00) -15.49 µm Rdc (40.00;5.00) -20.77 µm Rdc (50.00;5.00) -24.20 µm Rdc (60.00;5.00) -27.61 µm Rdc (70.00;5.00) -32.32 µm Rdc (80.00;5.00) -38.02 µm Rdc (90.00;5.00) -47.55 µm Rdc (100.00;5.00) -74.01 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (7.46;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.67 % R Mr (-2.00;5.00) 6.55 % R Mr (-3.00;5.00) 7.72 % R Mr (-4.00;5.00) 8.90 % R Mr (-5.00;5.00) 10.37 % R Mr (-6.00;5.00) 12.15 % R Mr (-7.00;5.00) 14.03 % R Mr (-8.00;5.00) 15.65 % R Mr (-9.00;5.00) 16.86 % R Mr (-10.00;5.00) 18.65 % R Mr (-11.00;5.00) 20.47 % R Mr (-12.00;5.00) 22.39 % R Mr (-13.00;5.00) 24.29 % R Mr (-14.00;5.00) 26.49 % R Mr (-15.00;5.00) 28.92 % R Mr (-16.00;5.00) 31.11 % R Mr (-17.00;5.00) 32.95 % R Mr (-18.00;5.00) 34.78 % R Mr (-19.00;5.00) 36.63 % R Mr (-20.00;5.00) 38.30 % R Mr (-21.00;5.00) 40.74 % R Mr (-22.00;5.00) 43.57 % R Mr (-23.00;5.00) 46.72 % R Mr (-24.00;5.00) 49.54 % R Mr (-25.00;5.00) 52.39 % R Mr (-26.00;5.00) 55.44 % R Mr (-27.00;5.00) 58.42 % R Mr (-28.00;5.00) 60.98 % R Mr (-29.00;5.00) 63.66 % R Mr (-30.00;5.00) 65.77 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 95.11 µm Rz2 86.88 µm Rz3 74.95 µm Rz4 83.00 µm Rz5 69.18 µm Rz sigma 10.13 µm Rz min 69.18 µm Rz max 95.11 µm Rz mean 81.82 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 35.60 µm Rp2 30.13 µm Rp3 26.97 µm Rp4 26.63 µm Rp5 29.34 µm Rp sigma 3.60 µm Rp min 26.63 µm Rp max 35.60 µm Rp mean 29.73 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	38.15 μm	Rdc (0.00;5.00)	12.85 μm
R3z2	29.31 μm	Rdc (10.00;5.00)	-3.61 μm
R3z3	31.15 μm	Rdc (20.00;5.00)	-8.46 μm
R3z4	27.18 μm	Rdc (30.00;5.00)	-12.20 μm
R3z5	36.13 μm	Rdc (40.00;5.00)	-15.97 μm
R3z sigma	4.62 μm	Rdc (50.00;5.00)	-19.45 μm
R3z min	27.18 μm	Rdc (60.00;5.00)	-23.76 μm
R3z max	38.15 μm	Rdc (70.00;5.00)	-27.71 μm
R3z mean	32.38 μm	Rdc (80.00;5.00)	-34.48 μm
		Rdc (90.00;5.00)	-48.89 μm
		Rdc (100.00;5.00)	-82.26 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 200ipm edge long.prf	 08/30/12, 11:38 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (12.85;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.01 %
R Mr (-2.00;5.00)	7.20 %
R Mr (-3.00;5.00)	8.92 %
R Mr (-4.00;5.00)	10.67 %
R Mr (-5.00;5.00)	12.44 %
R Mr (-6.00;5.00)	14.52 %
R Mr (-7.00;5.00)	16.65 %
R Mr (-8.00;5.00)	18.88 %
R Mr (-9.00;5.00)	21.58 %
R Mr (-10.00;5.00)	23.99 %
R Mr (-11.00;5.00)	26.42 %
R Mr (-12.00;5.00)	29.43 %
R Mr (-13.00;5.00)	31.96 %
R Mr (-14.00;5.00)	34.29 %
R Mr (-15.00;5.00)	36.98 %
R Mr (-16.00;5.00)	40.10 %
R Mr (-17.00;5.00)	42.88 %
R Mr (-18.00;5.00)	45.93 %
R Mr (-19.00;5.00)	48.67 %
R Mr (-20.00;5.00)	51.15 %
R Mr (-21.00;5.00)	53.78 %
R Mr (-22.00;5.00)	56.02 %
R Mr (-23.00;5.00)	58.34 %
R Mr (-24.00;5.00)	60.55 %
R Mr (-25.00;5.00)	62.94 %
R Mr (-26.00;5.00)	65.72 %
R Mr (-27.00;5.00)	68.14 %
R Mr (-28.00;5.00)	70.79 %
R Mr (-29.00;5.00)	73.12 %
R Mr (-30.00;5.00)	75.15 %

No Quick&Easy

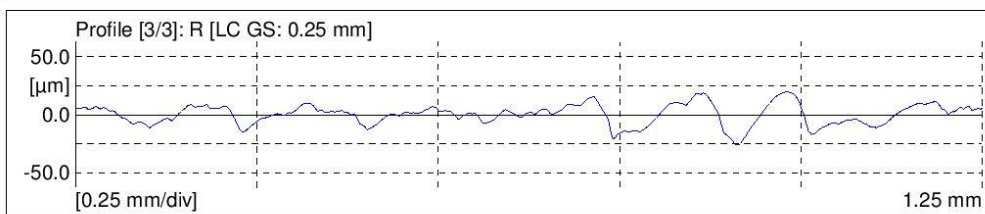
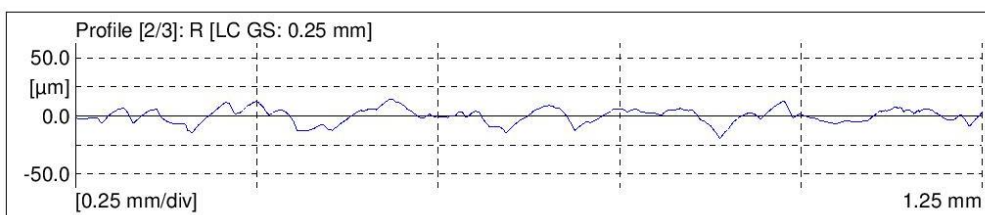
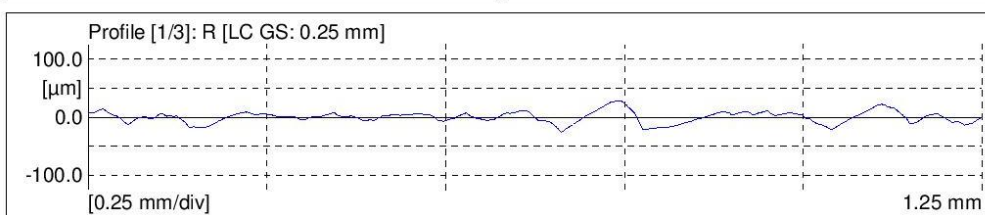
6

5.08 m/min, peripherally milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/30/12, 10:40 AM
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 1.75 mm [N=5] Ls: 2.5 μ m VB: ± 250 μ m Vt: 0.10 mm/s Points: 10500 [3]
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No Quick&Easy

1

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:40 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	7.674	9.864	37.644	53.68	53.68	24.782	53.68	18.86	18.79	---	119.78
2:	5.185	6.367	25.441	32.33	32.33	18.616	34.34	11.31	14.13	6.664	149.88
3:	6.949	8.723	31.299	45.67	45.67	26.185	45.67	13.02	18.28	---	165.42
Xb:	6.603	8.318	31.461	43.89	43.89	23.194	44.56	14.40	17.06	6.664	145.02
S:	1.280	1.783	6.103	10.78	10.78	4.026	9.72	3.96	2.56	0.000	23.20
Max:	7.674	9.864	37.644	53.68	53.68	26.185	53.68	18.86	18.79	6.664	165.42
Min:	5.185	6.367	25.441	32.33	32.33	18.616	34.34	11.31	14.13	6.664	119.78
R:	2.489	3.496	12.203	21.35	21.35	7.568	19.34	7.54	4.66	0.000	45.64

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
Rz1	31.81	μm	Rp1	13.55	μm
Rz2	14.15	μm	Rp2	7.28	μm
Rz3	53.68	μm	Rp3	27.92	μm
Rz4	44.89	μm	Rp4	23.37	μm
Rz5	43.69	μm	Rp5	22.16	μm
Rz sigma	15.26	μm	Rp sigma	8.30	μm
Rz min	14.15	μm	Rp min	7.28	μm
Rz max	53.68	μm	Rp max	27.92	μm
Rz mean	37.64	μm	Rp mean	18.86	μm

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
R3z1	---	μm	Rdc (0.00;5.00)	11.43	μm
R3z2	---	μm	Rdc (10.00;5.00)	-6.34	μm
R3z3	---	μm	Rdc (20.00;5.00)	-9.70	μm
R3z4	---	μm	Rdc (30.00;5.00)	-11.63	μm
R3z5	---	μm	Rdc (40.00;5.00)	-13.18	μm
R3z sigma	---	μm	Rdc (50.00;5.00)	-15.41	μm
R3z min	---	μm	Rdc (60.00;5.00)	-18.01	μm
R3z max	---	μm	Rdc (70.00;5.00)	-21.04	μm
R3z mean	---	μm	Rdc (80.00;5.00)	-24.60	μm
			Rdc (90.00;5.00)	-31.19	μm
			Rdc (100.00;5.00)	-42.25	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:40 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (11.43;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.53 % R Mr (-2.00;5.00) 6.12 % R Mr (-3.00;5.00) 6.73 % R Mr (-4.00;5.00) 7.29 % R Mr (-5.00;5.00) 8.16 % R Mr (-6.00;5.00) 9.44 % R Mr (-7.00;5.00) 10.90 % R Mr (-8.00;5.00) 13.37 % R Mr (-9.00;5.00) 16.91 % R Mr (-10.00;5.00) 21.27 % R Mr (-11.00;5.00) 26.37 % R Mr (-12.00;5.00) 32.45 % R Mr (-13.00;5.00) 39.23 % R Mr (-14.00;5.00) 43.37 % R Mr (-15.00;5.00) 47.72 % R Mr (-16.00;5.00) 54.03 % R Mr (-17.00;5.00) 57.03 % R Mr (-18.00;5.00) 59.97 % R Mr (-19.00;5.00) 63.61 % R Mr (-20.00;5.00) 67.04 % R Mr (-21.00;5.00) 69.89 % R Mr (-22.00;5.00) 73.17 % R Mr (-23.00;5.00) 76.34 % R Mr (-24.00;5.00) 78.67 % R Mr (-25.00;5.00) 80.76 % R Mr (-26.00;5.00) 82.48 % R Mr (-27.00;5.00) 84.16 % R Mr (-28.00;5.00) 86.00 % R Mr (-29.00;5.00) 87.54 % R Mr (-30.00;5.00) 88.86 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 27.19 µm Rz2 27.59 µm Rz3 23.70 µm Rz4 32.33 µm Rz5 16.39 µm Rz sigma 5.92 µm Rz min 16.39 µm Rz max 32.33 µm Rz mean 25.44 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 12.62 µm Rp2 14.68 µm Rp3 8.90 µm Rp4 12.67 µm Rp5 7.71 µm Rp sigma 2.90 µm Rp min 7.71 µm Rp max 14.68 µm Rp mean 11.31 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 12.73 µm R3z2 3.27 µm R3z3 4.99 µm R3z4 7.80 µm R3z5 4.53 µm R3z sigma 3.77 µm R3z min 3.27 µm R3z max 12.73 µm R3z mean 6.66 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:40 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 4.83 µm Rdc (10.00;5.00) -2.72 µm Rdc (20.00;5.00) -4.54 µm Rdc (30.00;5.00) -5.85 µm Rdc (40.00;5.00) -7.54 µm Rdc (50.00;5.00) -9.37 µm Rdc (60.00;5.00) -11.16 µm Rdc (70.00;5.00) -13.12 µm Rdc (80.00;5.00) -15.35 µm Rdc (90.00;5.00) -18.95 µm Rdc (100.00;5.00) -29.51 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (4.83;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.45 % R Mr (-2.00;5.00) 8.44 % R Mr (-3.00;5.00) 10.88 % R Mr (-4.00;5.00) 14.87 % R Mr (-5.00;5.00) 24.02 % R Mr (-6.00;5.00) 30.98 % R Mr (-7.00;5.00) 36.65 % R Mr (-8.00;5.00) 42.91 % R Mr (-9.00;5.00) 47.92 % R Mr (-10.00;5.00) 52.76 % R Mr (-11.00;5.00) 58.96 % R Mr (-12.00;5.00) 64.79 % R Mr (-13.00;5.00) 69.36 % R Mr (-14.00;5.00) 73.22 % R Mr (-15.00;5.00) 78.70 % R Mr (-16.00;5.00) 82.41 % R Mr (-17.00;5.00) 85.96 % R Mr (-18.00;5.00) 87.88 % R Mr (-19.00;5.00) 90.08 % R Mr (-20.00;5.00) 92.17 % R Mr (-21.00;5.00) 93.64 % R Mr (-22.00;5.00) 95.44 % R Mr (-23.00;5.00) 97.99 % R Mr (-24.00;5.00) 98.58 % R Mr (-25.00;5.00) 99.20 % R Mr (-26.00;5.00) 99.36 % R Mr (-27.00;5.00) 99.56 % R Mr (-28.00;5.00) 99.72 % R Mr (-29.00;5.00) 99.84 % R Mr (-29.51;5.00) 100.00 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 23.64 µm Rz2 22.55 µm Rz3 36.36 µm Rz4 45.67 µm Rz5 28.27 µm Rz sigma 9.70 µm Rz min 22.55 µm Rz max 45.67 µm Rz mean 31.30 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 8.95 µm Rp2 9.64 µm Rp3 15.65 µm Rp4 19.52 µm Rp5 11.32 µm Rp sigma 4.47 µm Rp min 8.95 µm Rp max 19.52 µm Rp mean 13.02 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:40 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 5.22 μm
R3z2	Rdc (10.00;5.00) -4.52 μm
R3z3	Rdc (20.00;5.00) -7.25 μm
R3z4	Rdc (30.00;5.00) -9.27 μm
R3z5	Rdc (40.00;5.00) -11.21 μm
R3z sigma	Rdc (50.00;5.00) -12.90 μm
R3z min	Rdc (60.00;5.00) -14.86 μm
R3z max	Rdc (70.00;5.00) -18.33 μm
R3z mean	Rdc (80.00;5.00) -21.68 μm
	Rdc (90.00;5.00) -26.05 μm
	Rdc (100.00;5.00) -40.45 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:40 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (5.22;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.74 %
R Mr (-2.00;5.00)	6.32 %
R Mr (-3.00;5.00)	6.93 %
R Mr (-4.00;5.00)	8.33 %
R Mr (-5.00;5.00)	12.06 %
R Mr (-6.00;5.00)	15.63 %
R Mr (-7.00;5.00)	19.19 %
R Mr (-8.00;5.00)	23.17 %
R Mr (-9.00;5.00)	28.16 %
R Mr (-10.00;5.00)	33.76 %
R Mr (-11.00;5.00)	38.43 %
R Mr (-12.00;5.00)	44.45 %
R Mr (-13.00;5.00)	50.60 %
R Mr (-14.00;5.00)	56.49 %
R Mr (-15.00;5.00)	60.77 %
R Mr (-16.00;5.00)	63.69 %
R Mr (-17.00;5.00)	65.99 %
R Mr (-18.00;5.00)	68.70 %
R Mr (-19.00;5.00)	72.00 %
R Mr (-20.00;5.00)	74.37 %
R Mr (-21.00;5.00)	77.33 %
R Mr (-22.00;5.00)	81.17 %
R Mr (-23.00;5.00)	83.56 %
R Mr (-24.00;5.00)	85.69 %
R Mr (-25.00;5.00)	88.12 %
R Mr (-26.00;5.00)	89.96 %
R Mr (-27.00;5.00)	91.02 %
R Mr (-28.00;5.00)	92.03 %
R Mr (-29.00;5.00)	94.46 %
R Mr (-30.00;5.00)	95.72 %

No Quick&Easy

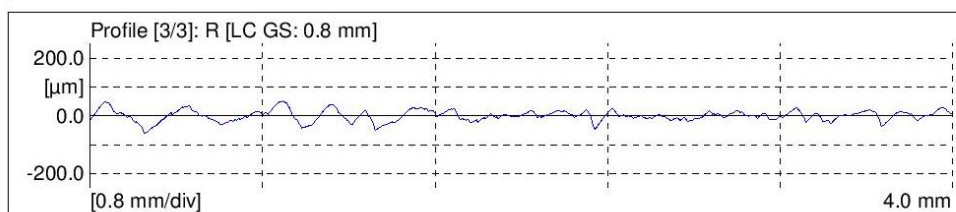
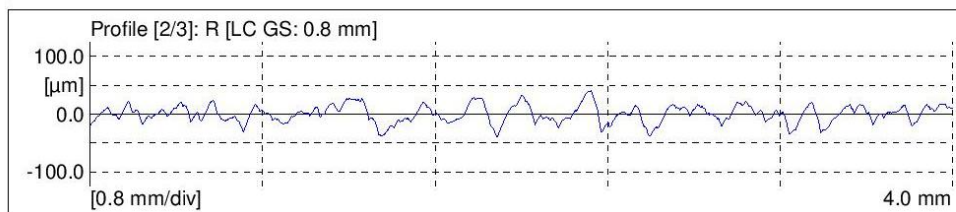
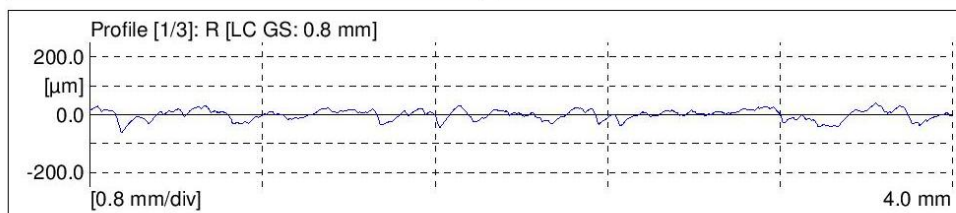
6

5.08 m/min, face milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/29/12
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [9.2 %]	Lt: 5.60 mm [N=5] Ls: 2.5 µm VB: ±250 µm Vt: 0.50 mm/s Points: 33600 [3]
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	Ra	Rq	Rz	Rz1	m...	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm ...
1:	14.782	18.158	75.942	92.38	92.38	92.38	53.734	101.53	30.81	45.13	41.052	365.20 ...
2:	11.747	14.708	63.074	80.92	80.92	80.92	42.428	80.92	26.85	36.22	39.685	211.06 ...
3:	14.293	18.625	78.960	111.52	111.52	111.52	53.304	113.00	35.97	42.99	41.545	277.89 ...
Xb:	13.607	17.164	72.658	94.94	94.94	94.94	49.822	98.49	31.21	41.45	40.761	284.72
S:	1.629	2.140	8.436	15.46	15.46	15.46	6.407	16.26	4.57	4.65	0.963	77.30
Max:	14.782	18.625	78.960	111.52	111.52	111.52	53.734	113.00	35.97	45.13	41.545	365.20
Min:	11.747	14.708	63.074	80.92	80.92	80.92	42.428	80.92	26.85	36.22	39.685	211.06
R:	3.035	3.917	15.886	30.60	30.60	30.60	11.306	32.08	9.12	8.91	1.859	154.14

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [1/3]: R [LC GS: 0.8 mm] Rz1 92.38 μm Rz2 59.36 μm Rz3 78.06 μm Rz4 67.29 μm Rz5 82.62 μm Rz sigma 12.94 μm Rz min 59.36 μm Rz max 92.38 μm Rz mean 75.94 μm	Profile [1/3]: R [LC GS: 0.8 mm] Rp1 30.32 μm Rp2 23.76 μm Rp3 32.53 μm Rp4 28.00 μm Rp5 39.47 μm Rp sigma 5.83 μm Rp min 23.76 μm Rp max 39.47 μm Rp mean 30.81 μm
Profile [1/3]: R [LC GS: 0.8 mm] R3z1 50.72 μm R3z2 23.97 μm R3z3 53.85 μm R3z4 21.28 μm R3z5 55.44 μm R3z sigma 16.93 μm R3z min 21.28 μm R3z max 55.44 μm R3z mean 41.05 μm	Profile [1/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 14.18 μm Rdc (10.00;5.00) -4.31 μm Rdc (20.00;5.00) -10.17 μm Rdc (30.00;5.00) -14.17 μm Rdc (40.00;5.00) -17.80 μm Rdc (50.00;5.00) -22.55 μm Rdc (60.00;5.00) -27.55 μm Rdc (70.00;5.00) -34.11 μm Rdc (80.00;5.00) -41.96 μm Rdc (90.00;5.00) -52.96 μm Rdc (100.00;5.00) -87.35 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (14.18;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.78 % R Mr (-2.00;5.00) 6.80 % R Mr (-3.00;5.00) 8.15 % R Mr (-4.00;5.00) 9.66 % R Mr (-5.00;5.00) 11.17 % R Mr (-6.00;5.00) 12.35 % R Mr (-7.00;5.00) 13.64 % R Mr (-8.00;5.00) 15.84 % R Mr (-9.00;5.00) 18.32 % R Mr (-10.00;5.00) 19.78 % R Mr (-11.00;5.00) 21.44 % R Mr (-12.00;5.00) 23.29 % R Mr (-13.00;5.00) 25.87 % R Mr (-14.00;5.00) 29.29 % R Mr (-15.00;5.00) 32.62 % R Mr (-16.00;5.00) 34.72 % R Mr (-17.00;5.00) 37.25 % R Mr (-18.00;5.00) 40.56 % R Mr (-19.00;5.00) 43.18 % R Mr (-20.00;5.00) 45.00 % R Mr (-21.00;5.00) 46.77 % R Mr (-22.00;5.00) 48.83 % R Mr (-23.00;5.00) 51.10 % R Mr (-24.00;5.00) 53.22 % R Mr (-25.00;5.00) 55.49 % R Mr (-26.00;5.00) 57.44 % R Mr (-27.00;5.00) 59.04 % R Mr (-28.00;5.00) 60.88 % R Mr (-29.00;5.00) 62.79 % R Mr (-30.00;5.00) 64.51 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 54.50 µm Rz2 64.64 µm Rz3 80.92 µm Rz4 59.54 µm Rz5 55.77 µm Rz sigma 10.73 µm Rz min 54.50 µm Rz max 80.92 µm Rz mean 63.07 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 24.23 µm Rp2 27.11 µm Rp3 40.46 µm Rp4 21.85 µm Rp5 20.61 µm Rp sigma 8.00 µm Rp min 20.61 µm Rp max 40.46 µm Rp mean 26.85 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 38.20 µm R3z2 33.11 µm R3z3 52.52 µm R3z4 36.76 µm R3z5 37.84 µm R3z sigma 7.45 µm R3z min 33.11 µm R3z max 52.52 µm R3z mean 39.69 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 15.92 µm Rdc (10.00;5.00) -6.09 µm Rdc (20.00;5.00) -11.51 µm Rdc (30.00;5.00) -15.92 µm Rdc (40.00;5.00) -20.56 µm Rdc (50.00;5.00) -23.93 µm Rdc (60.00;5.00) -27.68 µm Rdc (70.00;5.00) -31.99 µm Rdc (80.00;5.00) -35.89 µm Rdc (90.00;5.00) -43.85 µm Rdc (100.00;5.00) -65.01 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (15.92;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.63 % R Mr (-2.00;5.00) 6.14 % R Mr (-3.00;5.00) 6.79 % R Mr (-4.00;5.00) 7.48 % R Mr (-5.00;5.00) 8.70 % R Mr (-6.00;5.00) 9.88 % R Mr (-7.00;5.00) 10.87 % R Mr (-8.00;5.00) 12.56 % R Mr (-9.00;5.00) 14.64 % R Mr (-10.00;5.00) 16.62 % R Mr (-11.00;5.00) 18.99 % R Mr (-12.00;5.00) 20.97 % R Mr (-13.00;5.00) 23.09 % R Mr (-14.00;5.00) 25.95 % R Mr (-15.00;5.00) 28.35 % R Mr (-16.00;5.00) 30.21 % R Mr (-17.00;5.00) 32.04 % R Mr (-18.00;5.00) 34.18 % R Mr (-19.00;5.00) 36.28 % R Mr (-20.00;5.00) 38.63 % R Mr (-21.00;5.00) 41.31 % R Mr (-22.00;5.00) 44.44 % R Mr (-23.00;5.00) 47.53 % R Mr (-24.00;5.00) 50.24 % R Mr (-25.00;5.00) 53.39 % R Mr (-26.00;5.00) 56.17 % R Mr (-27.00;5.00) 58.61 % R Mr (-28.00;5.00) 60.67 % R Mr (-29.00;5.00) 62.74 % R Mr (-30.00;5.00) 64.66 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 111.52 µm Rz2 100.92 µm Rz3 71.85 µm Rz4 45.57 µm Rz5 64.94 µm Rz sigma 26.94 µm Rz min 45.57 µm Rz max 111.52 µm Rz mean 78.96 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 49.46 µm Rp2 50.95 µm Rp3 26.04 µm Rp4 25.53 µm Rp5 27.86 µm Rp sigma 13.03 µm Rp min 25.53 µm Rp max 50.95 µm Rp mean 35.97 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [3/3]: R [LC GS: 0.8 mm] R3z1 30.52 µm R3z2 59.42 µm R3z3 41.53 µm R3z4 32.93 µm R3z5 43.31 µm R3z sigma 11.38 µm R3z min 30.52 µm R3z max 59.42 µm R3z mean 41.54 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 21.28 µm Rdc (10.00;5.00) -6.30 µm Rdc (20.00;5.00) -14.87 µm Rdc (30.00;5.00) -20.30 µm Rdc (40.00;5.00) -24.71 µm Rdc (50.00;5.00) -29.17 µm Rdc (60.00;5.00) -32.74 µm Rdc (70.00;5.00) -37.49 µm Rdc (80.00;5.00) -43.63 µm Rdc (90.00;5.00) -52.95 µm Rdc (100.00;5.00) -91.73 µm
Profile [3/3]: R [LC GS: 0.8 mm] R Mr (21.28;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.38 % R Mr (-2.00;5.00) 5.75 % R Mr (-3.00;5.00) 7.01 % R Mr (-4.00;5.00) 8.11 % R Mr (-5.00;5.00) 9.01 % R Mr (-6.00;5.00) 9.66 % R Mr (-7.00;5.00) 10.56 % R Mr (-8.00;5.00) 11.28 % R Mr (-9.00;5.00) 11.84 % R Mr (-10.00;5.00) 12.63 % R Mr (-11.00;5.00) 14.08 % R Mr (-12.00;5.00) 15.43 % R Mr (-13.00;5.00) 16.95 % R Mr (-14.00;5.00) 18.54 % R Mr (-15.00;5.00) 20.24 % R Mr (-16.00;5.00) 22.32 % R Mr (-17.00;5.00) 24.15 % R Mr (-18.00;5.00) 25.84 % R Mr (-19.00;5.00) 27.67 % R Mr (-20.00;5.00) 29.41 % R Mr (-21.00;5.00) 31.15 % R Mr (-22.00;5.00) 33.76 % R Mr (-23.00;5.00) 35.79 % R Mr (-24.00;5.00) 38.41 % R Mr (-25.00;5.00) 40.55 % R Mr (-26.00;5.00) 42.60 % R Mr (-27.00;5.00) 44.67 % R Mr (-28.00;5.00) 46.72 % R Mr (-29.00;5.00) 49.49 % R Mr (-30.00;5.00) 52.42 %	

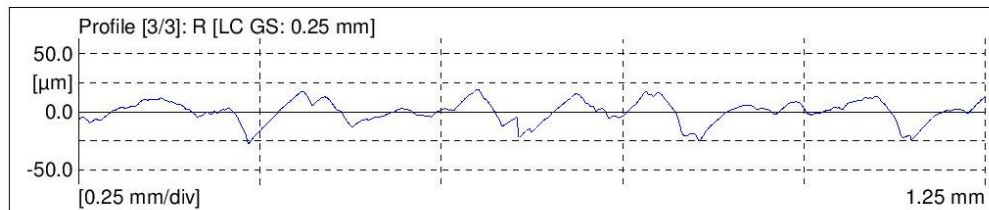
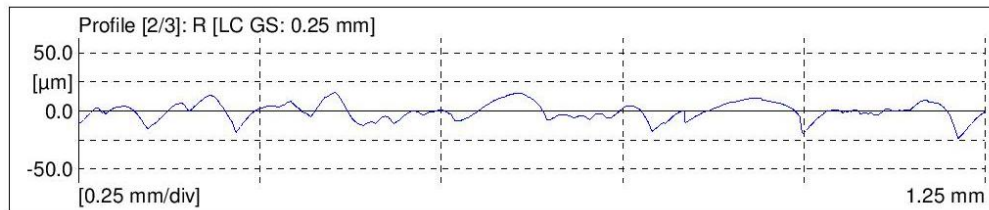
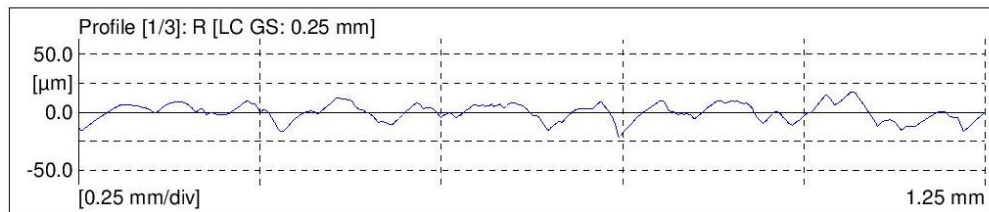
5.08 m/min, face milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μ m
VB: ± 250 μ m
Vt: 0.10 mm/s
Points: 10500 [3]



No Quick&Easy

1

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	6.002	7.372	29.378	33.95	33.95	22.380	38.71	11.66	17.72	8.715	138.07
2:	5.916	7.491	29.389	32.75	32.75	20.890	39.38	12.87	16.52	7.511	157.00
3:	7.362	9.481	39.150	42.43	42.43	29.664	47.00	15.87	23.28	---	194.50
Xb:	6.427	8.115	32.639	36.38	36.38	24.311	41.69	13.47	19.17	8.113	163.19
S:	0.811	1.185	5.639	5.28	5.28	4.695	4.60	2.17	3.61	0.851	28.72
Max:	7.362	9.481	39.150	42.43	42.43	29.664	47.00	15.87	23.28	8.715	194.50
Min:	5.916	7.372	29.378	32.75	32.75	20.890	38.71	11.66	16.52	7.511	138.07
R:	1.447	2.109	9.773	9.68	9.68	8.774	8.29	4.22	6.76	1.203	56.43

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
Rz1	25.48	μm	Rp1	9.45	μm
Rz2	28.95	μm	Rp2	12.25	μm
Rz3	30.33	μm	Rp3	9.07	μm
Rz4	28.19	μm	Rp4	10.07	μm
Rz5	33.95	μm	Rp5	17.44	μm
Rz sigma	3.11	μm	Rp sigma	3.46	μm
Rz min	25.48	μm	Rp min	9.07	μm
Rz max	33.95	μm	Rp max	17.44	μm
Rz mean	29.38	μm	Rp mean	11.66	μm

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
R3z1	7.50	μm	Rdc (0.00;5.00)	7.28	μm
R3z2	5.38	μm	Rdc (10.00;5.00)	-1.46	μm
R3z3	11.57	μm	Rdc (20.00;5.00)	-3.60	μm
R3z4	6.42	μm	Rdc (30.00;5.00)	-5.51	μm
R3z5	12.70	μm	Rdc (40.00;5.00)	-7.69	μm
R3z sigma	3.24	μm	Rdc (50.00;5.00)	-9.87	μm
R3z min	5.38	μm	Rdc (60.00;5.00)	-11.70	μm
R3z max	12.70	μm	Rdc (70.00;5.00)	-13.80	μm
R3z mean	8.71	μm	Rdc (80.00;5.00)	-17.27	μm
			Rdc (90.00;5.00)	-20.92	μm
			Rdc (100.00;5.00)	-31.43	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (7.28;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 8.16 % R Mr (-2.00;5.00) 11.91 % R Mr (-3.00;5.00) 17.09 % R Mr (-4.00;5.00) 22.04 % R Mr (-5.00;5.00) 28.02 % R Mr (-6.00;5.00) 31.80 % R Mr (-7.00;5.00) 36.54 % R Mr (-8.00;5.00) 41.45 % R Mr (-9.00;5.00) 45.07 % R Mr (-10.00;5.00) 50.74 % R Mr (-11.00;5.00) 56.19 % R Mr (-12.00;5.00) 62.43 % R Mr (-13.00;5.00) 67.14 % R Mr (-14.00;5.00) 70.71 % R Mr (-15.00;5.00) 74.39 % R Mr (-16.00;5.00) 76.82 % R Mr (-17.00;5.00) 78.99 % R Mr (-18.00;5.00) 82.03 % R Mr (-19.00;5.00) 85.63 % R Mr (-20.00;5.00) 87.97 % R Mr (-21.00;5.00) 90.29 % R Mr (-22.00;5.00) 91.99 % R Mr (-23.00;5.00) 94.32 % R Mr (-24.00;5.00) 95.69 % R Mr (-25.00;5.00) 96.88 % R Mr (-26.00;5.00) 98.19 % R Mr (-27.00;5.00) 99.28 % R Mr (-28.00;5.00) 99.40 % R Mr (-29.00;5.00) 99.56 % R Mr (-30.00;5.00) 99.68 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 31.56 µm Rz2 28.24 µm Rz3 24.22 µm Rz4 30.17 µm Rz5 32.75 µm Rz sigma 3.34 µm Rz min 24.22 µm Rz max 32.75 µm Rz mean 29.39 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 13.20 µm Rp2 15.79 µm Rp3 15.37 µm Rp4 10.82 µm Rp5 9.17 µm Rp sigma 2.86 µm Rp min 9.17 µm Rp max 15.79 µm Rp mean 12.87 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 15.07 µm R3z2 5.59 µm R3z3 4.26 µm R3z4 10.12 µm R3z5 2.51 µm R3z sigma 5.08 µm R3z min 2.51 µm R3z max 15.07 µm R3z mean 7.51 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 3.90 µm Rdc (10.00;5.00) -2.38 µm Rdc (20.00;5.00) -5.65 µm Rdc (30.00;5.00) -8.45 µm Rdc (40.00;5.00) -10.96 µm Rdc (50.00;5.00) -12.29 µm Rdc (60.00;5.00) -14.03 µm Rdc (70.00;5.00) -15.98 µm Rdc (80.00;5.00) -18.35 µm Rdc (90.00;5.00) -22.00 µm Rdc (100.00;5.00) -35.47 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (3.90;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.52 % R Mr (-2.00;5.00) 9.42 % R Mr (-3.00;5.00) 11.70 % R Mr (-4.00;5.00) 14.28 % R Mr (-5.00;5.00) 17.82 % R Mr (-6.00;5.00) 21.08 % R Mr (-7.00;5.00) 23.58 % R Mr (-8.00;5.00) 28.13 % R Mr (-9.00;5.00) 32.55 % R Mr (-10.00;5.00) 36.45 % R Mr (-11.00;5.00) 40.31 % R Mr (-12.00;5.00) 48.28 % R Mr (-13.00;5.00) 54.60 % R Mr (-14.00;5.00) 59.91 % R Mr (-15.00;5.00) 65.16 % R Mr (-16.00;5.00) 70.09 % R Mr (-17.00;5.00) 74.79 % R Mr (-18.00;5.00) 78.89 % R Mr (-19.00;5.00) 81.83 % R Mr (-20.00;5.00) 84.72 % R Mr (-21.00;5.00) 87.18 % R Mr (-22.00;5.00) 89.99 % R Mr (-23.00;5.00) 92.23 % R Mr (-24.00;5.00) 93.78 % R Mr (-25.00;5.00) 94.96 % R Mr (-26.00;5.00) 95.85 % R Mr (-27.00;5.00) 96.63 % R Mr (-28.00;5.00) 97.39 % R Mr (-29.00;5.00) 98.11 % R Mr (-30.00;5.00) 98.71 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 39.68 µm Rz2 34.04 µm Rz3 41.65 µm Rz4 42.43 µm Rz5 37.94 µm Rz sigma 3.35 µm Rz min 34.04 µm Rz max 42.43 µm Rz mean 39.15 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 11.90 µm Rp2 17.57 µm Rp3 19.21 µm Rp4 17.21 µm Rp5 13.48 µm Rp sigma 3.06 µm Rp min 11.90 µm Rp max 19.21 µm Rp mean 15.87 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 5.00 μm
R3z2	Rdc (10.00;5.00) -2.54 μm
R3z3	Rdc (20.00;5.00) -5.87 μm
R3z4	Rdc (30.00;5.00) -9.29 μm
R3z5	Rdc (40.00;5.00) -11.69 μm
R3z sigma	Rdc (50.00;5.00) -13.09 μm
R3z min	Rdc (60.00;5.00) -15.17 μm
R3z max	Rdc (70.00;5.00) -17.87 μm
R3z mean	Rdc (80.00;5.00) -21.04 μm
	Rdc (90.00;5.00) -28.13 μm
	Rdc (100.00;5.00) -41.99 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:29 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (5.00;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.29 %
R Mr (-2.00;5.00)	8.36 %
R Mr (-3.00;5.00)	11.23 %
R Mr (-4.00;5.00)	14.21 %
R Mr (-5.00;5.00)	17.47 %
R Mr (-6.00;5.00)	20.39 %
R Mr (-7.00;5.00)	23.42 %
R Mr (-8.00;5.00)	26.19 %
R Mr (-9.00;5.00)	29.18 %
R Mr (-10.00;5.00)	32.59 %
R Mr (-11.00;5.00)	36.13 %
R Mr (-12.00;5.00)	42.73 %
R Mr (-13.00;5.00)	49.39 %
R Mr (-14.00;5.00)	54.89 %
R Mr (-15.00;5.00)	59.15 %
R Mr (-16.00;5.00)	63.68 %
R Mr (-17.00;5.00)	67.35 %
R Mr (-18.00;5.00)	70.72 %
R Mr (-19.00;5.00)	74.52 %
R Mr (-20.00;5.00)	77.26 %
R Mr (-21.00;5.00)	79.80 %
R Mr (-22.00;5.00)	82.48 %
R Mr (-23.00;5.00)	84.08 %
R Mr (-24.00;5.00)	85.52 %
R Mr (-25.00;5.00)	86.62 %
R Mr (-26.00;5.00)	87.80 %
R Mr (-27.00;5.00)	88.93 %
R Mr (-28.00;5.00)	89.88 %
R Mr (-29.00;5.00)	90.56 %
R Mr (-30.00;5.00)	91.51 %

No Quick&Easy

6

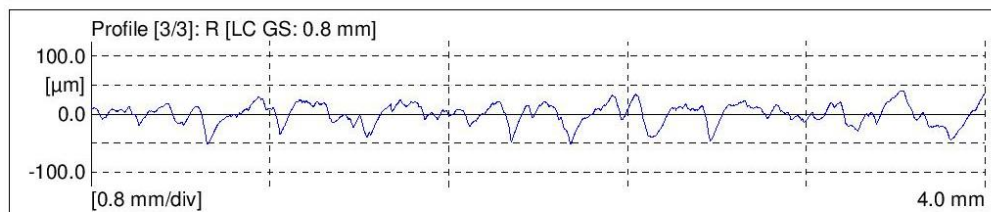
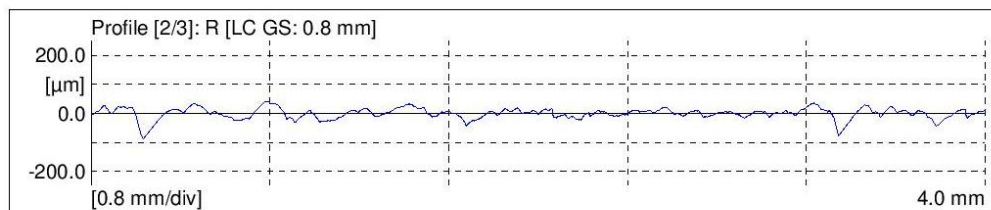
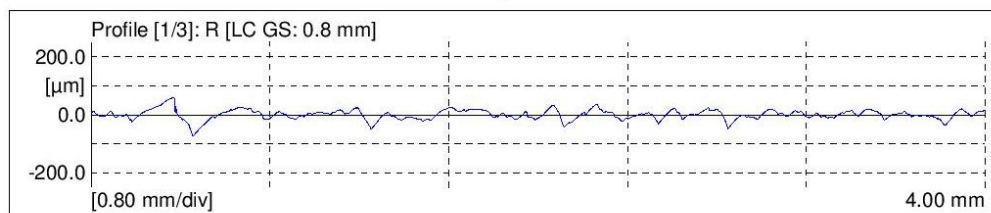
10.16 m/min, peripherally milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 400ipm edge long.prf	 08/30/12, 11:40 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 5.60 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.50 mm/s
Points: 33600 [3]



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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm
1:	12.823	17.010	82.939	131.36	131.36	47.985	131.36	32.60	50.34	33.123	227.47
2:	13.593	18.810	81.614	128.68	128.68	47.103	128.68	30.50	51.11	31.815	201.81
3:	13.935	17.463	78.886	84.23	84.23	47.813	91.47	32.08	46.81	37.811	241.75
Xb:	13.450	17.761	81.147	114.76	114.76	47.634	117.17	31.73	49.42	34.250	223.67
S:	0.570	0.936	2.067	26.47	26.47	0.467	22.30	1.09	2.30	3.153	20.24
Max:	13.935	18.810	82.939	131.36	131.36	47.985	131.36	32.60	51.11	37.811	241.75
Min:	12.823	17.010	78.886	84.23	84.23	47.103	91.47	30.50	46.81	31.815	201.81
R:	1.112	1.800	4.053	47.13	47.13	0.882	39.89	2.10	4.31	5.996	39.94

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
Rz1	131.36 μm	Rp1	58.72 μm
Rz2	74.28 μm	Rp2	24.34 μm
Rz3	78.71 μm	Rp3	35.38 μm
Rz4	72.67 μm	Rp4	24.27 μm
Rz5	57.68 μm	Rp5	20.30 μm
Rz sigma	28.20 μm	Rp sigma	15.64 μm
Rz min	57.68 μm	Rp min	20.30 μm
Rz max	131.36 μm	Rp max	58.72 μm
Rz mean	82.94 μm	Rp mean	32.60 μm

Profile [1/3]: R [LC GS: 0.8 mm]		Profile [1/3]: R [LC GS: 0.8 mm]	
R3z1	29.32 μm	Rdc (0.00;5.00)	34.94 μm
R3z2	30.29 μm	Rdc (10.00;5.00)	-4.88 μm
R3z3	43.17 μm	Rdc (20.00;5.00)	-10.49 μm
R3z4	36.48 μm	Rdc (30.00;5.00)	-15.05 μm
R3z5	26.36 μm	Rdc (40.00;5.00)	-18.86 μm
R3z sigma	6.72 μm	Rdc (50.00;5.00)	-23.05 μm
R3z min	26.36 μm	Rdc (60.00;5.00)	-27.53 μm
R3z max	43.17 μm	Rdc (70.00;5.00)	-31.03 μm
R3z mean	33.12 μm	Rdc (80.00;5.00)	-35.37 μm
		Rdc (90.00;5.00)	-42.11 μm
		Rdc (100.00;5.00)	-96.42 μm

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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (34.94;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.89 % R Mr (-2.00;5.00) 6.67 % R Mr (-3.00;5.00) 7.47 % R Mr (-4.00;5.00) 8.50 % R Mr (-5.00;5.00) 10.24 % R Mr (-6.00;5.00) 12.15 % R Mr (-7.00;5.00) 14.18 % R Mr (-8.00;5.00) 15.76 % R Mr (-9.00;5.00) 17.53 % R Mr (-10.00;5.00) 19.16 % R Mr (-11.00;5.00) 21.01 % R Mr (-12.00;5.00) 23.36 % R Mr (-13.00;5.00) 25.62 % R Mr (-14.00;5.00) 27.70 % R Mr (-15.00;5.00) 29.88 % R Mr (-16.00;5.00) 32.23 % R Mr (-17.00;5.00) 34.69 % R Mr (-18.00;5.00) 37.60 % R Mr (-19.00;5.00) 40.29 % R Mr (-20.00;5.00) 42.65 % R Mr (-21.00;5.00) 44.91 % R Mr (-22.00;5.00) 47.34 % R Mr (-23.00;5.00) 49.87 % R Mr (-24.00;5.00) 52.42 % R Mr (-25.00;5.00) 54.26 % R Mr (-26.00;5.00) 55.80 % R Mr (-27.00;5.00) 58.51 % R Mr (-28.00;5.00) 61.38 % R Mr (-29.00;5.00) 64.01 % R Mr (-30.00;5.00) 66.79 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 128.68 µm Rz2 66.02 µm Rz3 61.77 µm Rz4 38.46 µm Rz5 113.14 µm Rz sigma 37.78 µm Rz min 38.46 µm Rz max 128.68 µm Rz mean 81.61 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 41.58 µm Rp2 34.96 µm Rp3 18.62 µm Rp4 21.80 µm Rp5 35.53 µm Rp sigma 9.81 µm Rp min 18.62 µm Rp max 41.58 µm Rp mean 30.50 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 31.06 µm R3z2 31.55 µm R3z3 31.59 µm R3z4 25.10 µm R3z5 39.77 µm R3z sigma 5.22 µm R3z min 25.10 µm R3z max 39.77 µm R3z mean 31.81 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 400ipm edge long.prf	 08/30/12, 11:40 AM
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Profile [2/3]: R [LC GS: 0.8 mm] <table> <tr><td>Rdc (0.00;5.00)</td><td>14.02 μm</td></tr> <tr><td>Rdc (10.00;5.00)</td><td>-6.53 μm</td></tr> <tr><td>Rdc (20.00;5.00)</td><td>-15.23 μm</td></tr> <tr><td>Rdc (30.00;5.00)</td><td>-19.45 μm</td></tr> <tr><td>Rdc (40.00;5.00)</td><td>-22.30 μm</td></tr> <tr><td>Rdc (50.00;5.00)</td><td>-25.42 μm</td></tr> <tr><td>Rdc (60.00;5.00)</td><td>-29.40 μm</td></tr> <tr><td>Rdc (70.00;5.00)</td><td>-34.37 μm</td></tr> <tr><td>Rdc (80.00;5.00)</td><td>-39.70 μm</td></tr> <tr><td>Rdc (90.00;5.00)</td><td>-50.50 μm</td></tr> <tr><td>Rdc (100.00;5.00)</td><td>-114.66 μm</td></tr> </table>	Rdc (0.00;5.00)	14.02 μm	Rdc (10.00;5.00)	-6.53 μm	Rdc (20.00;5.00)	-15.23 μm	Rdc (30.00;5.00)	-19.45 μm	Rdc (40.00;5.00)	-22.30 μm	Rdc (50.00;5.00)	-25.42 μm	Rdc (60.00;5.00)	-29.40 μm	Rdc (70.00;5.00)	-34.37 μm	Rdc (80.00;5.00)	-39.70 μm	Rdc (90.00;5.00)	-50.50 μm	Rdc (100.00;5.00)	-114.66 μm	Profile [2/3]: R [LC GS: 0.8 mm] <table> <tr><td>R Mr (14.02;5.00)</td><td>0.00 %</td></tr> <tr><td>R Mr (0.00;5.00)</td><td>5.00 %</td></tr> <tr><td>R Mr (-1.00;5.00)</td><td>5.50 %</td></tr> <tr><td>R Mr (-2.00;5.00)</td><td>6.07 %</td></tr> <tr><td>R Mr (-3.00;5.00)</td><td>6.54 %</td></tr> <tr><td>R Mr (-4.00;5.00)</td><td>7.34 %</td></tr> <tr><td>R Mr (-5.00;5.00)</td><td>8.20 %</td></tr> <tr><td>R Mr (-6.00;5.00)</td><td>9.25 %</td></tr> <tr><td>R Mr (-7.00;5.00)</td><td>10.63 %</td></tr> <tr><td>R Mr (-8.00;5.00)</td><td>11.45 %</td></tr> <tr><td>R Mr (-9.00;5.00)</td><td>12.38 %</td></tr> <tr><td>R Mr (-10.00;5.00)</td><td>13.60 %</td></tr> <tr><td>R Mr (-11.00;5.00)</td><td>14.71 %</td></tr> <tr><td>R Mr (-12.00;5.00)</td><td>15.73 %</td></tr> <tr><td>R Mr (-13.00;5.00)</td><td>17.12 %</td></tr> <tr><td>R Mr (-14.00;5.00)</td><td>18.37 %</td></tr> <tr><td>R Mr (-15.00;5.00)</td><td>19.59 %</td></tr> <tr><td>R Mr (-16.00;5.00)</td><td>21.43 %</td></tr> <tr><td>R Mr (-17.00;5.00)</td><td>23.58 %</td></tr> <tr><td>R Mr (-18.00;5.00)</td><td>26.48 %</td></tr> <tr><td>R Mr (-19.00;5.00)</td><td>28.85 %</td></tr> <tr><td>R Mr (-20.00;5.00)</td><td>31.58 %</td></tr> <tr><td>R Mr (-21.00;5.00)</td><td>35.54 %</td></tr> <tr><td>R Mr (-22.00;5.00)</td><td>38.89 %</td></tr> <tr><td>R Mr (-23.00;5.00)</td><td>42.57 %</td></tr> <tr><td>R Mr (-24.00;5.00)</td><td>45.88 %</td></tr> <tr><td>R Mr (-25.00;5.00)</td><td>48.79 %</td></tr> <tr><td>R Mr (-26.00;5.00)</td><td>51.87 %</td></tr> <tr><td>R Mr (-27.00;5.00)</td><td>54.52 %</td></tr> <tr><td>R Mr (-28.00;5.00)</td><td>56.94 %</td></tr> <tr><td>R Mr (-29.00;5.00)</td><td>59.06 %</td></tr> <tr><td>R Mr (-30.00;5.00)</td><td>61.41 %</td></tr> </table>	R Mr (14.02;5.00)	0.00 %	R Mr (0.00;5.00)	5.00 %	R Mr (-1.00;5.00)	5.50 %	R Mr (-2.00;5.00)	6.07 %	R Mr (-3.00;5.00)	6.54 %	R Mr (-4.00;5.00)	7.34 %	R Mr (-5.00;5.00)	8.20 %	R Mr (-6.00;5.00)	9.25 %	R Mr (-7.00;5.00)	10.63 %	R Mr (-8.00;5.00)	11.45 %	R Mr (-9.00;5.00)	12.38 %	R Mr (-10.00;5.00)	13.60 %	R Mr (-11.00;5.00)	14.71 %	R Mr (-12.00;5.00)	15.73 %	R Mr (-13.00;5.00)	17.12 %	R Mr (-14.00;5.00)	18.37 %	R Mr (-15.00;5.00)	19.59 %	R Mr (-16.00;5.00)	21.43 %	R Mr (-17.00;5.00)	23.58 %	R Mr (-18.00;5.00)	26.48 %	R Mr (-19.00;5.00)	28.85 %	R Mr (-20.00;5.00)	31.58 %	R Mr (-21.00;5.00)	35.54 %	R Mr (-22.00;5.00)	38.89 %	R Mr (-23.00;5.00)	42.57 %	R Mr (-24.00;5.00)	45.88 %	R Mr (-25.00;5.00)	48.79 %	R Mr (-26.00;5.00)	51.87 %	R Mr (-27.00;5.00)	54.52 %	R Mr (-28.00;5.00)	56.94 %	R Mr (-29.00;5.00)	59.06 %	R Mr (-30.00;5.00)	61.41 %
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Profile [3/3]: R [LC GS: 0.8 mm] <table> <tr><td>Rz1</td><td>81.69 μm</td></tr> <tr><td>Rz2</td><td>64.74 μm</td></tr> <tr><td>Rz3</td><td>83.57 μm</td></tr> <tr><td>Rz4</td><td>80.21 μm</td></tr> <tr><td>Rz5</td><td>84.23 μm</td></tr> <tr><td>Rz sigma</td><td>8.07 μm</td></tr> <tr><td>Rz min</td><td>64.74 μm</td></tr> <tr><td>Rz max</td><td>84.23 μm</td></tr> <tr><td>Rz mean</td><td>78.89 μm</td></tr> </table>	Rz1	81.69 μm	Rz2	64.74 μm	Rz3	83.57 μm	Rz4	80.21 μm	Rz5	84.23 μm	Rz sigma	8.07 μm	Rz min	64.74 μm	Rz max	84.23 μm	Rz mean	78.89 μm	Profile [3/3]: R [LC GS: 0.8 mm] <table> <tr><td>Rp1</td><td>29.92 μm</td></tr> <tr><td>Rp2</td><td>24.52 μm</td></tr> <tr><td>Rp3</td><td>32.12 μm</td></tr> <tr><td>Rp4</td><td>34.15 μm</td></tr> <tr><td>Rp5</td><td>39.70 μm</td></tr> <tr><td>Rp sigma</td><td>5.57 μm</td></tr> <tr><td>Rp min</td><td>24.52 μm</td></tr> <tr><td>Rp max</td><td>39.70 μm</td></tr> <tr><td>Rp mean</td><td>32.08 μm</td></tr> </table>	Rp1	29.92 μm	Rp2	24.52 μm	Rp3	32.12 μm	Rp4	34.15 μm	Rp5	39.70 μm	Rp sigma	5.57 μm	Rp min	24.52 μm	Rp max	39.70 μm	Rp mean	32.08 μm																																																		
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 400ipm edge long.prf	 08/30/12, 11:40 AM
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Profile [3/3]: R [LC GS: 0.8 mm]		Profile [3/3]: R [LC GS: 0.8 mm]	
R3z1	32.98 μm	Rdc (0.00;5.00)	16.17 μm
R3z2	45.29 μm	Rdc (10.00;5.00)	-3.82 μm
R3z3	42.34 μm	Rdc (20.00;5.00)	-9.09 μm
R3z4	31.70 μm	Rdc (30.00;5.00)	-13.24 μm
R3z5	36.75 μm	Rdc (40.00;5.00)	-16.92 μm
R3z sigma	5.88 μm	Rdc (50.00;5.00)	-21.62 μm
R3z min	31.70 μm	Rdc (60.00;5.00)	-26.48 μm
R3z max	45.29 μm	Rdc (70.00;5.00)	-31.21 μm
R3z mean	37.81 μm	Rdc (80.00;5.00)	-37.79 μm
		Rdc (90.00;5.00)	-48.15 μm
		Rdc (100.00;5.00)	-75.30 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc cb1100 DOE 6k 400ipm edge long.prf	 08/30/12, 11:40 AM
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Profile [3/3]: R [LC GS: 0.8 mm]	
R Mr (16.17;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	5.79 %
R Mr (-2.00;5.00)	6.62 %
R Mr (-3.00;5.00)	8.34 %
R Mr (-4.00;5.00)	10.45 %
R Mr (-5.00;5.00)	12.20 %
R Mr (-6.00;5.00)	13.93 %
R Mr (-7.00;5.00)	15.85 %
R Mr (-8.00;5.00)	17.79 %
R Mr (-9.00;5.00)	19.79 %
R Mr (-10.00;5.00)	22.33 %
R Mr (-11.00;5.00)	24.81 %
R Mr (-12.00;5.00)	27.04 %
R Mr (-13.00;5.00)	29.35 %
R Mr (-14.00;5.00)	32.10 %
R Mr (-15.00;5.00)	34.59 %
R Mr (-16.00;5.00)	37.21 %
R Mr (-17.00;5.00)	40.21 %
R Mr (-18.00;5.00)	42.68 %
R Mr (-19.00;5.00)	45.04 %
R Mr (-20.00;5.00)	46.99 %
R Mr (-21.00;5.00)	48.65 %
R Mr (-22.00;5.00)	50.70 %
R Mr (-23.00;5.00)	52.37 %
R Mr (-24.00;5.00)	54.80 %
R Mr (-25.00;5.00)	57.03 %
R Mr (-26.00;5.00)	59.10 %
R Mr (-27.00;5.00)	61.26 %
R Mr (-28.00;5.00)	63.58 %
R Mr (-29.00;5.00)	65.52 %
R Mr (-30.00;5.00)	67.55 %

No Quick&Easy

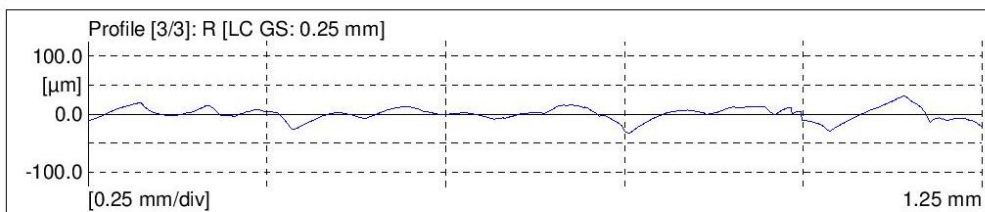
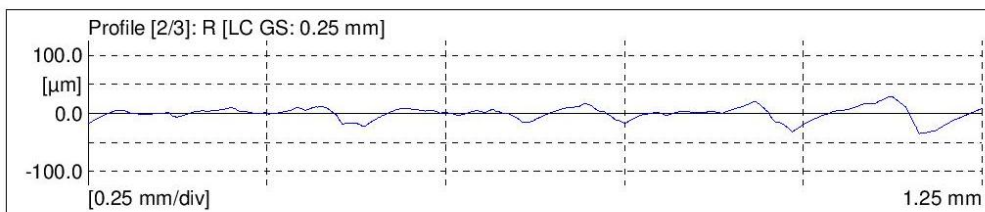
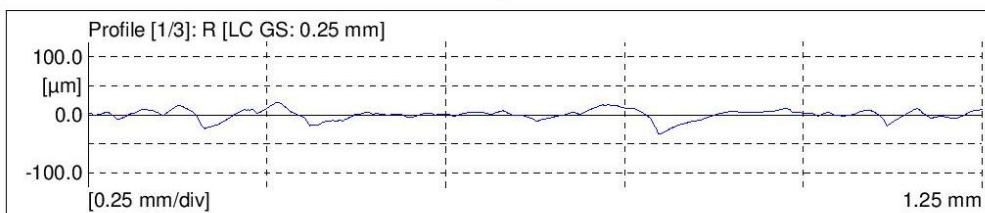
6

10.16 m/min, peripherally milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/30/12, 10:44 AM
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [8.0 %]	Lt: 1.75 mm [N=5] Ls: 2.5 μ m VB: $\pm$ 250 μ m Vt: 0.10 mm/s Points: 10500 [3]
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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:44 AM
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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	6.652	9.002	36.356	45.47	45.47	25.338	54.90	15.13	21.22	---	166.43 ...
2:	8.218	11.287	42.634	63.64	63.64	35.058	63.64	17.55	25.09	---	200.75 ...
3:	8.528	11.159	44.486	60.86	60.86	33.256	64.08	18.54	25.95	---	211.40 ...
Xb:	7.800	10.483	41.159	56.65	56.65	31.217	60.87	17.07	24.09	192.86	
S:	1.006	1.284	4.261	9.79	9.79	5.171	5.18	1.75	2.52	23.50	
Max:	8.528	11.287	44.486	63.64	63.64	35.058	64.08	18.54	25.95	211.40	
Min:	6.652	9.002	36.356	45.47	45.47	25.338	54.90	15.13	21.22	166.43	
R:	1.877	2.285	8.129	18.17	18.17	9.720	9.18	3.41	4.72	44.97	

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
Rz1	39.35	μm	Rp1	15.42	μm
Rz2	40.11	μm	Rp2	21.18	μm
Rz3	27.79	μm	Rp3	16.99	μm
Rz4	45.47	μm	Rp4	11.75	μm
Rz5	29.06	μm	Rp5	10.32	μm
Rz sigma	7.63	μm	Rp sigma	4.32	μm
Rz min	27.79	μm	Rp min	10.32	μm
Rz max	45.47	μm	Rp max	21.18	μm
Rz mean	36.36	μm	Rp mean	15.13	μm

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
R3z1	---	μm	Rdc (0.00;5.00)	7.29	μm
R3z2	---	μm	Rdc (10.00;5.00)	-4.07	μm
R3z3	---	μm	Rdc (20.00;5.00)	-7.54	μm
R3z4	---	μm	Rdc (30.00;5.00)	-9.79	μm
R3z5	---	μm	Rdc (40.00;5.00)	-10.82	μm
R3z sigma	---	μm	Rdc (50.00;5.00)	-12.59	μm
R3z min	---	μm	Rdc (60.00;5.00)	-14.11	μm
R3z max	---	μm	Rdc (70.00;5.00)	-16.16	μm
R3z mean	---	μm	Rdc (80.00;5.00)	-19.78	μm
			Rdc (90.00;5.00)	-25.68	μm
			Rdc (100.00;5.00)	-47.61	μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:44 AM
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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (7.29;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.87 % R Mr (-2.00;5.00) 6.64 % R Mr (-3.00;5.00) 7.36 % R Mr (-4.00;5.00) 9.93 % R Mr (-5.00;5.00) 12.03 % R Mr (-6.00;5.00) 15.49 % R Mr (-7.00;5.00) 18.41 % R Mr (-8.00;5.00) 21.44 % R Mr (-9.00;5.00) 25.90 % R Mr (-10.00;5.00) 31.67 % R Mr (-11.00;5.00) 41.22 % R Mr (-12.00;5.00) 46.19 % R Mr (-13.00;5.00) 52.94 % R Mr (-14.00;5.00) 59.28 % R Mr (-15.00;5.00) 64.85 % R Mr (-16.00;5.00) 69.57 % R Mr (-17.00;5.00) 72.30 % R Mr (-18.00;5.00) 75.46 % R Mr (-19.00;5.00) 78.38 % R Mr (-20.00;5.00) 80.93 % R Mr (-21.00;5.00) 82.78 % R Mr (-22.00;5.00) 84.24 % R Mr (-23.00;5.00) 85.16 % R Mr (-24.00;5.00) 86.91 % R Mr (-25.00;5.00) 89.48 % R Mr (-26.00;5.00) 90.32 % R Mr (-27.00;5.00) 90.98 % R Mr (-28.00;5.00) 91.68 % R Mr (-29.00;5.00) 92.32 % R Mr (-30.00;5.00) 93.14 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 28.28 µm Rz2 33.91 µm Rz3 34.74 µm Rz4 52.60 µm Rz5 63.64 µm Rz sigma 14.87 µm Rz min 28.28 µm Rz max 63.64 µm Rz mean 42.63 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 9.87 µm Rp2 11.45 µm Rp3 16.87 µm Rp4 20.76 µm Rp5 28.80 µm Rp sigma 7.64 µm Rp min 9.87 µm Rp max 28.80 µm Rp mean 17.55 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:44 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 11.87 µm Rdc (10.00;5.00) -5.64 µm Rdc (20.00;5.00) -9.68 µm Rdc (30.00;5.00) -12.25 µm Rdc (40.00;5.00) -13.81 µm Rdc (50.00;5.00) -15.67 µm Rdc (60.00;5.00) -17.02 µm Rdc (70.00;5.00) -19.41 µm Rdc (80.00;5.00) -25.67 µm Rdc (90.00;5.00) -33.73 µm Rdc (100.00;5.00) -51.77 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (11.87;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.96 % R Mr (-2.00;5.00) 6.69 % R Mr (-3.00;5.00) 7.54 % R Mr (-4.00;5.00) 8.20 % R Mr (-5.00;5.00) 8.85 % R Mr (-6.00;5.00) 10.97 % R Mr (-7.00;5.00) 12.81 % R Mr (-8.00;5.00) 15.19 % R Mr (-9.00;5.00) 18.21 % R Mr (-10.00;5.00) 20.70 % R Mr (-11.00;5.00) 24.20 % R Mr (-12.00;5.00) 28.66 % R Mr (-13.00;5.00) 34.90 % R Mr (-14.00;5.00) 41.30 % R Mr (-15.00;5.00) 46.13 % R Mr (-16.00;5.00) 52.96 % R Mr (-17.00;5.00) 59.92 % R Mr (-18.00;5.00) 64.87 % R Mr (-19.00;5.00) 68.54 % R Mr (-20.00;5.00) 71.36 % R Mr (-21.00;5.00) 73.51 % R Mr (-22.00;5.00) 75.00 % R Mr (-23.00;5.00) 76.81 % R Mr (-24.00;5.00) 78.14 % R Mr (-25.00;5.00) 79.30 % R Mr (-26.00;5.00) 80.41 % R Mr (-27.00;5.00) 81.58 % R Mr (-28.00;5.00) 82.66 % R Mr (-29.00;5.00) 83.81 % R Mr (-30.00;5.00) 85.15 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 32.41 µm Rz2 39.14 µm Rz3 43.58 µm Rz4 46.44 µm Rz5 60.86 µm Rz sigma 10.57 µm Rz min 32.41 µm Rz max 60.86 µm Rz mean 44.49 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 19.55 µm Rp2 12.66 µm Rp3 16.12 µm Rp4 13.36 µm Rp5 31.00 µm Rp sigma 7.47 µm Rp min 12.66 µm Rp max 31.00 µm Rp mean 18.54 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:44 AM
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Profile [3/3]: R [LC GS: 0.25 mm]		Profile [3/3]: R [LC GS: 0.25 mm]	
R3z1	-.- μm	Rdc (0.00;5.00)	14.92 μm
R3z2	-.- μm	Rdc (10.00;5.00)	-2.87 μm
R3z3	-.- μm	Rdc (20.00;5.00)	-5.85 μm
R3z4	-.- μm	Rdc (30.00;5.00)	-10.22 μm
R3z5	-.- μm	Rdc (40.00;5.00)	-13.09 μm
R3z sigma	-.- μm	Rdc (50.00;5.00)	-14.78 μm
R3z min	-.- μm	Rdc (60.00;5.00)	-16.90 μm
R3z max	-.- μm	Rdc (70.00;5.00)	-19.68 μm
R3z mean	-.- μm	Rdc (80.00;5.00)	-23.93 μm
		Rdc (90.00;5.00)	-30.32 μm
		Rdc (100.00;5.00)	-49.15 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:44 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (14.92;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	6.61 %
R Mr (-2.00;5.00)	8.60 %
R Mr (-3.00;5.00)	10.41 %
R Mr (-4.00;5.00)	13.57 %
R Mr (-5.00;5.00)	17.66 %
R Mr (-6.00;5.00)	20.16 %
R Mr (-7.00;5.00)	22.16 %
R Mr (-8.00;5.00)	23.87 %
R Mr (-9.00;5.00)	26.07 %
R Mr (-10.00;5.00)	29.42 %
R Mr (-11.00;5.00)	31.89 %
R Mr (-12.00;5.00)	34.99 %
R Mr (-13.00;5.00)	39.68 %
R Mr (-14.00;5.00)	44.95 %
R Mr (-15.00;5.00)	51.26 %
R Mr (-16.00;5.00)	55.87 %
R Mr (-17.00;5.00)	60.49 %
R Mr (-18.00;5.00)	63.83 %
R Mr (-19.00;5.00)	68.35 %
R Mr (-20.00;5.00)	70.69 %
R Mr (-21.00;5.00)	72.70 %
R Mr (-22.00;5.00)	74.42 %
R Mr (-23.00;5.00)	76.72 %
R Mr (-24.00;5.00)	80.20 %
R Mr (-25.00;5.00)	82.56 %
R Mr (-26.00;5.00)	83.92 %
R Mr (-27.00;5.00)	85.40 %
R Mr (-28.00;5.00)	87.32 %
R Mr (-29.00;5.00)	88.60 %
R Mr (-30.00;5.00)	89.64 %

No Quick&Easy

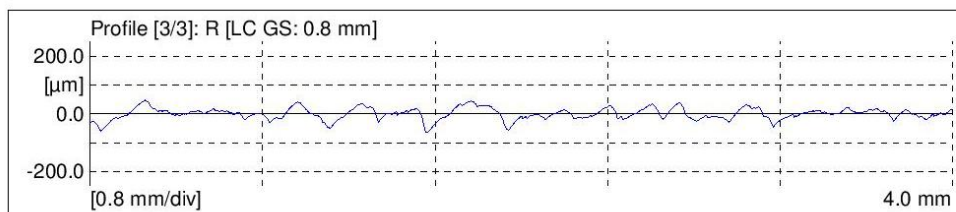
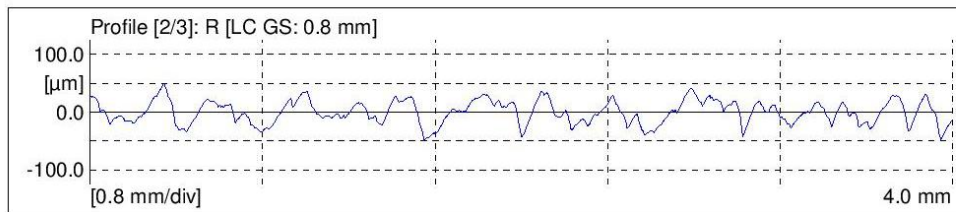
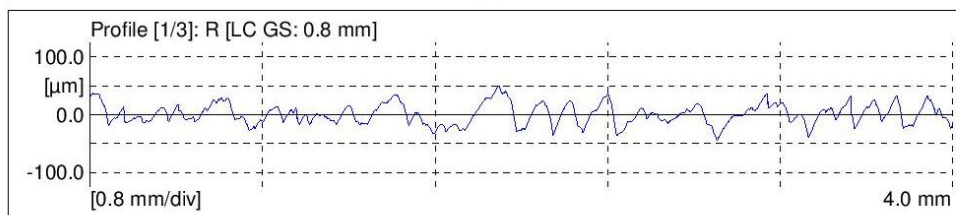
6

10.16 m/min, face milled, longitudinal direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory	 08/29/12
	apoc New Measurement	

Object: Number: Comment:

Meas. Instrum.: Mahr Data Acquisition Board Drive Unit: GD 25 Pick-up: MFW-250 [9.2 %]	Lt: 5.60 mm [N=5] Ls: 2.5 µm VB: ±250 µm Vt: 0.50 mm/s Points: 33600 [3]
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	Ra	Rq	Rz	Rz1	m...	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm	µm ...
1:	14.103	17.287	73.991	85.94	85.94	85.94	45.825	94.75	38.25	35.74	43.657	195.24 ...
2:	16.350	19.619	82.384	85.19	85.19	85.19	58.013	99.16	38.88	43.50	45.702	274.69 ...
3:	15.397	19.874	88.859	106.15	106.15	106.15	60.048	111.99	38.46	50.39	33.233	316.00 ...
Xb:	15.283	18.927	81.745	92.42	92.42	92.42	54.629	101.96	38.53	43.21	40.864	261.98
S:	1.128	1.426	7.454	11.89	11.89	11.89	7.692	8.96	0.32	7.33	6.687	61.38
Max:	16.350	19.874	88.859	106.15	106.15	106.15	60.048	111.99	38.88	50.39	45.702	316.00
Min:	14.103	17.287	73.991	85.19	85.19	85.19	45.825	94.75	38.25	35.74	33.233	195.24
R:	2.248	2.587	14.868	20.96	20.96	20.96	14.224	17.24	0.63	14.66	12.469	120.76

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [1/3]: R [LC GS: 0.8 mm] Rz1 63.29 μm Rz2 67.24 μm Rz3 85.94 μm Rz4 81.31 μm Rz5 72.18 μm Rz sigma 9.48 μm Rz min 63.29 μm Rz max 85.94 μm Rz mean 73.99 μm	Profile [1/3]: R [LC GS: 0.8 mm] Rp1 36.68 μm Rp2 34.12 μm Rp3 50.30 μm Rp4 36.86 μm Rp5 33.32 μm Rp sigma 6.91 μm Rp min 33.32 μm Rp max 50.30 μm Rp mean 38.25 μm
Profile [1/3]: R [LC GS: 0.8 mm] R3z1 40.57 μm R3z2 31.03 μm R3z3 53.86 μm R3z4 36.46 μm R3z5 56.37 μm R3z sigma 11.03 μm R3z min 31.03 μm R3z max 56.37 μm R3z mean 43.66 μm	Profile [1/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 19.70 μm Rdc (10.00;5.00) -5.81 μm Rdc (20.00;5.00) -14.39 μm Rdc (30.00;5.00) -20.86 μm Rdc (40.00;5.00) -25.70 μm Rdc (50.00;5.00) -31.24 μm Rdc (60.00;5.00) -35.76 μm Rdc (70.00;5.00) -39.92 μm Rdc (80.00;5.00) -44.76 μm Rdc (90.00;5.00) -51.75 μm Rdc (100.00;5.00) -75.05 μm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [1/3]: R [LC GS: 0.8 mm] R Mr (19.70;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.57 % R Mr (-2.00;5.00) 6.31 % R Mr (-3.00;5.00) 7.43 % R Mr (-4.00;5.00) 8.25 % R Mr (-5.00;5.00) 9.15 % R Mr (-6.00;5.00) 10.15 % R Mr (-7.00;5.00) 11.14 % R Mr (-8.00;5.00) 12.20 % R Mr (-9.00;5.00) 13.19 % R Mr (-10.00;5.00) 14.47 % R Mr (-11.00;5.00) 15.98 % R Mr (-12.00;5.00) 17.35 % R Mr (-13.00;5.00) 18.44 % R Mr (-14.00;5.00) 19.53 % R Mr (-15.00;5.00) 20.77 % R Mr (-16.00;5.00) 22.24 % R Mr (-17.00;5.00) 23.35 % R Mr (-18.00;5.00) 24.87 % R Mr (-19.00;5.00) 26.68 % R Mr (-20.00;5.00) 28.57 % R Mr (-21.00;5.00) 30.24 % R Mr (-22.00;5.00) 32.47 % R Mr (-23.00;5.00) 34.71 % R Mr (-24.00;5.00) 37.12 % R Mr (-25.00;5.00) 38.86 % R Mr (-26.00;5.00) 40.46 % R Mr (-27.00;5.00) 41.99 % R Mr (-28.00;5.00) 43.82 % R Mr (-29.00;5.00) 45.49 % R Mr (-30.00;5.00) 47.30 %	Profile [2/3]: R [LC GS: 0.8 mm] Rz1 84.46 µm Rz2 85.19 µm Rz3 80.41 µm Rz4 83.51 µm Rz5 78.36 µm Rz sigma 2.90 µm Rz min 78.36 µm Rz max 85.19 µm Rz mean 82.38 µm
Profile [2/3]: R [LC GS: 0.8 mm] Rp1 49.82 µm Rp2 35.85 µm Rp3 36.57 µm Rp4 41.43 µm Rp5 30.74 µm Rp sigma 7.19 µm Rp min 30.74 µm Rp max 49.82 µm Rp mean 38.88 µm	Profile [2/3]: R [LC GS: 0.8 mm] R3z1 43.23 µm R3z2 37.51 µm R3z3 44.27 µm R3z4 56.81 µm R3z5 46.69 µm R3z sigma 7.06 µm R3z min 37.51 µm R3z max 56.81 µm R3z mean 45.70 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [2/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 20.35 µm Rdc (10.00;5.00) -4.19 µm Rdc (20.00;5.00) -11.16 µm Rdc (30.00;5.00) -16.92 µm Rdc (40.00;5.00) -23.14 µm Rdc (50.00;5.00) -29.41 µm Rdc (60.00;5.00) -35.51 µm Rdc (70.00;5.00) -40.15 µm Rdc (80.00;5.00) -47.98 µm Rdc (90.00;5.00) -57.25 µm Rdc (100.00;5.00) -78.80 µm	Profile [2/3]: R [LC GS: 0.8 mm] R Mr (20.35;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.99 % R Mr (-2.00;5.00) 6.91 % R Mr (-3.00;5.00) 8.37 % R Mr (-4.00;5.00) 9.67 % R Mr (-5.00;5.00) 11.25 % R Mr (-6.00;5.00) 12.51 % R Mr (-7.00;5.00) 13.58 % R Mr (-8.00;5.00) 15.01 % R Mr (-9.00;5.00) 16.19 % R Mr (-10.00;5.00) 17.75 % R Mr (-11.00;5.00) 19.57 % R Mr (-12.00;5.00) 21.21 % R Mr (-13.00;5.00) 22.94 % R Mr (-14.00;5.00) 24.98 % R Mr (-15.00;5.00) 26.68 % R Mr (-16.00;5.00) 28.30 % R Mr (-17.00;5.00) 30.17 % R Mr (-18.00;5.00) 32.19 % R Mr (-19.00;5.00) 33.78 % R Mr (-20.00;5.00) 35.41 % R Mr (-21.00;5.00) 37.32 % R Mr (-22.00;5.00) 38.79 % R Mr (-23.00;5.00) 39.88 % R Mr (-24.00;5.00) 40.88 % R Mr (-25.00;5.00) 41.95 % R Mr (-26.00;5.00) 43.28 % R Mr (-27.00;5.00) 45.09 % R Mr (-28.00;5.00) 47.03 % R Mr (-29.00;5.00) 49.07 % R Mr (-30.00;5.00) 50.91 %
Profile [3/3]: R [LC GS: 0.8 mm] Rz1 106.15 µm Rz2 105.76 µm Rz3 99.69 µm Rz4 84.43 µm Rz5 48.26 µm Rz sigma 24.34 µm Rz min 48.26 µm Rz max 106.15 µm Rz mean 88.86 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rp1 46.86 µm Rp2 40.63 µm Rp3 43.68 µm Rp4 38.59 µm Rp5 22.56 µm Rp sigma 9.43 µm Rp min 22.56 µm Rp max 46.86 µm Rp mean 38.46 µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/29/12
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Profile [3/3]: R [LC GS: 0.8 mm] R3z1 18.05 µm R3z2 48.48 µm R3z3 16.58 µm R3z4 58.21 µm R3z5 24.85 µm R3z sigma 18.94 µm R3z min 16.58 µm R3z max 58.21 µm R3z mean 33.23 µm	Profile [3/3]: R [LC GS: 0.8 mm] Rdc (0.00;5.00) 14.50 µm Rdc (10.00;5.00) -5.36 µm Rdc (20.00;5.00) -16.74 µm Rdc (30.00;5.00) -22.66 µm Rdc (40.00;5.00) -27.14 µm Rdc (50.00;5.00) -31.96 µm Rdc (60.00;5.00) -36.33 µm Rdc (70.00;5.00) -41.83 µm Rdc (80.00;5.00) -46.86 µm Rdc (90.00;5.00) -55.96 µm Rdc (100.00;5.00) -97.49 µm
Profile [3/3]: R [LC GS: 0.8 mm] R Mr (14.50;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 5.50 % R Mr (-2.00;5.00) 6.17 % R Mr (-3.00;5.00) 6.89 % R Mr (-4.00;5.00) 8.36 % R Mr (-5.00;5.00) 9.56 % R Mr (-6.00;5.00) 10.44 % R Mr (-7.00;5.00) 11.09 % R Mr (-8.00;5.00) 11.64 % R Mr (-9.00;5.00) 12.47 % R Mr (-10.00;5.00) 13.42 % R Mr (-11.00;5.00) 14.17 % R Mr (-12.00;5.00) 15.17 % R Mr (-13.00;5.00) 16.17 % R Mr (-14.00;5.00) 17.13 % R Mr (-15.00;5.00) 18.02 % R Mr (-16.00;5.00) 19.04 % R Mr (-17.00;5.00) 20.42 % R Mr (-18.00;5.00) 21.66 % R Mr (-19.00;5.00) 23.08 % R Mr (-20.00;5.00) 24.68 % R Mr (-21.00;5.00) 26.69 % R Mr (-22.00;5.00) 28.43 % R Mr (-23.00;5.00) 30.82 % R Mr (-24.00;5.00) 33.37 % R Mr (-25.00;5.00) 35.49 % R Mr (-26.00;5.00) 37.29 % R Mr (-27.00;5.00) 39.71 % R Mr (-28.00;5.00) 41.99 % R Mr (-29.00;5.00) 43.89 % R Mr (-30.00;5.00) 45.52 %	

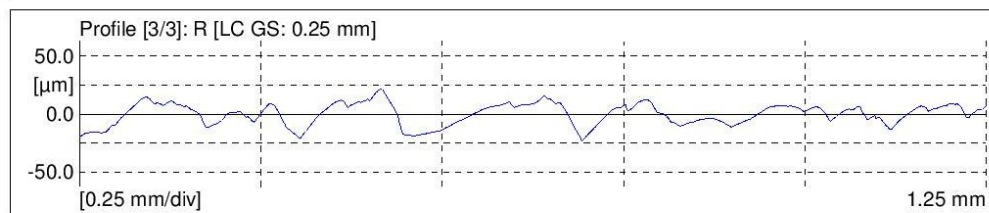
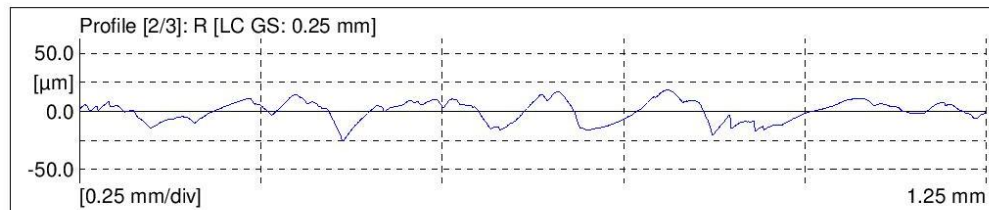
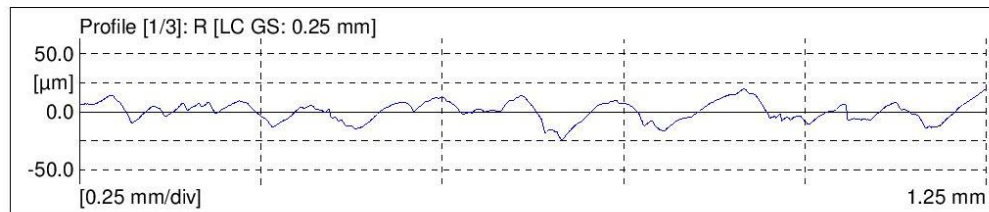
10.16 m/min, face milled, transverse direction:

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:33 AM
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Object:
Number:
Comment:

Meas. Instrum.: Mahr Data Acquisition Board
Drive Unit: GD 25
Pick-up: MFW-250 [8.0 %]

Lt: 1.75 mm [N=5]
Ls: 2.5 μm
VB: $\pm 250 \mu\text{m}$
Vt: 0.10 mm/s
Points: 10500 [3]



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	Ra	Rq	Rz	Rz1 max	Rmax	RzJ	Rt	Rp	Rv	R3z	R Sm ...
	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm	μm ...
1:	6.935	8.436	31.729	38.30	38.30	22.657	44.08	15.77	15.96	---	139.25 ...
2:	7.479	8.917	30.976	39.72	39.72	27.883	44.21	14.47	16.51	---	208.88 ...
3:	7.741	9.215	32.365	42.45	42.45	26.028	44.40	14.45	17.92	---	154.43 ...
Xb:	7.385	8.856	31.690	40.15	40.15	25.523	44.23	14.90	16.79	167.52	
S:	0.411	0.393	0.695	2.11	2.11	2.650	0.16	0.76	1.01	36.61	
Max:	7.741	9.215	32.365	42.45	42.45	27.883	44.40	15.77	17.92	208.88	
Min:	6.935	8.436	30.976	38.30	38.30	22.657	44.08	14.45	15.96	139.25	
R:	0.806	0.778	1.389	4.15	4.15	5.226	0.32	1.32	1.96	69.62	

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
Rz1	23.76	μm	Rp1	14.08	μm
Rz2	27.31	μm	Rp2	12.29	μm
Rz3	38.30	μm	Rp3	13.88	μm
Rz4	36.39	μm	Rp4	19.66	μm
Rz5	32.89	μm	Rp5	18.94	μm
Rz sigma	6.11	μm	Rp sigma	3.31	μm
Rz min	23.76	μm	Rp min	12.29	μm
Rz max	38.30	μm	Rp max	19.66	μm
Rz mean	31.73	μm	Rp mean	15.77	μm

Profile [1/3]: R [LC GS: 0.25 mm]			Profile [1/3]: R [LC GS: 0.25 mm]		
R3z1	---	μm	Rdc (0.00;5.00)	6.03	μm
R3z2	---	μm	Rdc (10.00;5.00)	-2.88	μm
R3z3	---	μm	Rdc (20.00;5.00)	-6.16	μm
R3z4	---	μm	Rdc (30.00;5.00)	-7.90	μm
R3z5	---	μm	Rdc (40.00;5.00)	-10.28	μm
R3z sigma	---	μm	Rdc (50.00;5.00)	-12.50	μm
R3z min	---	μm	Rdc (60.00;5.00)	-14.79	μm
R3z max	---	μm	Rdc (70.00;5.00)	-18.19	μm
R3z mean	---	μm	Rdc (80.00;5.00)	-20.60	μm
			Rdc (90.00;5.00)	-25.40	μm
			Rdc (100.00;5.00)	-38.05	μm

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Profile [1/3]: R [LC GS: 0.25 mm] R Mr (6.03;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.37 % R Mr (-2.00;5.00) 8.47 % R Mr (-3.00;5.00) 10.19 % R Mr (-4.00;5.00) 12.03 % R Mr (-5.00;5.00) 15.33 % R Mr (-6.00;5.00) 19.24 % R Mr (-7.00;5.00) 25.25 % R Mr (-8.00;5.00) 30.38 % R Mr (-9.00;5.00) 34.37 % R Mr (-10.00;5.00) 38.70 % R Mr (-11.00;5.00) 42.66 % R Mr (-12.00;5.00) 47.41 % R Mr (-13.00;5.00) 52.08 % R Mr (-14.00;5.00) 57.05 % R Mr (-15.00;5.00) 60.65 % R Mr (-16.00;5.00) 64.00 % R Mr (-17.00;5.00) 66.24 % R Mr (-18.00;5.00) 69.42 % R Mr (-19.00;5.00) 73.46 % R Mr (-20.00;5.00) 77.21 % R Mr (-21.00;5.00) 81.38 % R Mr (-22.00;5.00) 83.93 % R Mr (-23.00;5.00) 85.82 % R Mr (-24.00;5.00) 87.77 % R Mr (-25.00;5.00) 89.37 % R Mr (-26.00;5.00) 91.60 % R Mr (-27.00;5.00) 93.86 % R Mr (-28.00;5.00) 95.52 % R Mr (-29.00;5.00) 96.27 % R Mr (-30.00;5.00) 97.48 %	Profile [2/3]: R [LC GS: 0.25 mm] Rz1 25.76 µm Rz2 39.72 µm Rz3 32.91 µm Rz4 39.30 µm Rz5 17.19 µm Rz sigma 9.58 µm Rz min 17.19 µm Rz max 39.72 µm Rz mean 30.98 µm
Profile [2/3]: R [LC GS: 0.25 mm] Rp1 11.35 µm Rp2 14.09 µm Rp3 17.08 µm Rp4 18.59 µm Rp5 11.22 µm Rp sigma 3.32 µm Rp min 11.22 µm Rp max 18.59 µm Rp mean 14.47 µm	Profile [2/3]: R [LC GS: 0.25 mm] R3z1 --- µm R3z2 --- µm R3z3 --- µm R3z4 --- µm R3z5 --- µm R3z sigma --- µm R3z min --- µm R3z max --- µm R3z mean --- µm

 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:33 AM
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Profile [2/3]: R [LC GS: 0.25 mm] Rdc (0.00;5.00) 5.61 µm Rdc (10.00;5.00) -2.47 µm Rdc (20.00;5.00) -4.97 µm Rdc (30.00;5.00) -7.18 µm Rdc (40.00;5.00) -8.87 µm Rdc (50.00;5.00) -11.44 µm Rdc (60.00;5.00) -14.18 µm Rdc (70.00;5.00) -17.99 µm Rdc (80.00;5.00) -21.91 µm Rdc (90.00;5.00) -26.25 µm Rdc (100.00;5.00) -38.60 µm	Profile [2/3]: R [LC GS: 0.25 mm] R Mr (5.61;5.00) 0.00 % R Mr (0.00;5.00) 5.00 % R Mr (-1.00;5.00) 6.17 % R Mr (-2.00;5.00) 8.44 % R Mr (-3.00;5.00) 12.28 % R Mr (-4.00;5.00) 15.81 % R Mr (-5.00;5.00) 20.18 % R Mr (-6.00;5.00) 24.36 % R Mr (-7.00;5.00) 29.09 % R Mr (-8.00;5.00) 34.62 % R Mr (-9.00;5.00) 40.83 % R Mr (-10.00;5.00) 45.12 % R Mr (-11.00;5.00) 48.77 % R Mr (-12.00;5.00) 52.11 % R Mr (-13.00;5.00) 56.38 % R Mr (-14.00;5.00) 59.65 % R Mr (-15.00;5.00) 63.67 % R Mr (-16.00;5.00) 65.71 % R Mr (-17.00;5.00) 67.47 % R Mr (-18.00;5.00) 70.03 % R Mr (-19.00;5.00) 72.76 % R Mr (-20.00;5.00) 75.02 % R Mr (-21.00;5.00) 77.41 % R Mr (-22.00;5.00) 80.34 % R Mr (-23.00;5.00) 82.97 % R Mr (-24.00;5.00) 84.90 % R Mr (-25.00;5.00) 87.24 % R Mr (-26.00;5.00) 89.37 % R Mr (-27.00;5.00) 92.41 % R Mr (-28.00;5.00) 95.26 % R Mr (-29.00;5.00) 97.59 % R Mr (-30.00;5.00) 98.07 %
Profile [3/3]: R [LC GS: 0.25 mm] Rz1 34.63 µm Rz2 42.45 µm Rz3 38.59 µm Rz4 23.64 µm Rz5 22.52 µm Rz sigma 8.92 µm Rz min 22.52 µm Rz max 42.45 µm Rz mean 32.37 µm	Profile [3/3]: R [LC GS: 0.25 mm] Rp1 14.53 µm Rp2 21.25 µm Rp3 15.44 µm Rp4 12.13 µm Rp5 8.89 µm Rp sigma 4.57 µm Rp min 8.89 µm Rp max 21.25 µm Rp mean 14.45 µm

No Quick&Easy

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 MarSurf XR 20 V1.40-3 (SP1)	University of Washington Mechanical Engineering Manufacturing Science and Technology Laboratory apoc New Measurement	 08/30/12, 10:33 AM
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Profile [3/3]: R [LC GS: 0.25 mm]	Profile [3/3]: R [LC GS: 0.25 mm]
R3z1	Rdc (0.00;5.00) 9.22 μm
R3z2	Rdc (10.00;5.00) -1.89 μm
R3z3	Rdc (20.00;5.00) -4.23 μm
R3z4	Rdc (30.00;5.00) -5.84 μm
R3z5	Rdc (40.00;5.00) -7.95 μm
R3z sigma	Rdc (50.00;5.00) -10.63 μm
R3z min	Rdc (60.00;5.00) -14.16 μm
R3z max	Rdc (70.00;5.00) -17.14 μm
R3z mean	Rdc (80.00;5.00) -20.99 μm
	Rdc (90.00;5.00) -27.00 μm
	Rdc (100.00;5.00) -35.18 μm



MarSurf XR 20
V1.40-3 (SP1)

University of Washington
Mechanical Engineering
Manufacturing Science and Technology Laboratory

apoc
New Measurement



08/30/12, 10:33 AM

Profile [3/3]: R [LC GS: 0.25 mm]	
R Mr (9.22;5.00)	0.00 %
R Mr (0.00;5.00)	5.00 %
R Mr (-1.00;5.00)	7.80 %
R Mr (-2.00;5.00)	10.56 %
R Mr (-3.00;5.00)	13.79 %
R Mr (-4.00;5.00)	18.64 %
R Mr (-5.00;5.00)	24.10 %
R Mr (-6.00;5.00)	30.78 %
R Mr (-7.00;5.00)	36.16 %
R Mr (-8.00;5.00)	40.29 %
R Mr (-9.00;5.00)	44.69 %
R Mr (-10.00;5.00)	47.76 %
R Mr (-11.00;5.00)	51.63 %
R Mr (-12.00;5.00)	54.74 %
R Mr (-13.00;5.00)	57.22 %
R Mr (-14.00;5.00)	59.59 %
R Mr (-15.00;5.00)	62.23 %
R Mr (-16.00;5.00)	66.16 %
R Mr (-17.00;5.00)	69.42 %
R Mr (-18.00;5.00)	72.43 %
R Mr (-19.00;5.00)	75.04 %
R Mr (-20.00;5.00)	77.76 %
R Mr (-21.00;5.00)	80.05 %
R Mr (-22.00;5.00)	82.69 %
R Mr (-23.00;5.00)	84.89 %
R Mr (-24.00;5.00)	86.61 %
R Mr (-25.00;5.00)	87.76 %
R Mr (-26.00;5.00)	88.86 %
R Mr (-27.00;5.00)	90.00 %
R Mr (-28.00;5.00)	92.70 %
R Mr (-29.00;5.00)	94.65 %
R Mr (-30.00;5.00)	96.43 %

Appendix: D. Feasibility investigation cutting forces

1.) Parameter Tables

Table D-1: Parameter set for depth of cut variation study

Speed [rpm]:	Feed [in/min]:	Depth of Cut [in]	Radial Depth of Cut [in]:
6000	50	0.125	0.4375
6000	50	0.25	0.4375
6000	50	0.375	0.4375
6000	50	0.5	0.4375
6000	50	0.625	0.4375
6000	50	0.75	0.4375
6000	50	0.875	0.4375
6000	50	1	0.4375

Table D-2: Parameter set for feed rate variation study

Speed [rpm]:	Feed [in/min]:	Depth of Cut [in]	Radial Depth of Cut [in]:
6000	20	0.5	0.4375
6000	30	0.5	0.4375
6000	40	0.5	0.4375
6000	50	0.5	0.4375
6000	60	0.5	0.4375
6000	70	0.5	0.4375
6000	80	0.5	0.4375

Table D-3: Parameter set for cutting speed variation study

Speed [rpm]:	Feed [in/min]:	Depth of Cut [in]	Radial Depth of Cut [in]:
5000	50	0.5	0.4375
5500	50	0.5	0.4375
6000	50	0.5	0.4375
5000	40	0.5	0.4375
5500	40	0.5	0.4375
6000	40	0.5	0.4375
5000	30	0.5	0.4375
5500	30	0.5	0.4375
6000	30	0.5	0.4375
5000	20	0.5	0.4375
5500	20	0.5	0.4375
6000	20	0.5	0.4375

2.) CB1100 Cutting Forces

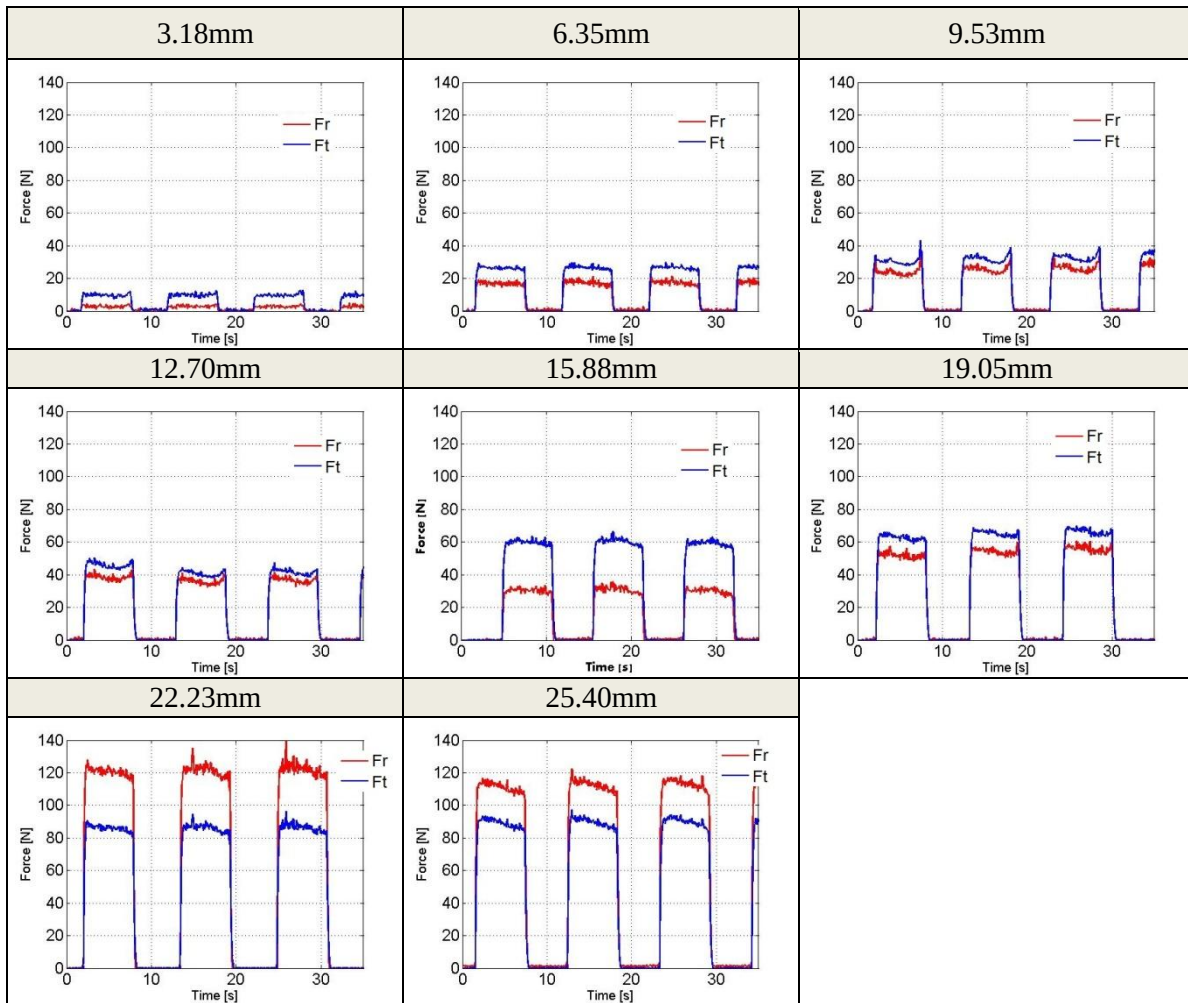


Figure D-2: Cb1100 cutting force plots for different depths of cut using diamond abrasive cutting tool (15.88mm, 40grit) at a speed:6000rpm, feed 1.27m/min, 15.88mm RDOC

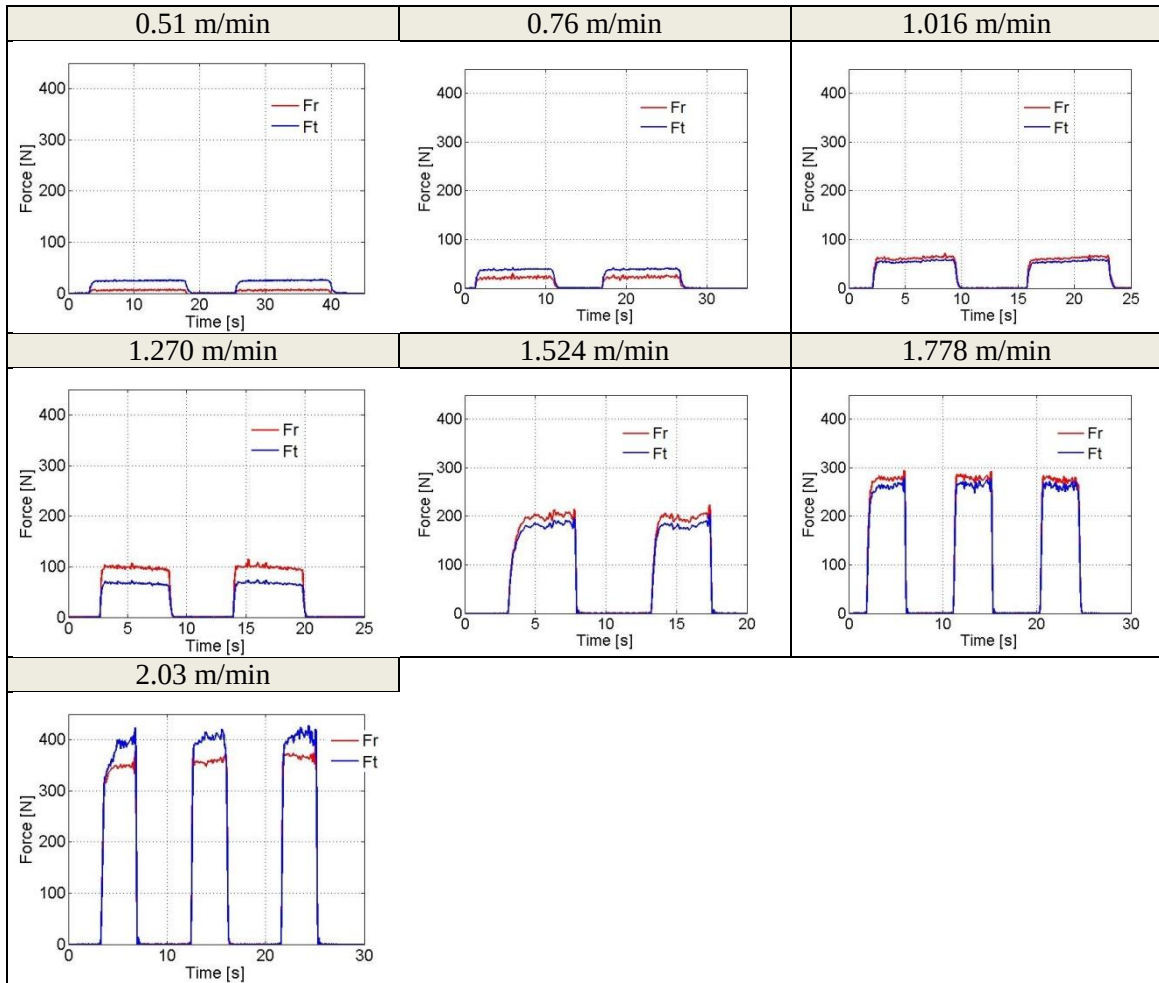


Figure D-3: Cutting force plots for different feed rates using diamond abrasive cutting tool in CB1100 (15.88mm dia 40grit) [speed:6000 RPM, 12.70mm ADOC, 15.88mm RDOC]

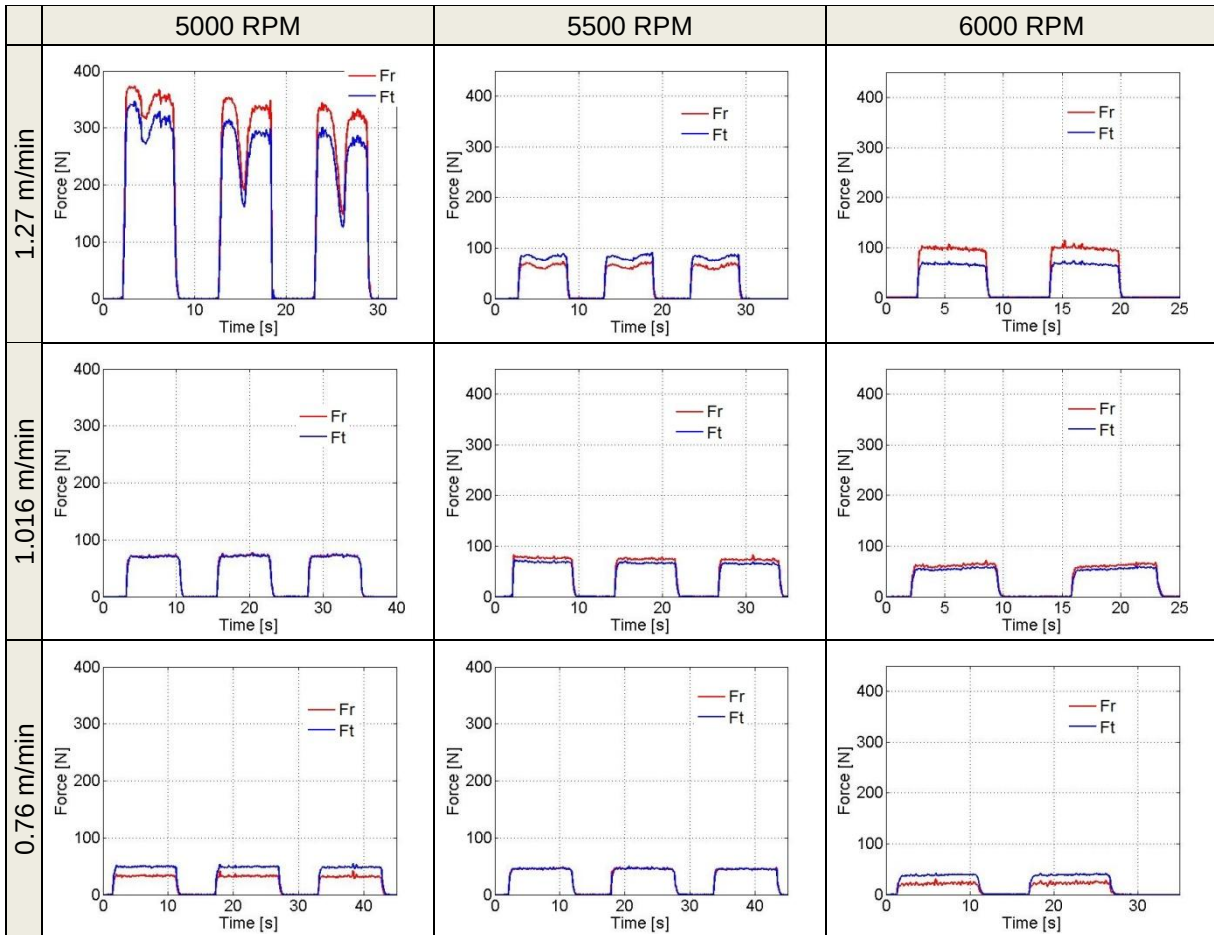


Figure D-4: CB1100 cutting force plots of diamond abrasive tool (15.88mm diameter, 40grit) at 12.70mm ADOC, and 15.88mm RDOC arranged according to feed and speed.

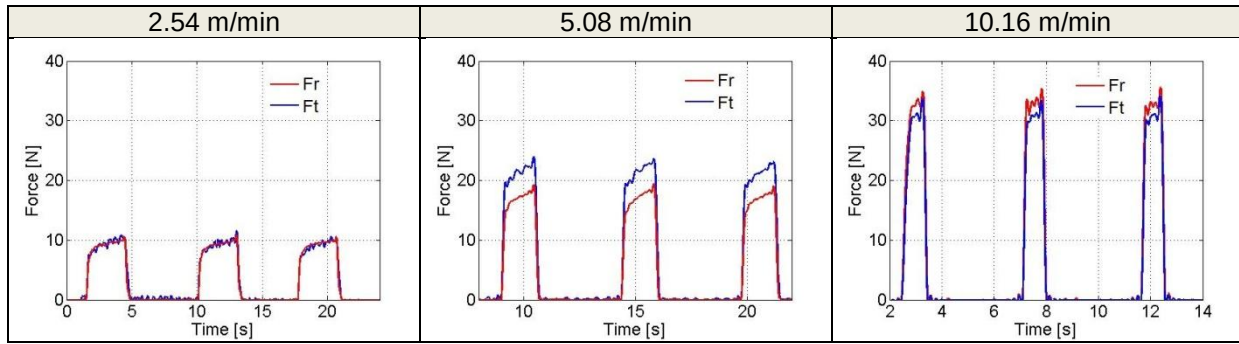


Figure D-5: CB1100 Tangential and radial cutting force plots of PCD tooling at different feed rates [speed: 6000rpm, 3.18mm ADOC].

3.) AAC Cutting Forces

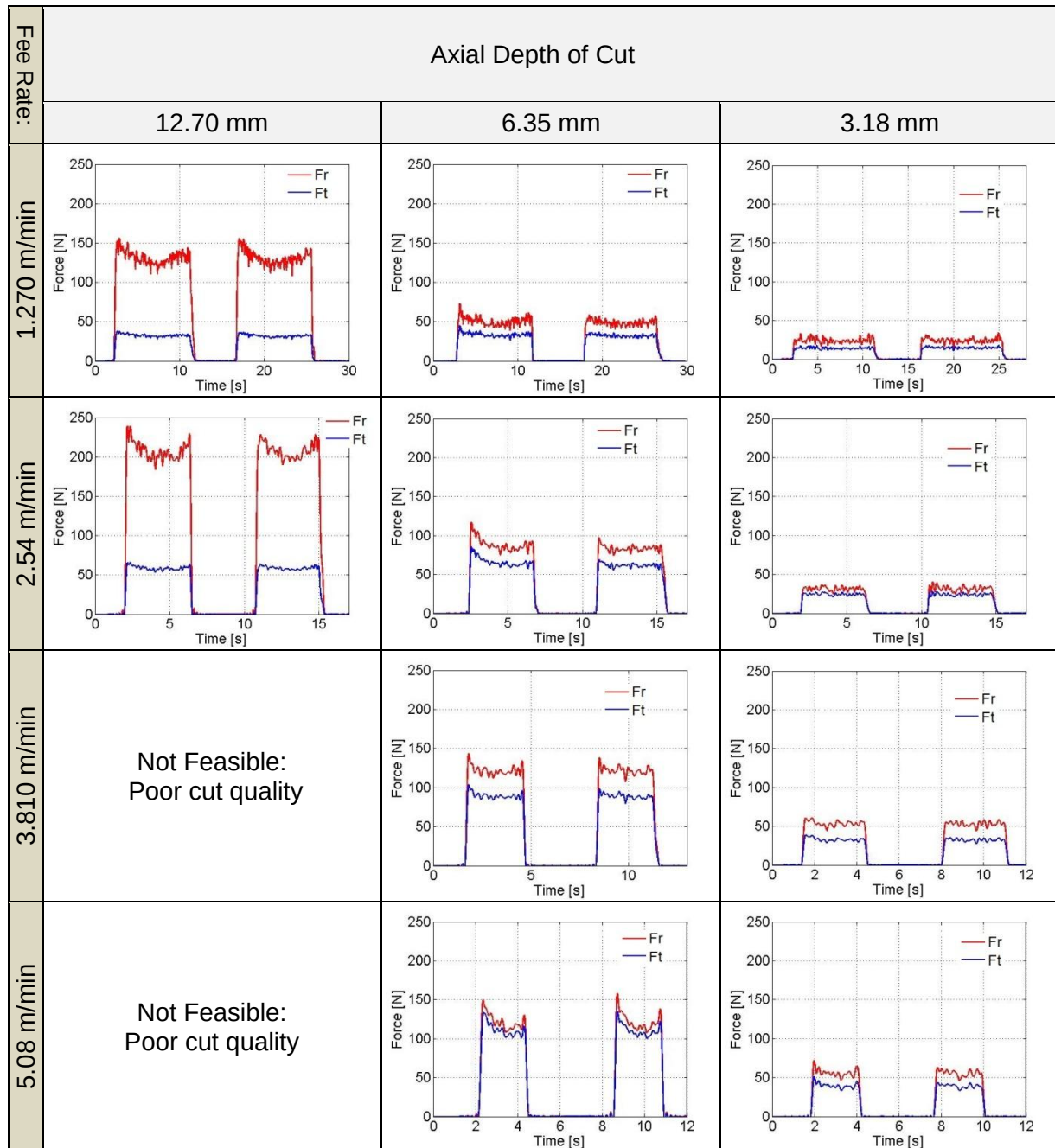


Figure D-6: Cutting force plots of AAC machined at various feed rates and axial depths of cut using diamond abrasive cutting tool at 6000 RPM and 15.88mm RDOC

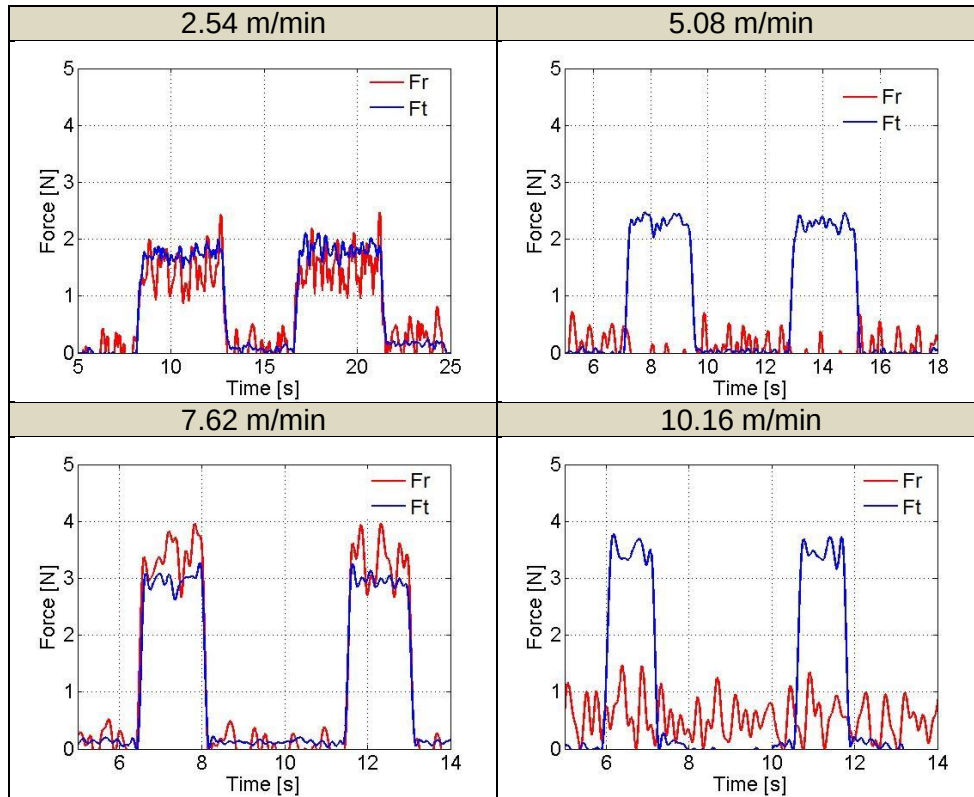


Figure D-7: Cutting force plots of AAC machined at various feed rates using PCD cutting tool at 6000 RPM and 31.75mm RDOC and 3.18mm ADOC

4.) Cfoam Cutting Forces

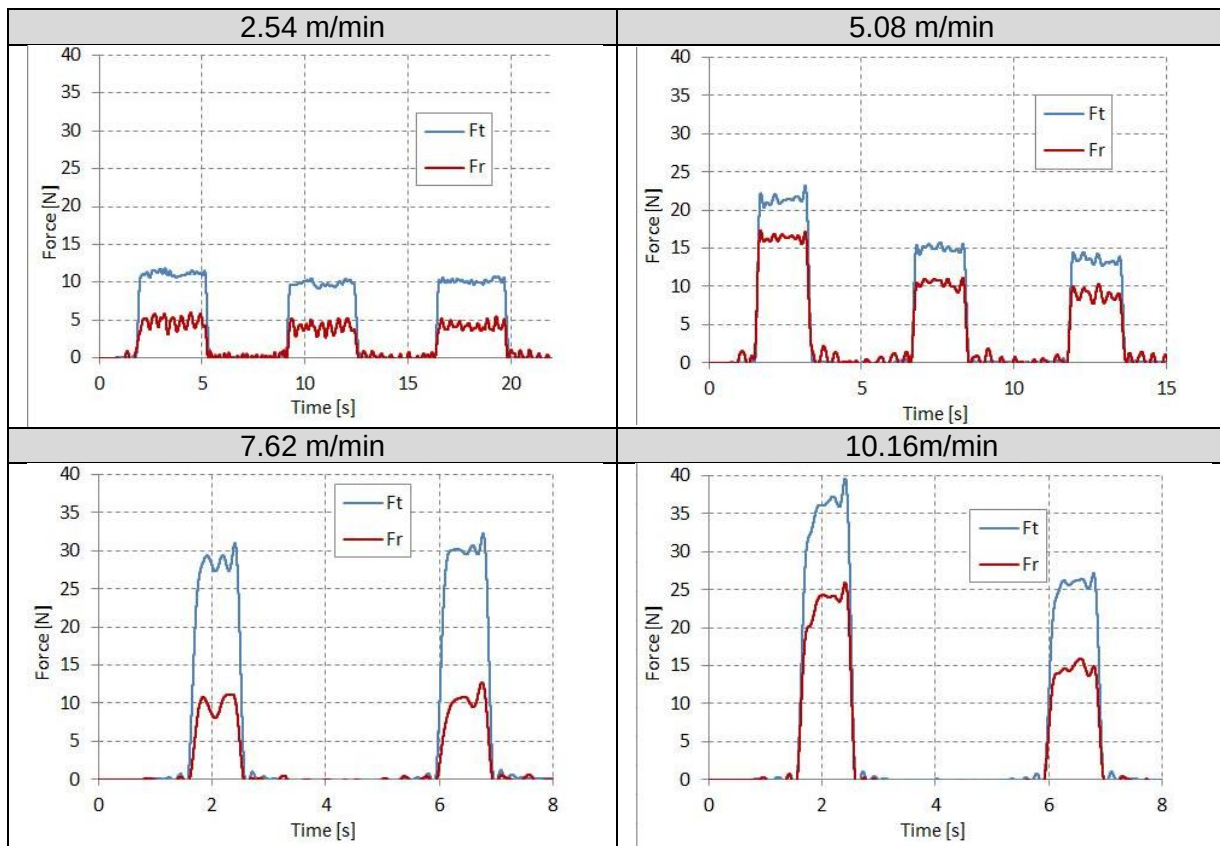


Figure D-8: Cutting force plots of Cfoam machined at various feed rates using diamond abrasive cutting tool at 6000 RPM, 25.40mm ADOC and 15.88mm RDOC.

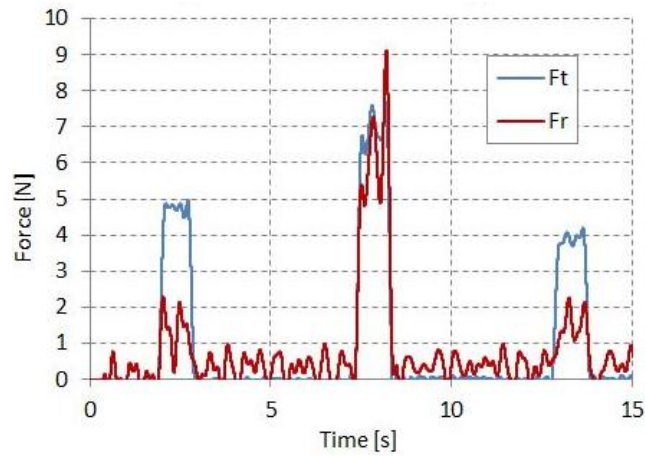


Figure D-9: Tangential and radial cutting force of Cfoam using PCD cutting tool at 6000 RPM, 10.16 m/min, 3.18mm ADOC, and 31.75mm RDOC

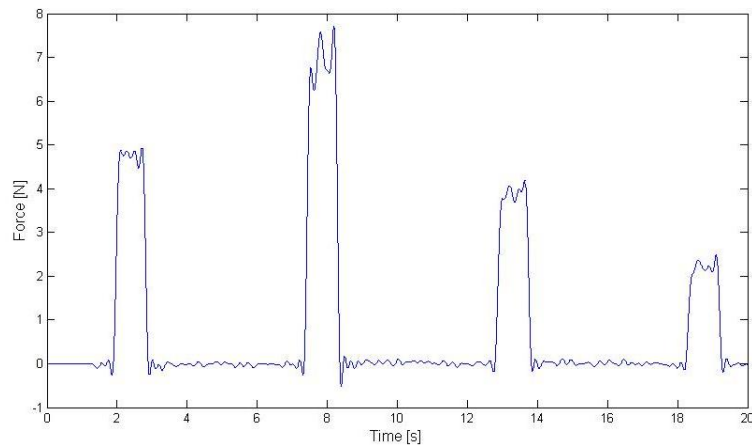


Figure D-10: Tangential cutting forces obtained using PCD tooling in Cfoam at 6000 RPM, 10.16 m/min feed rate, and 3.18mm axial depth of cut

Appendix: E. CB1100 cutting force DOE results

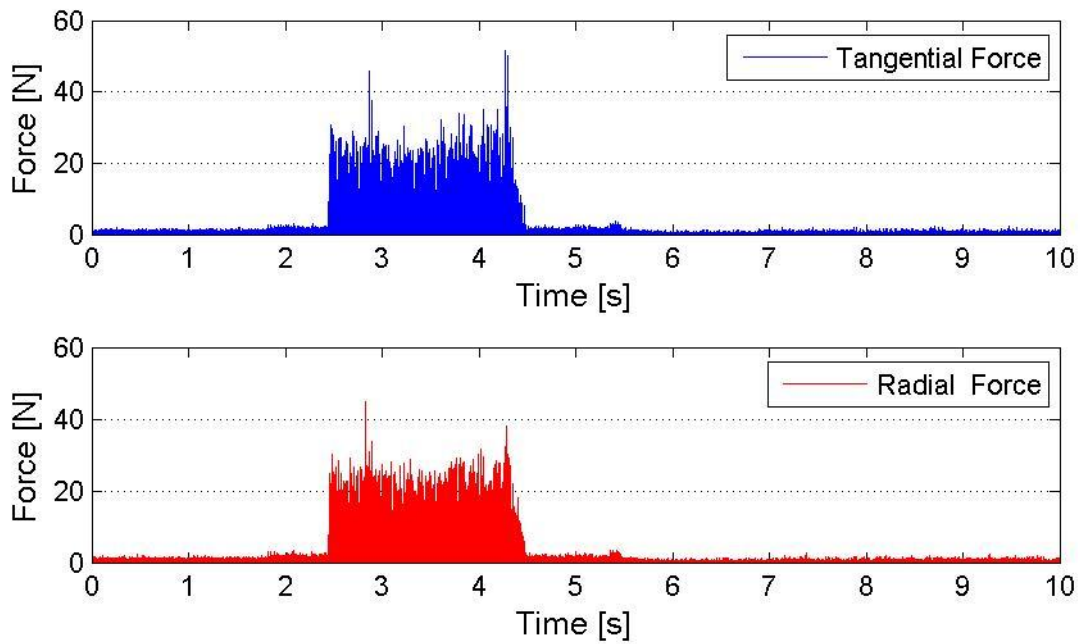


Figure E --11: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

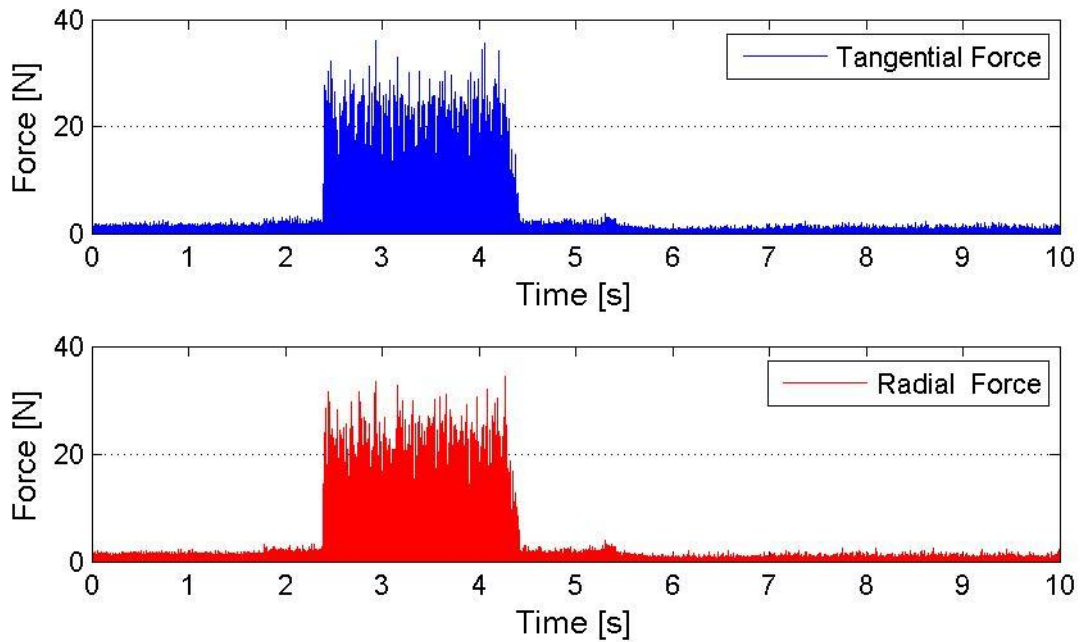


Figure E --12: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

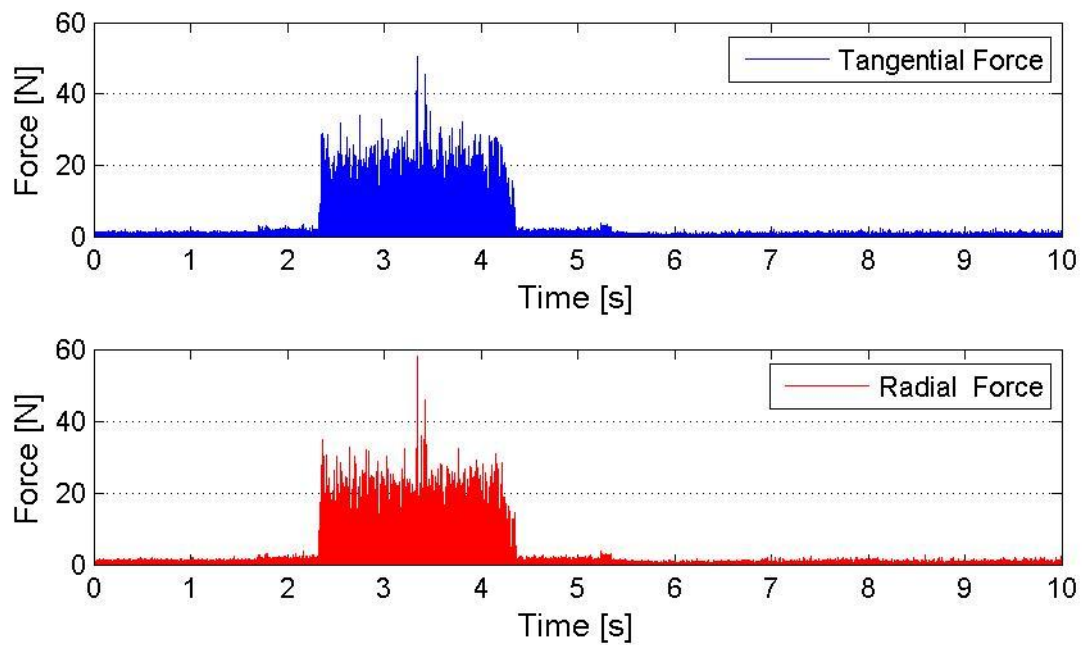


Figure E --13: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

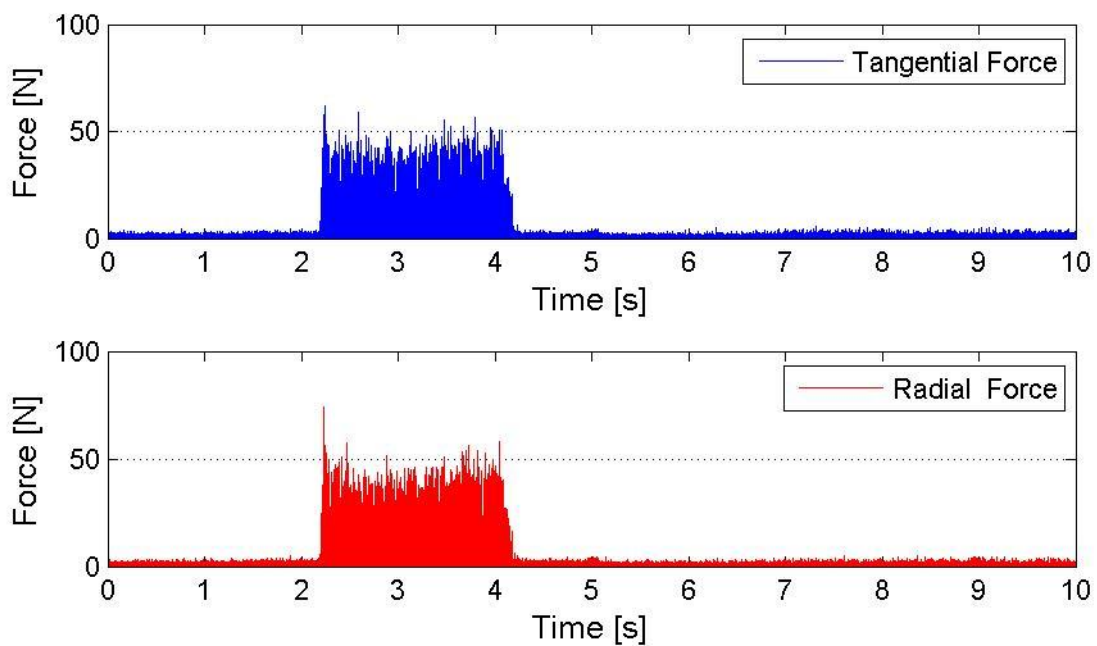


Figure E --14: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

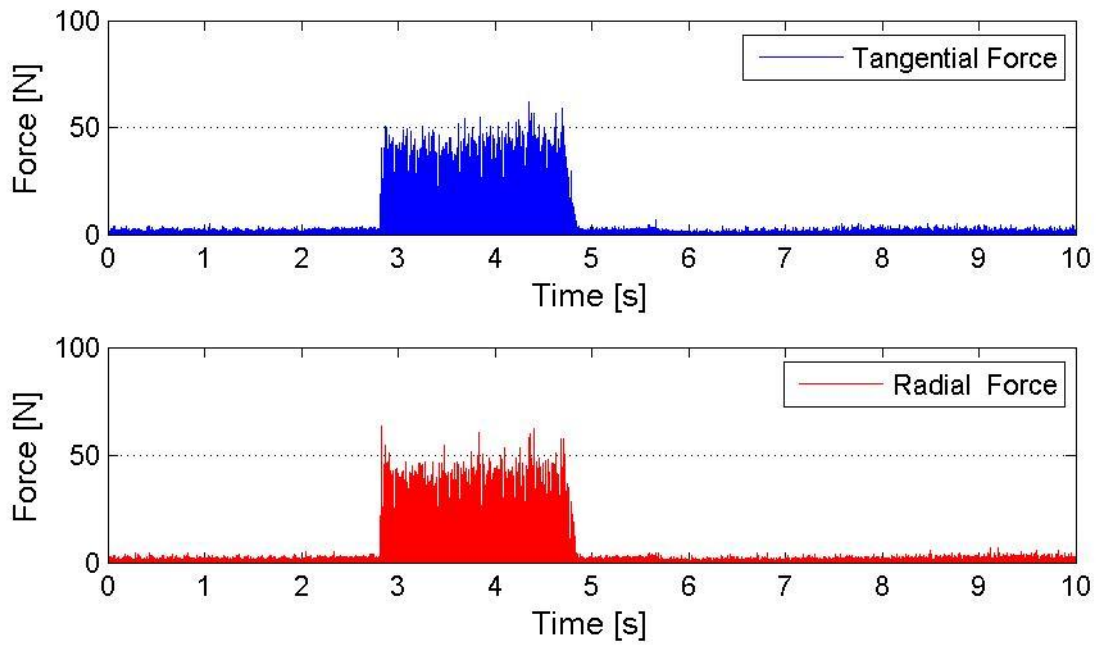


Figure E --15: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

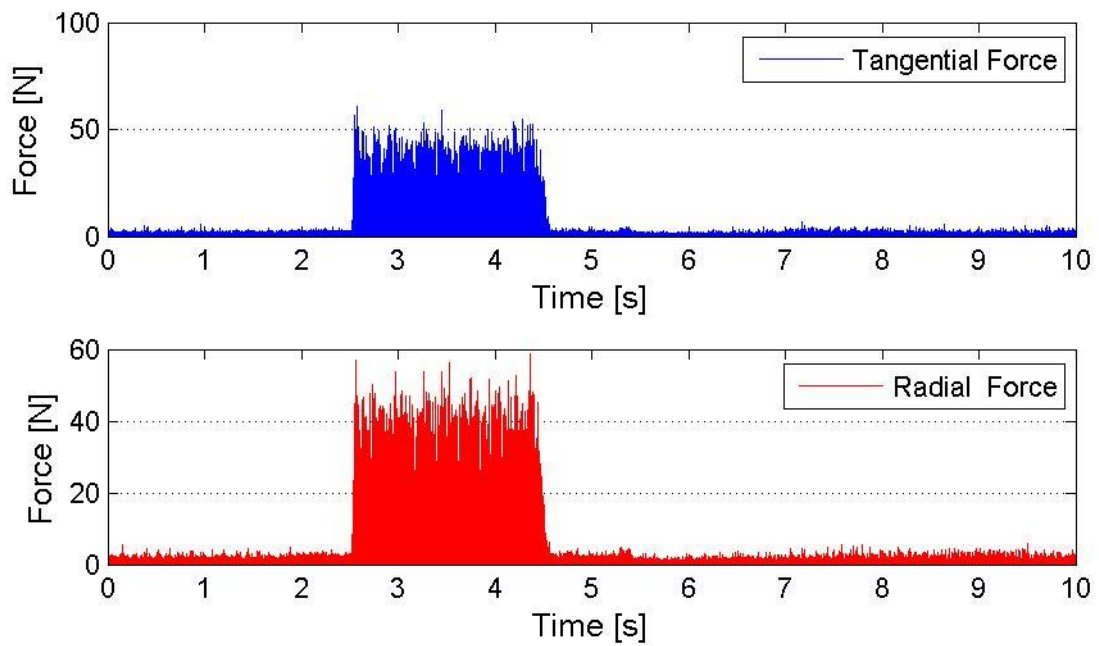


Figure E --16: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

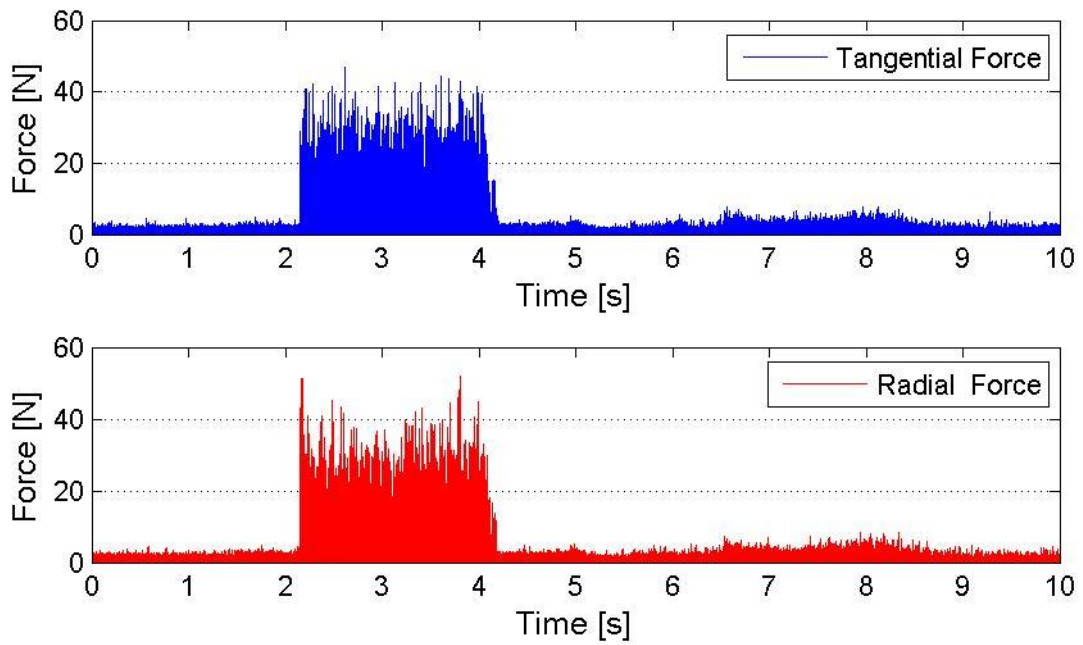


Figure E --17: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

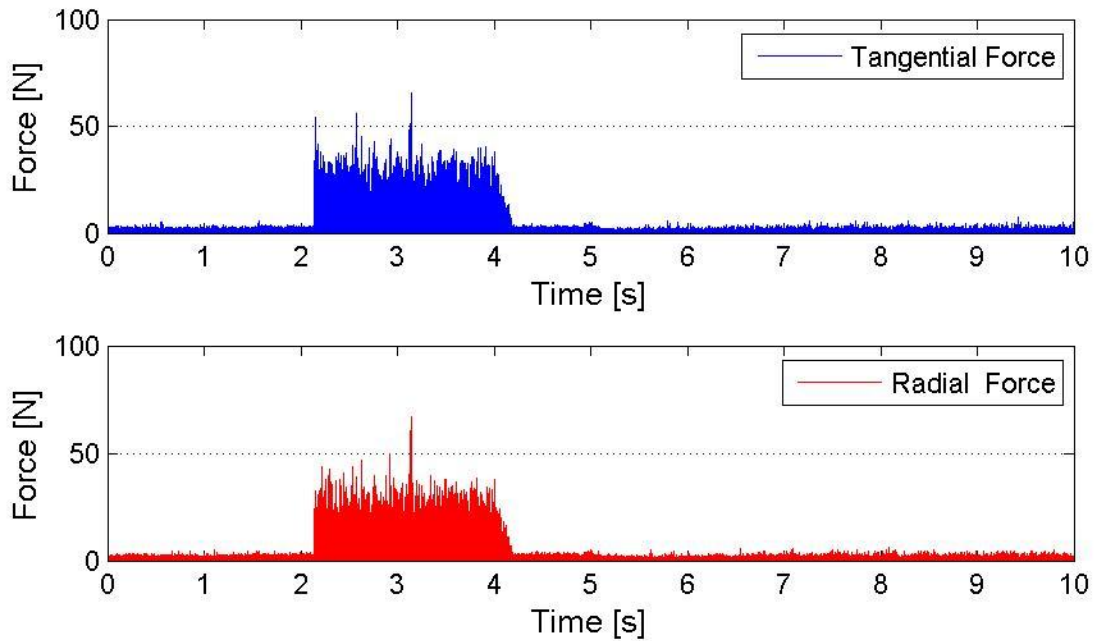


Figure E-18: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

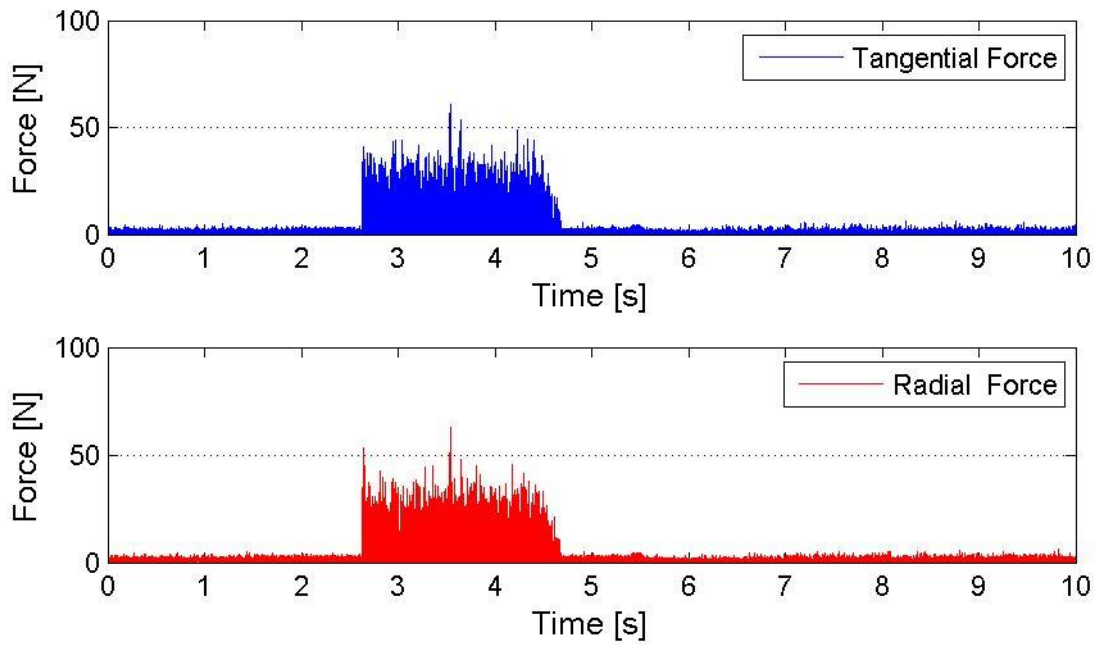


Figure E-19: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

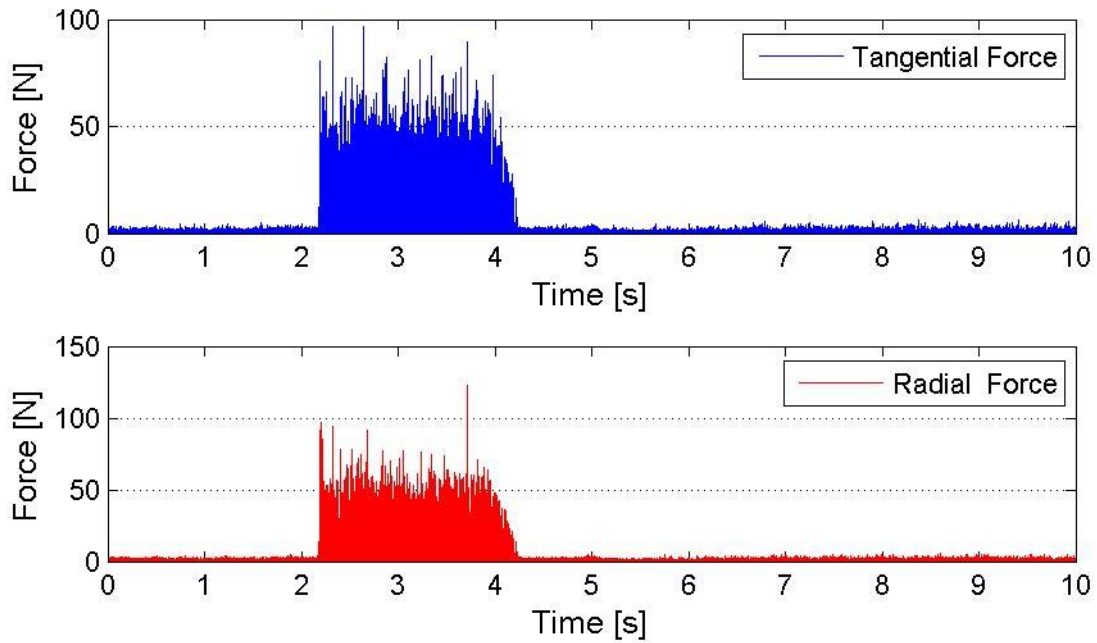


Figure E-20: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

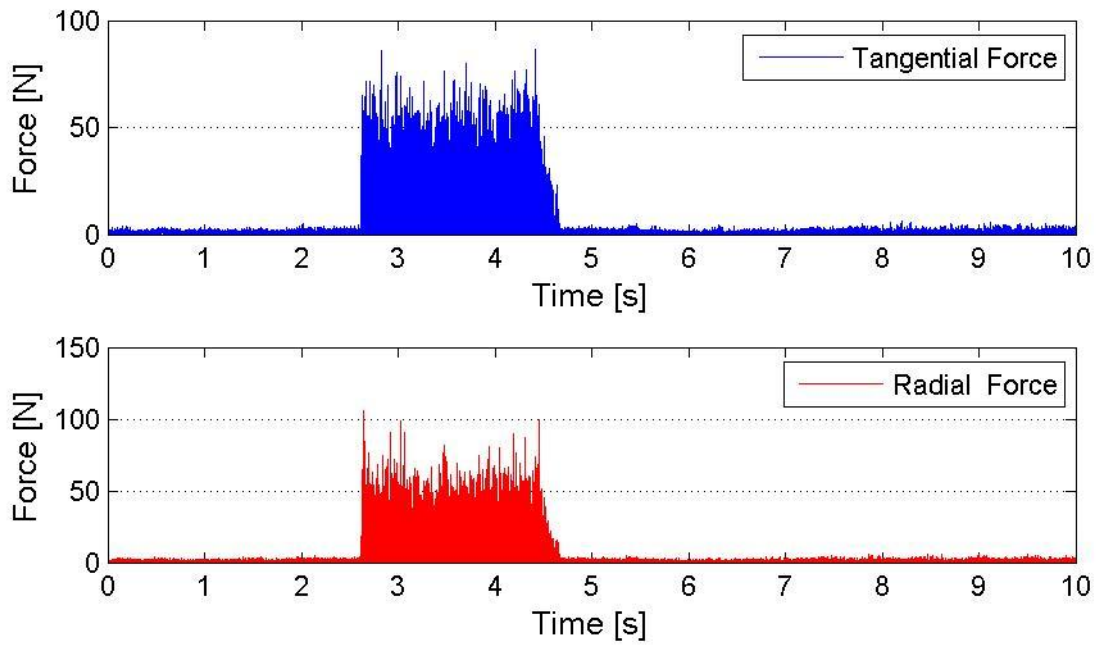


Figure E-21: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

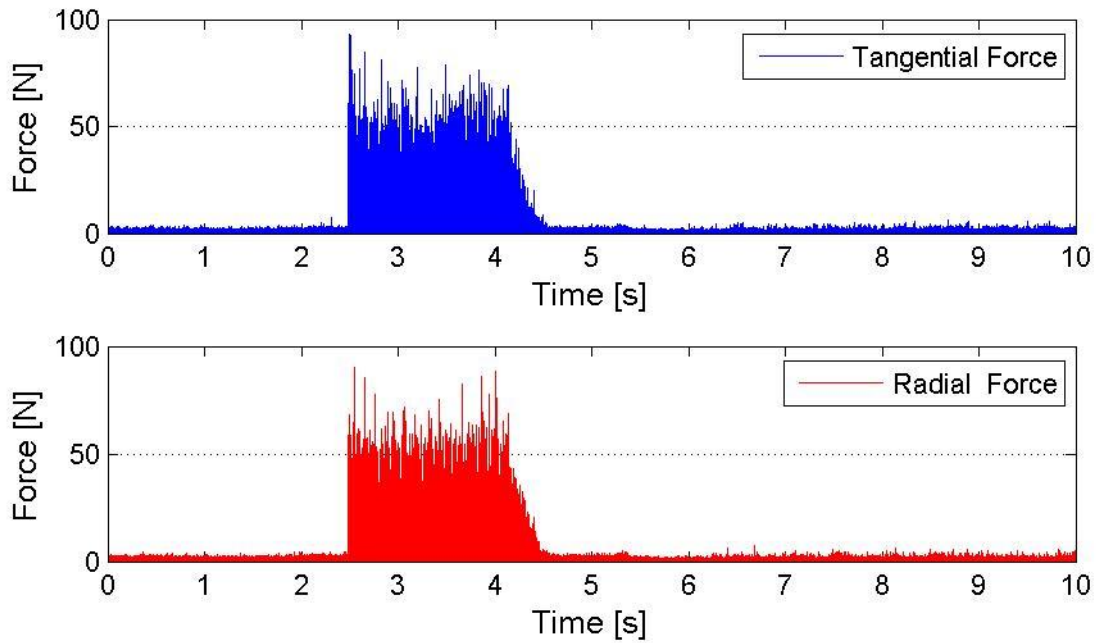


Figure E-22: Tangential and radial cutting force of CB1100 at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

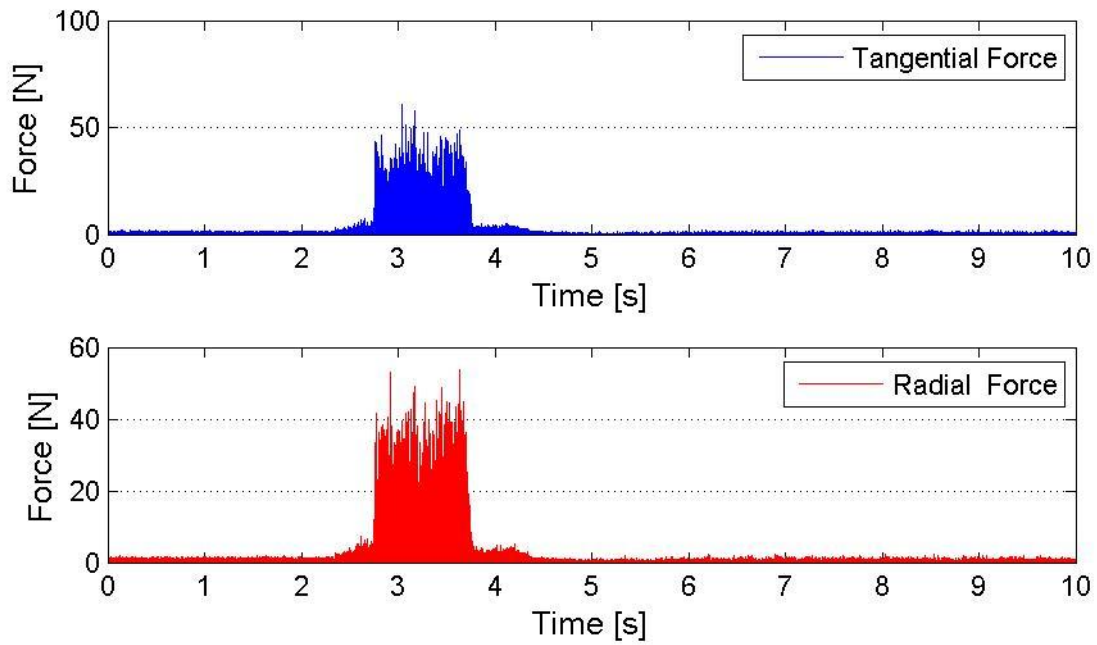


Figure E-23: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

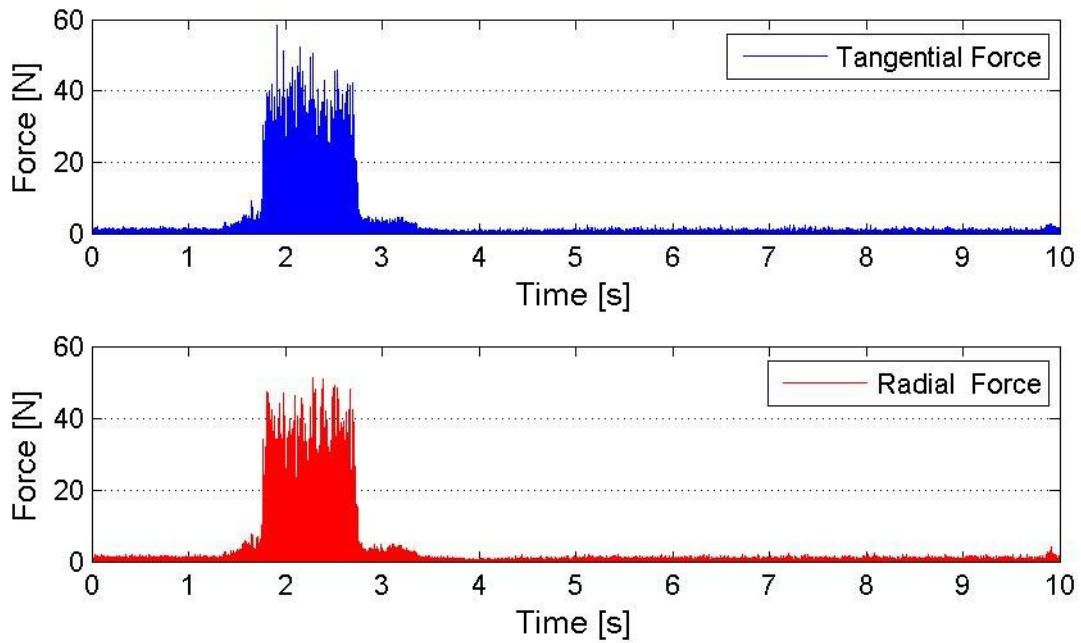


Figure E-24: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

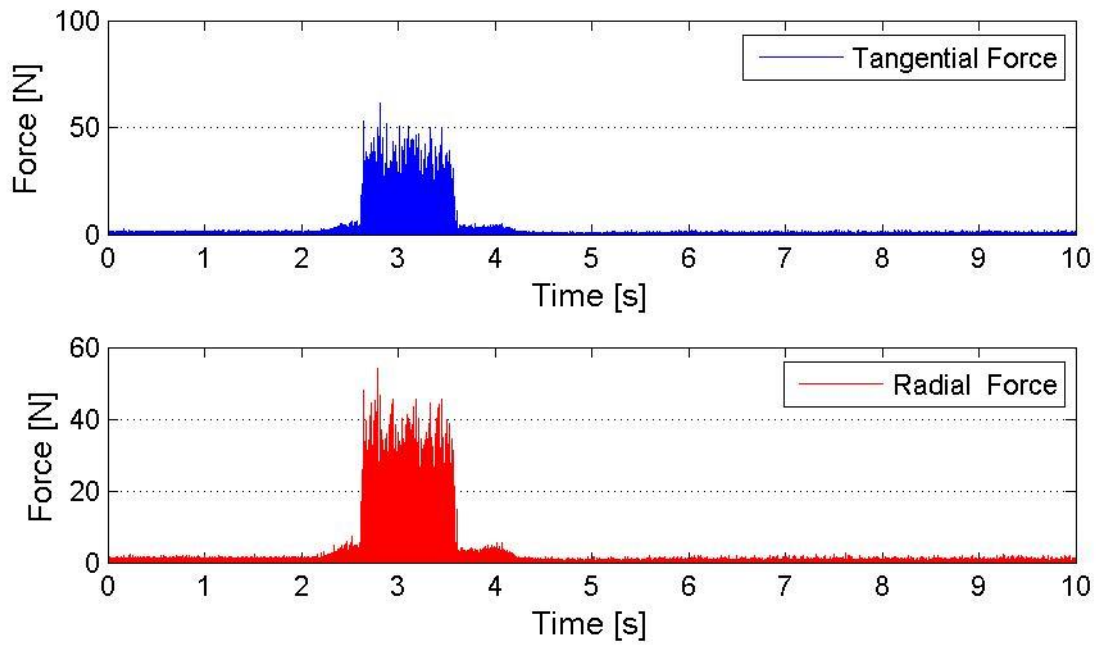


Figure E-25: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

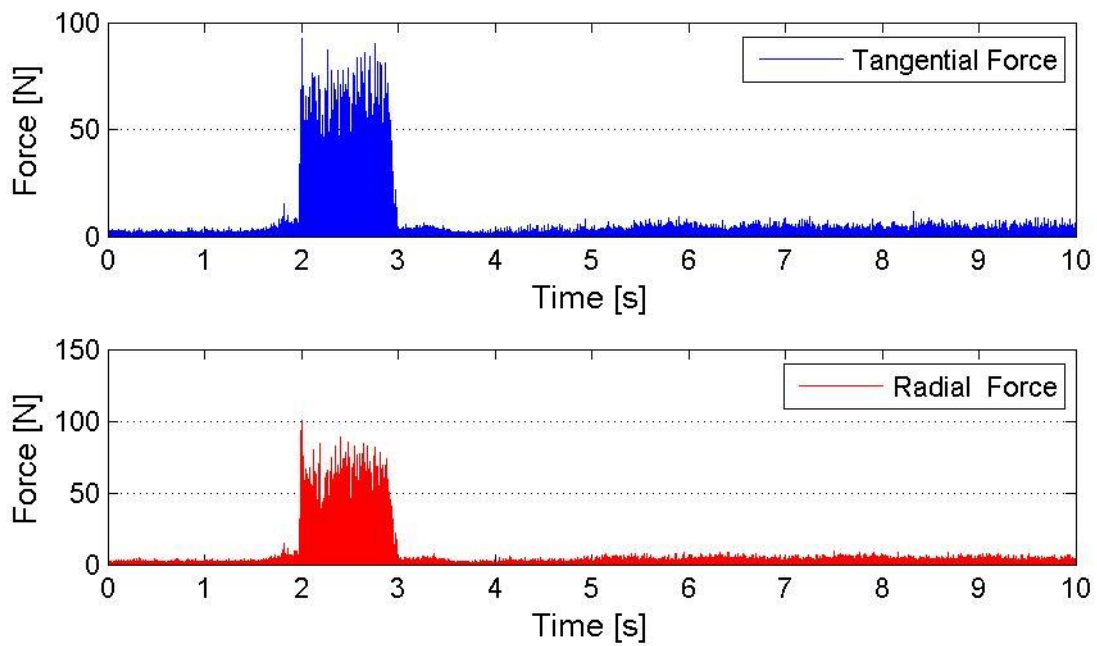


Figure E-26: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

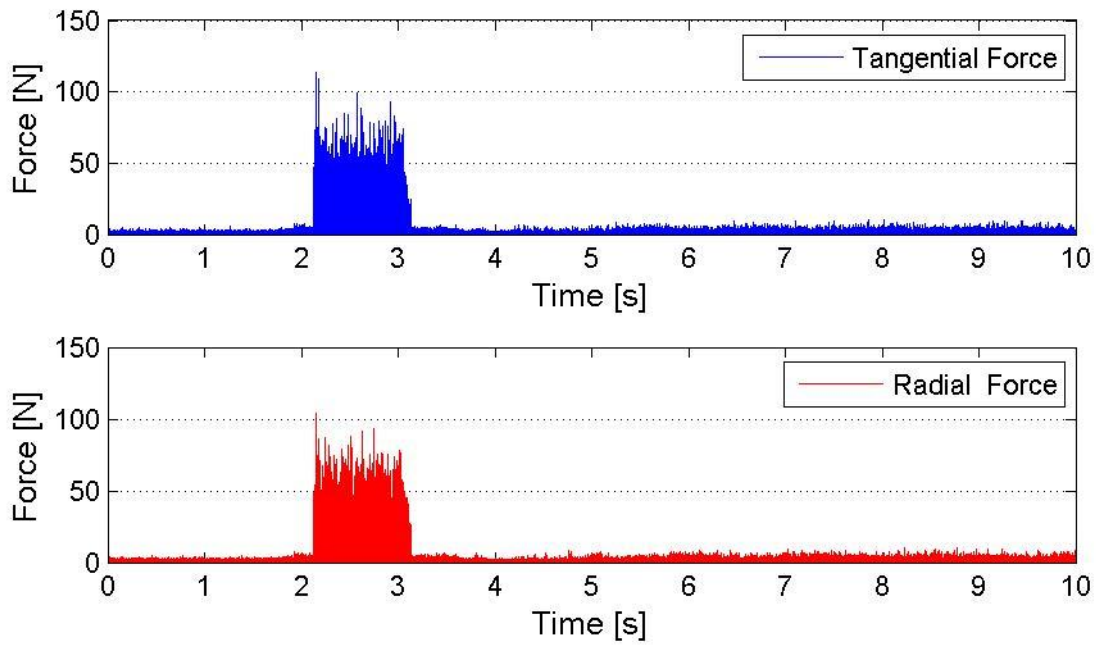


Figure E-27: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

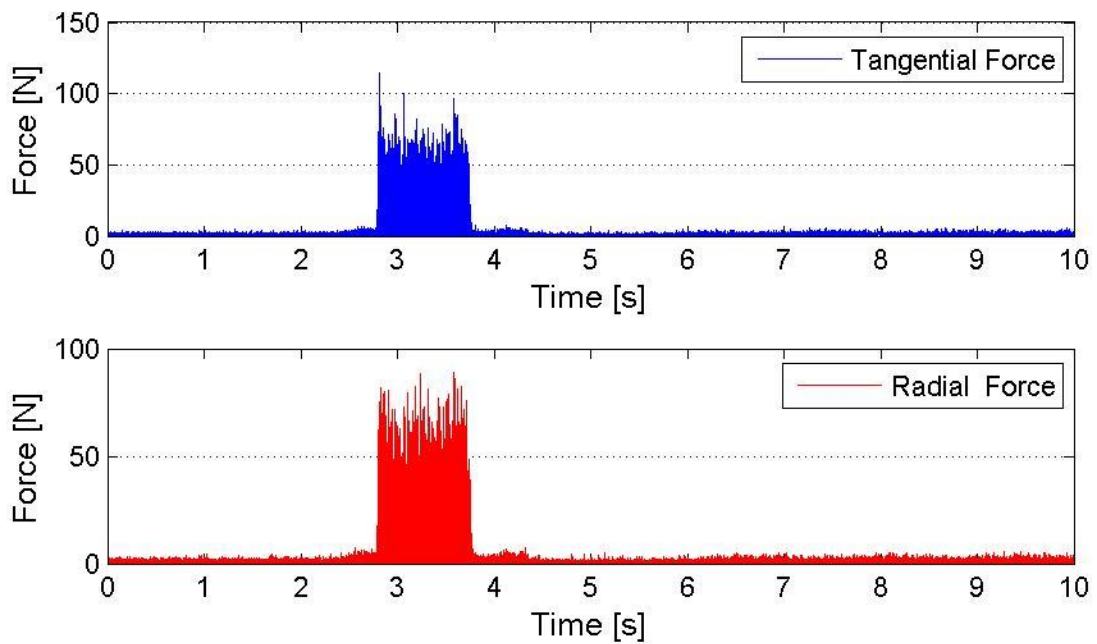


Figure E-28: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

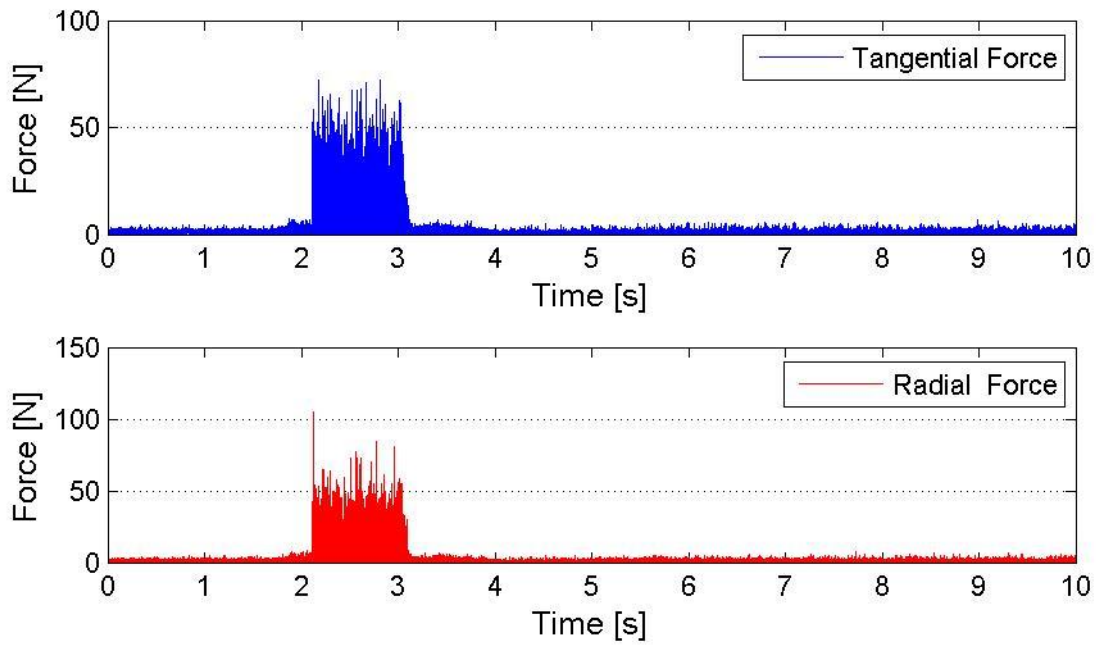


Figure E-29: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

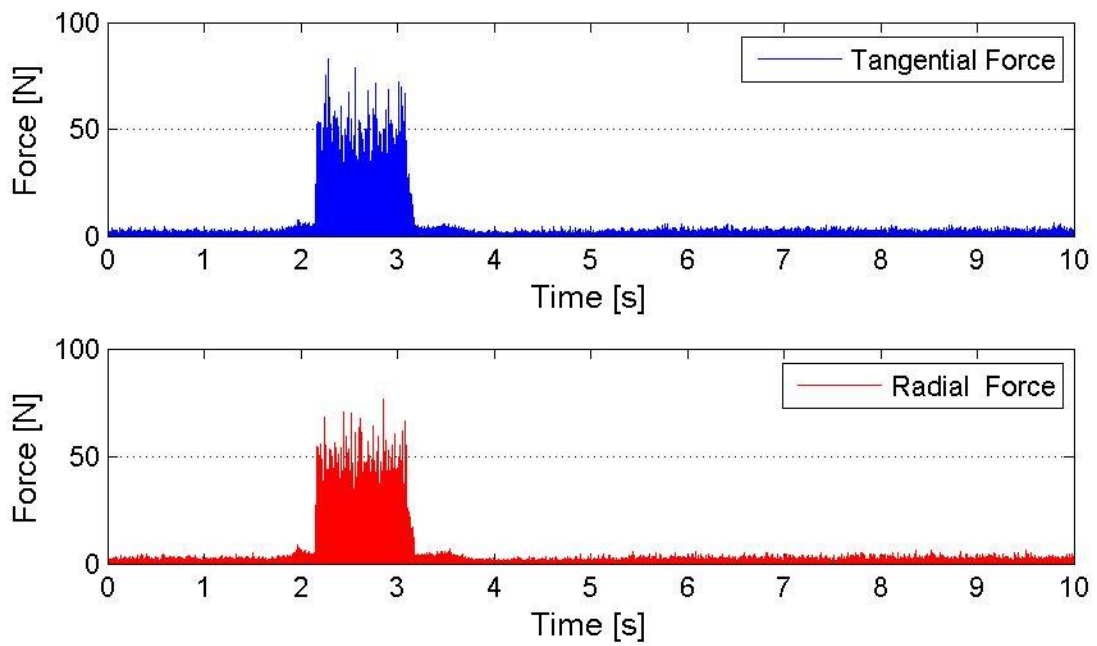


Figure E-30: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

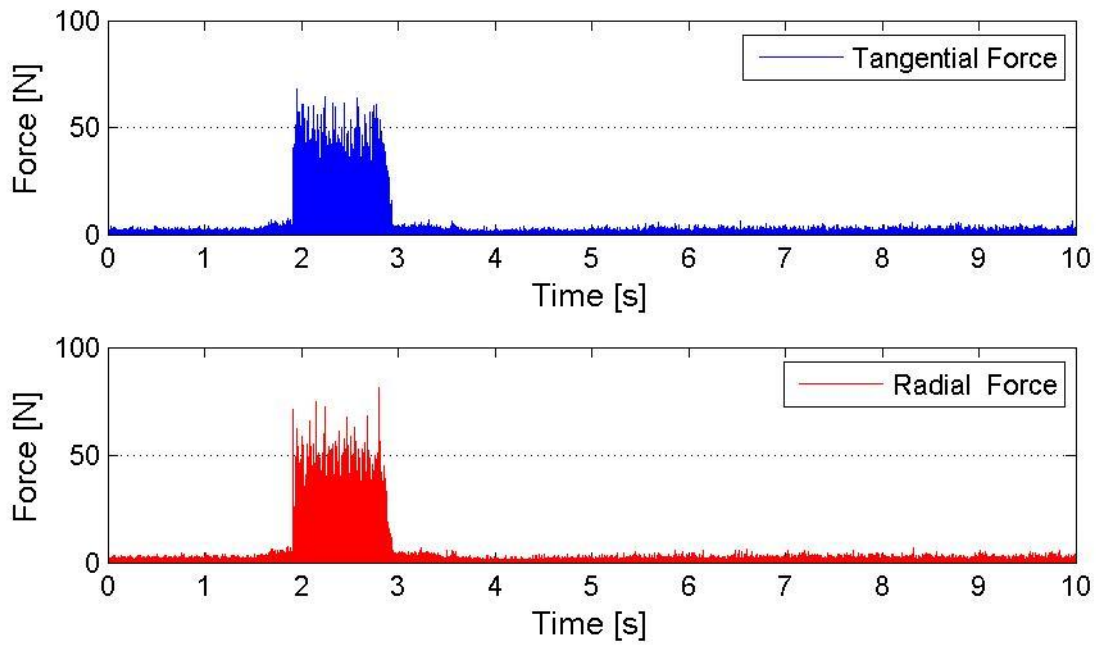


Figure E-31: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

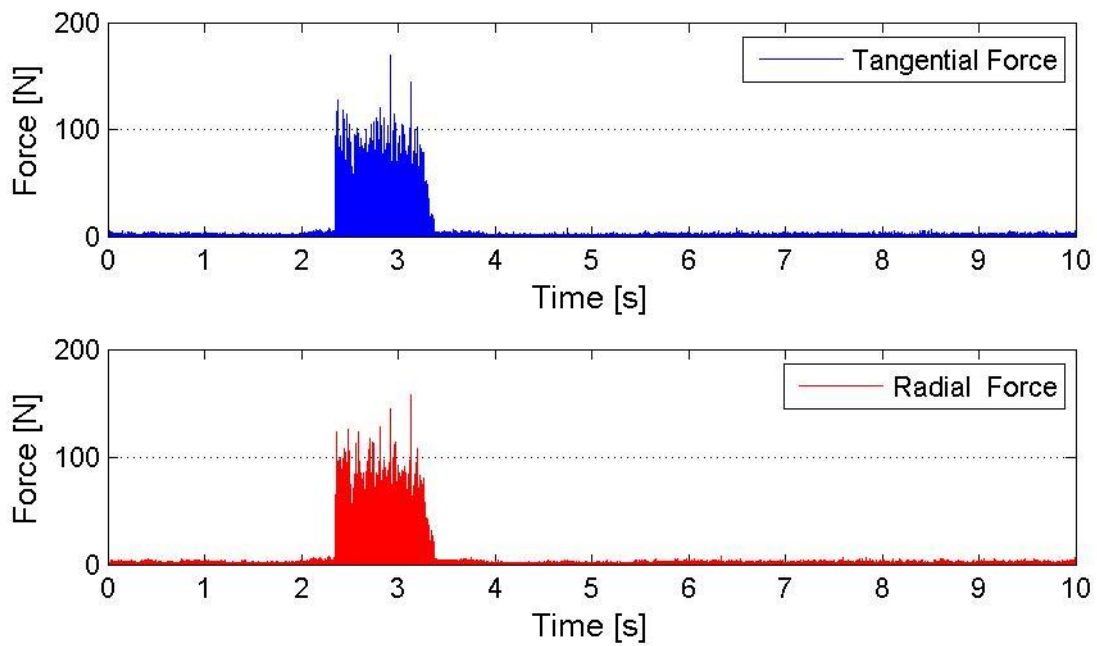


Figure E-32: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

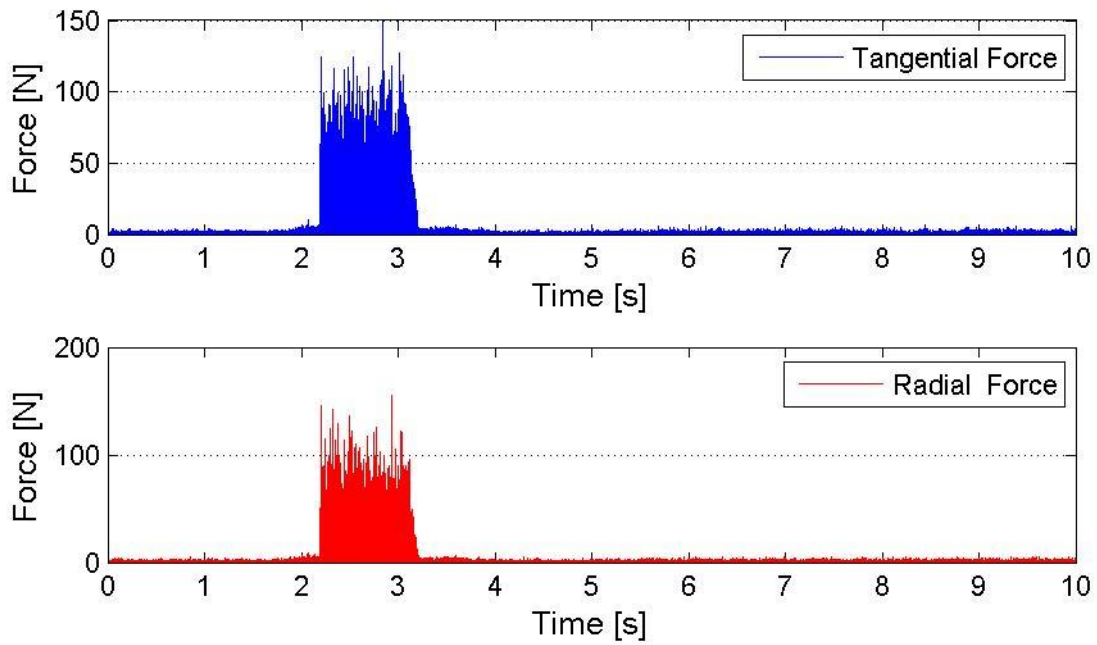


Figure E-33: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

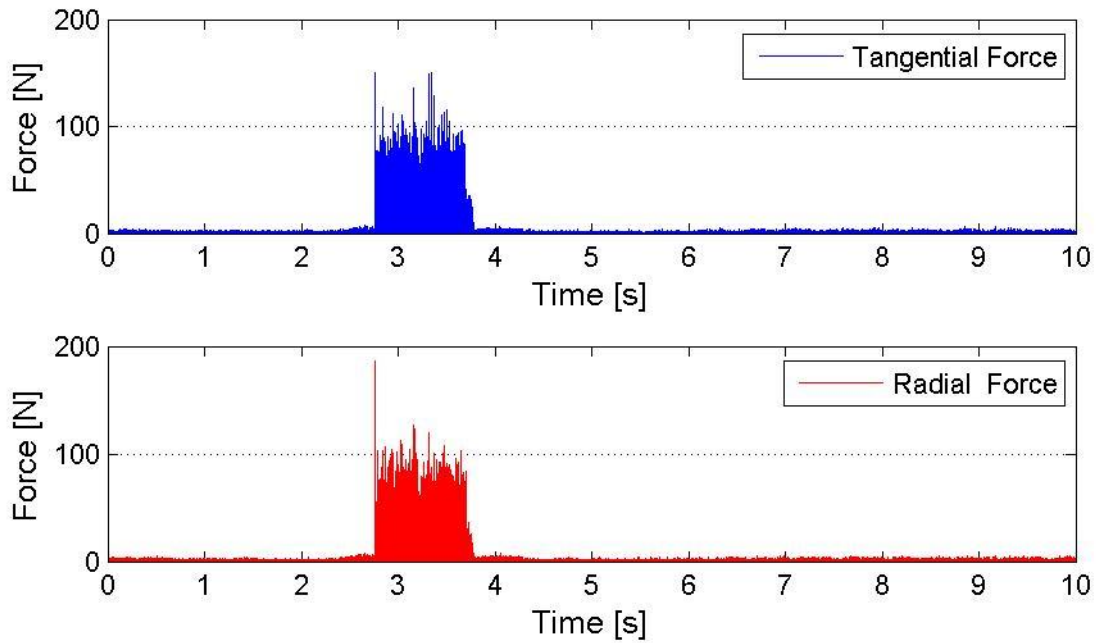


Figure E-34: Tangential and radial cutting force of CB1100 at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

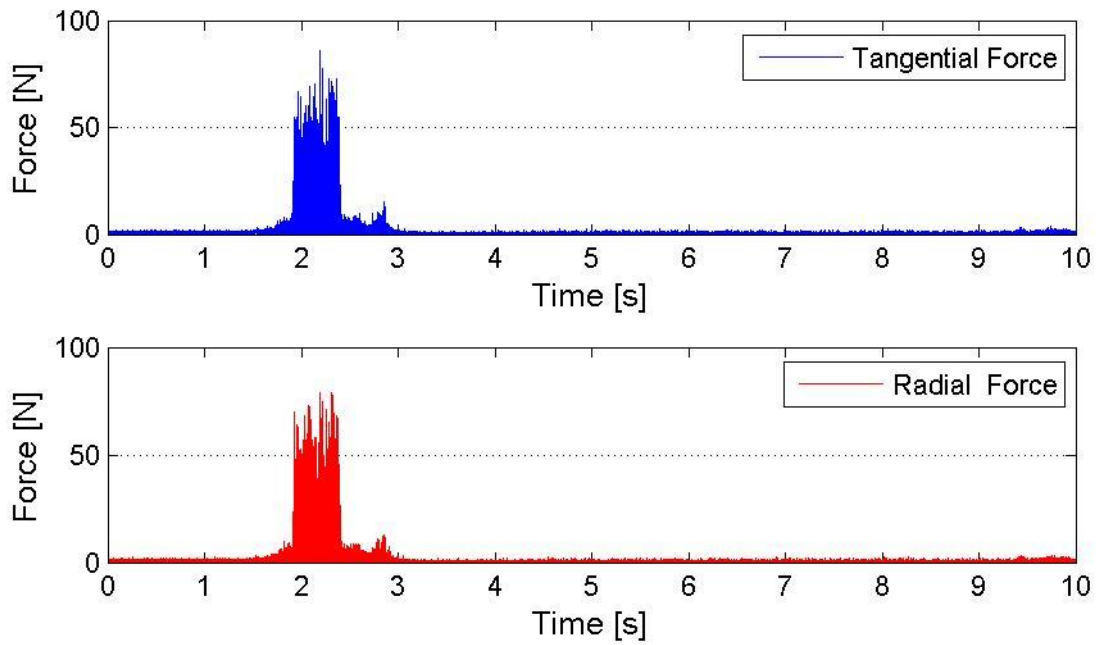


Figure E-35: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

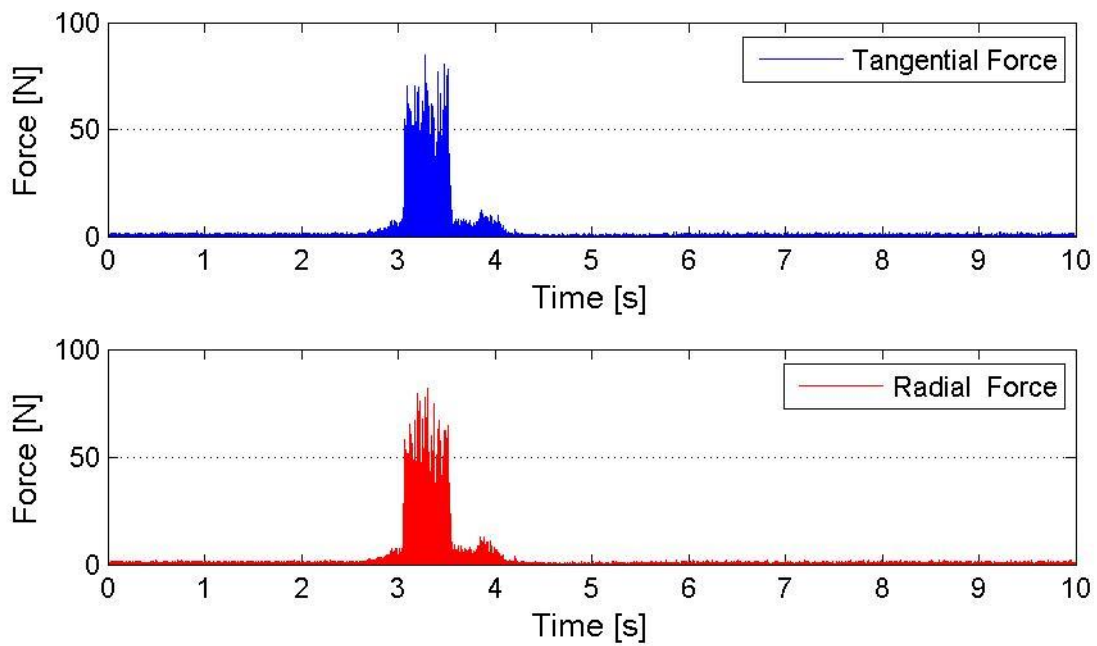


Figure E-36: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

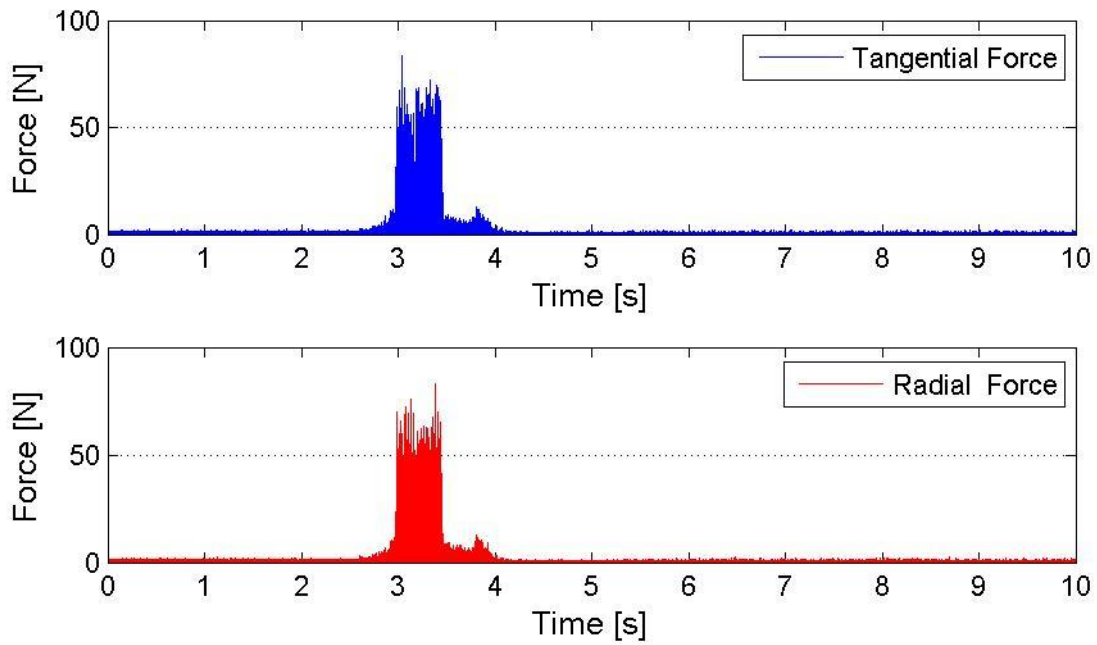


Figure E-37: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

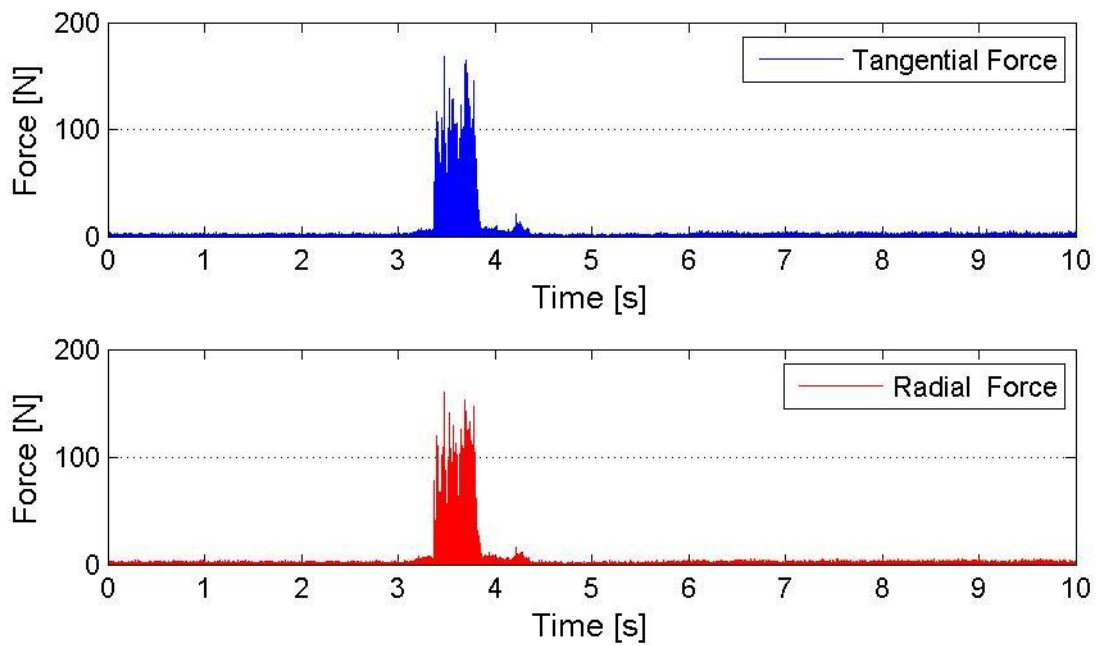


Figure E-38: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

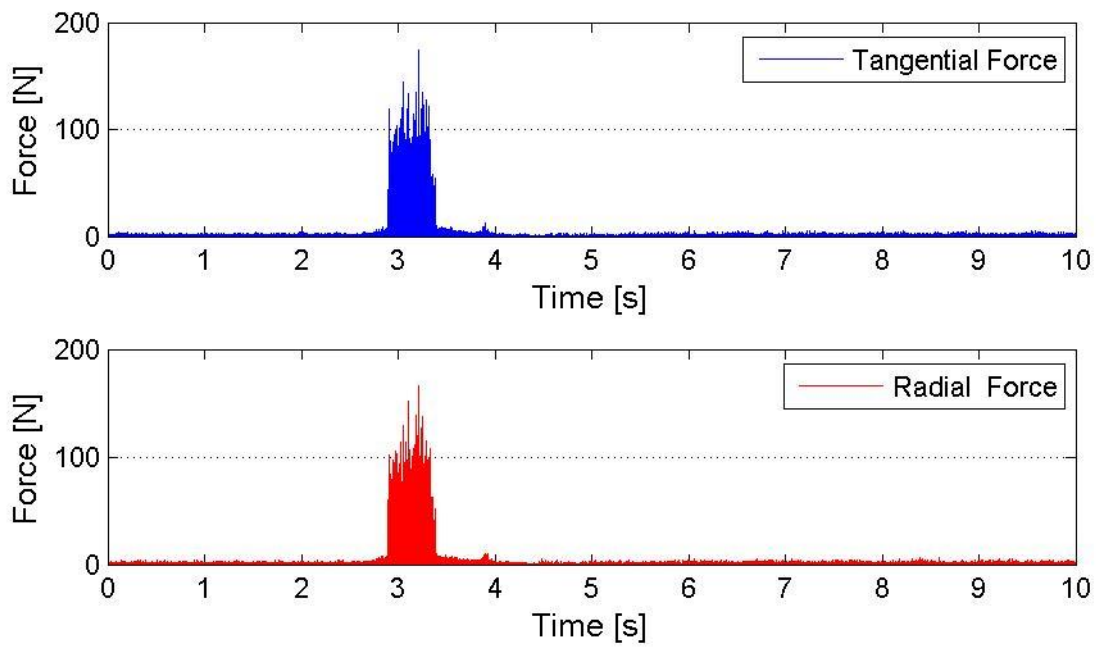


Figure E-39: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

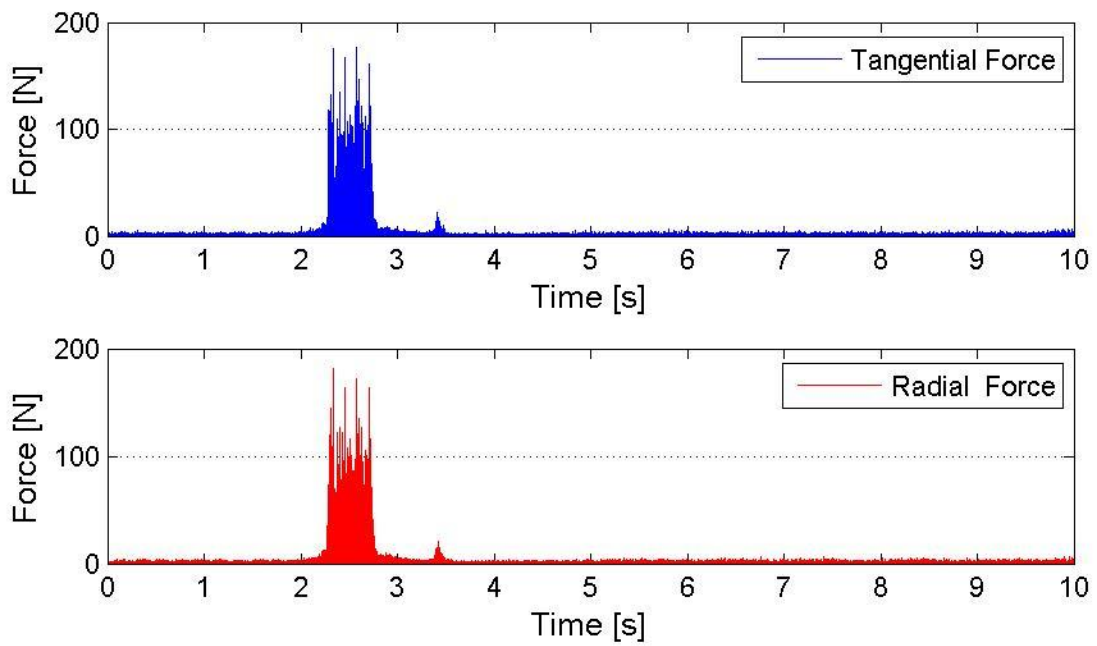


Figure E-40: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

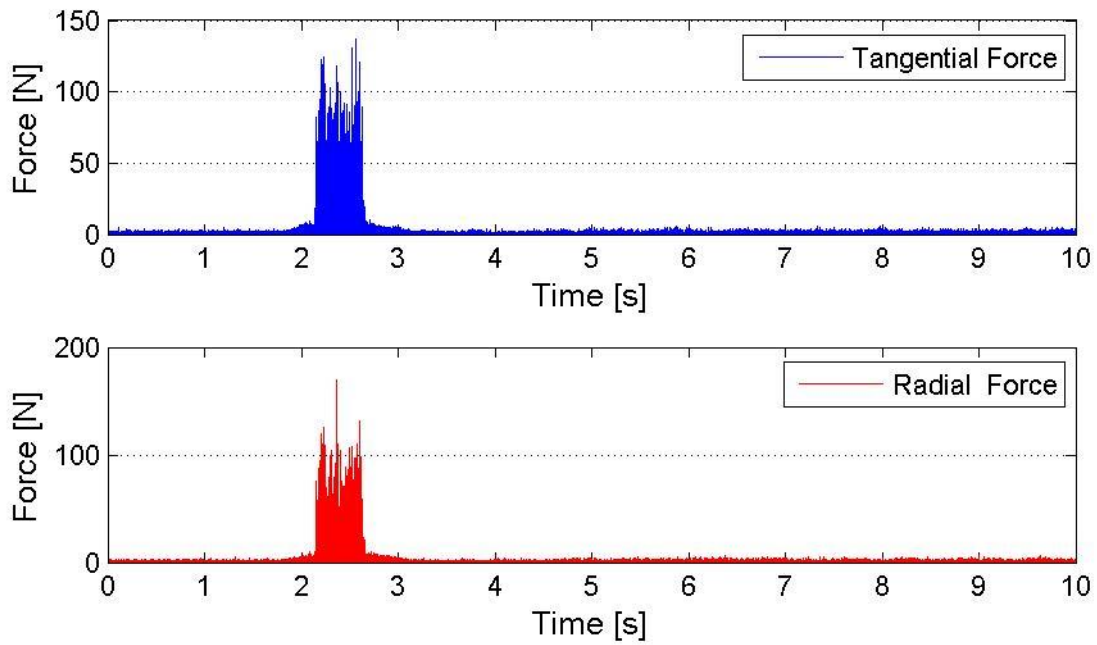


Figure E-41: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

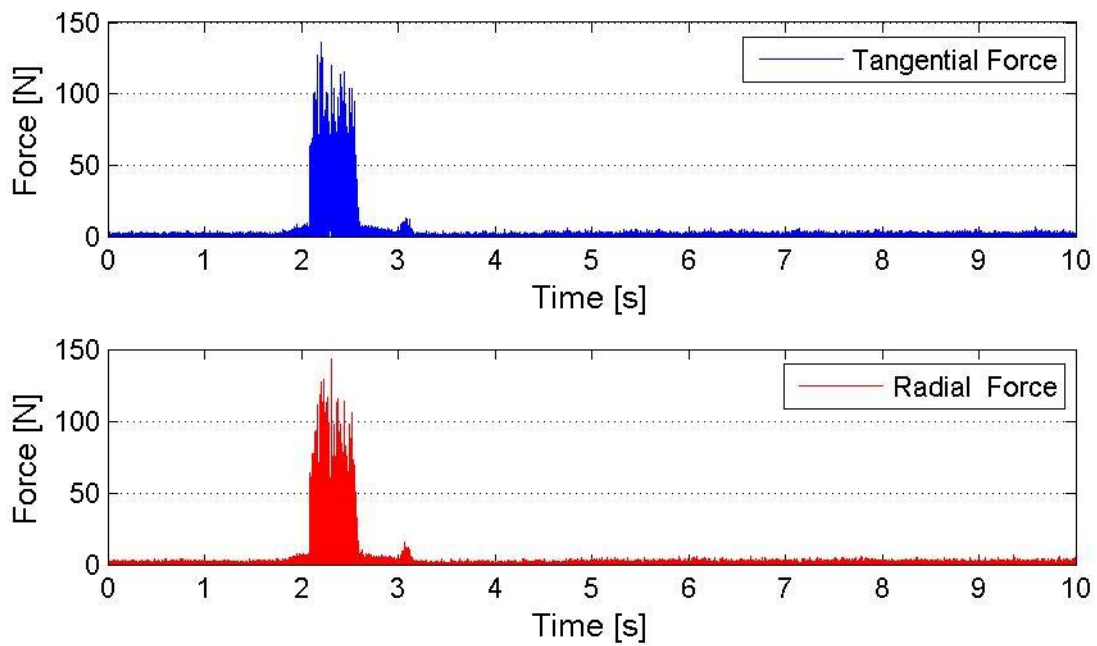


Figure E-42: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

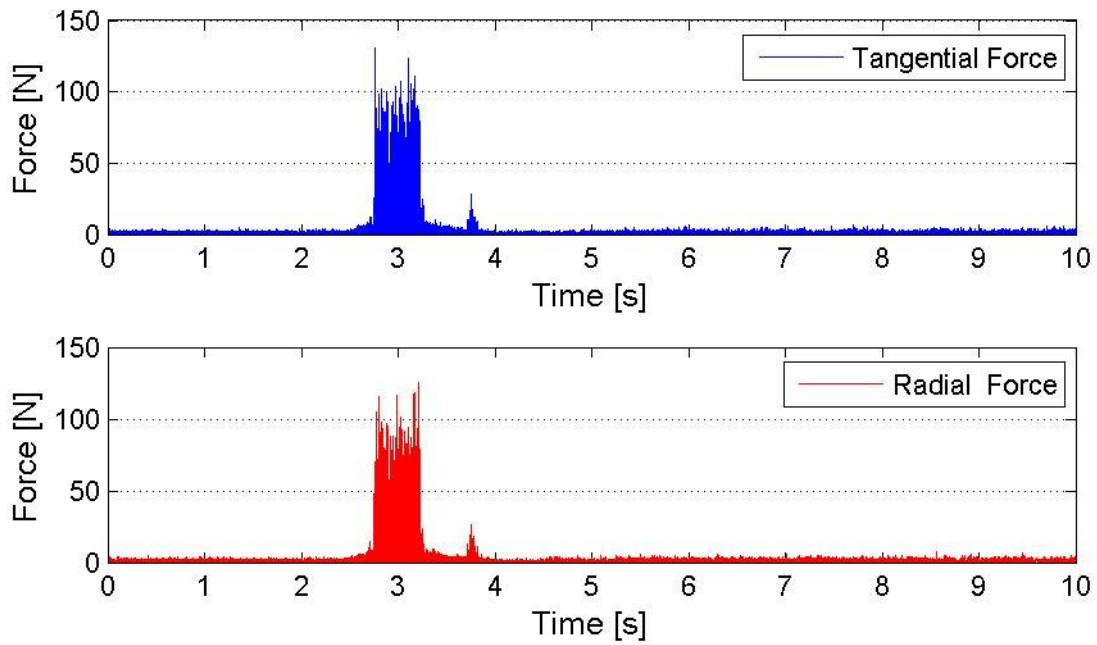


Figure E-43: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

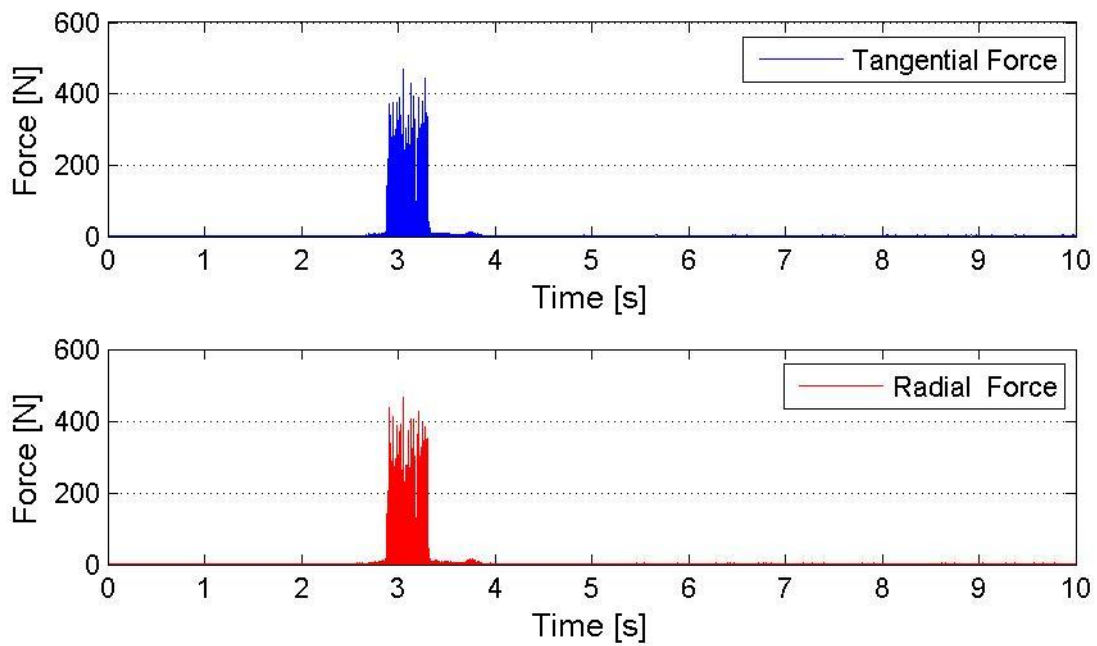


Figure E-44: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

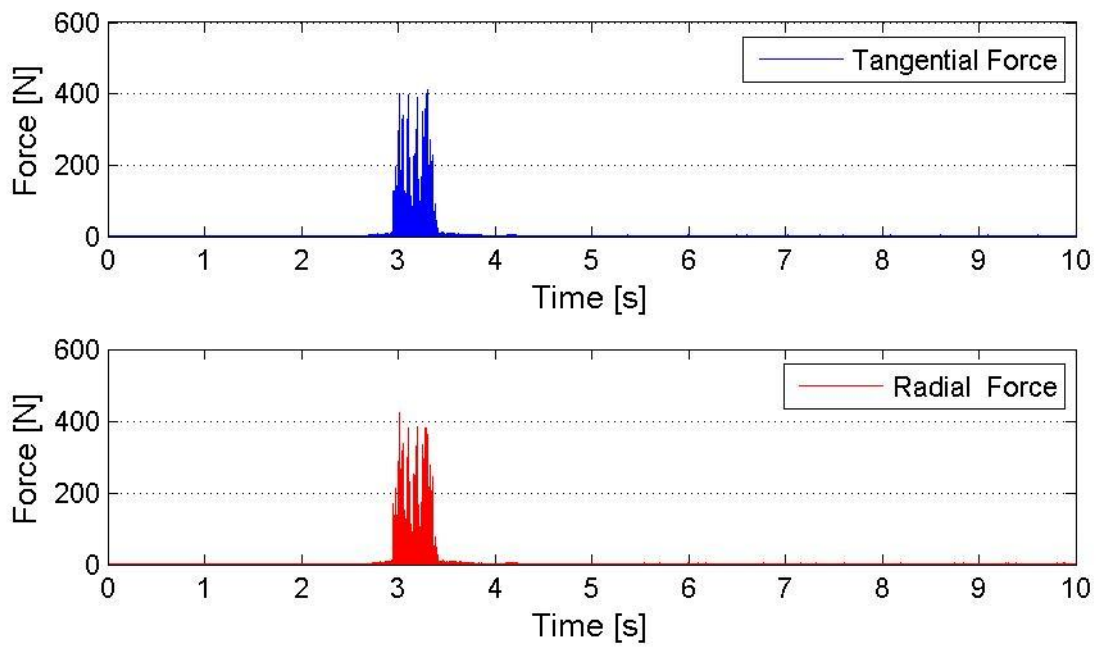


Figure E-45: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

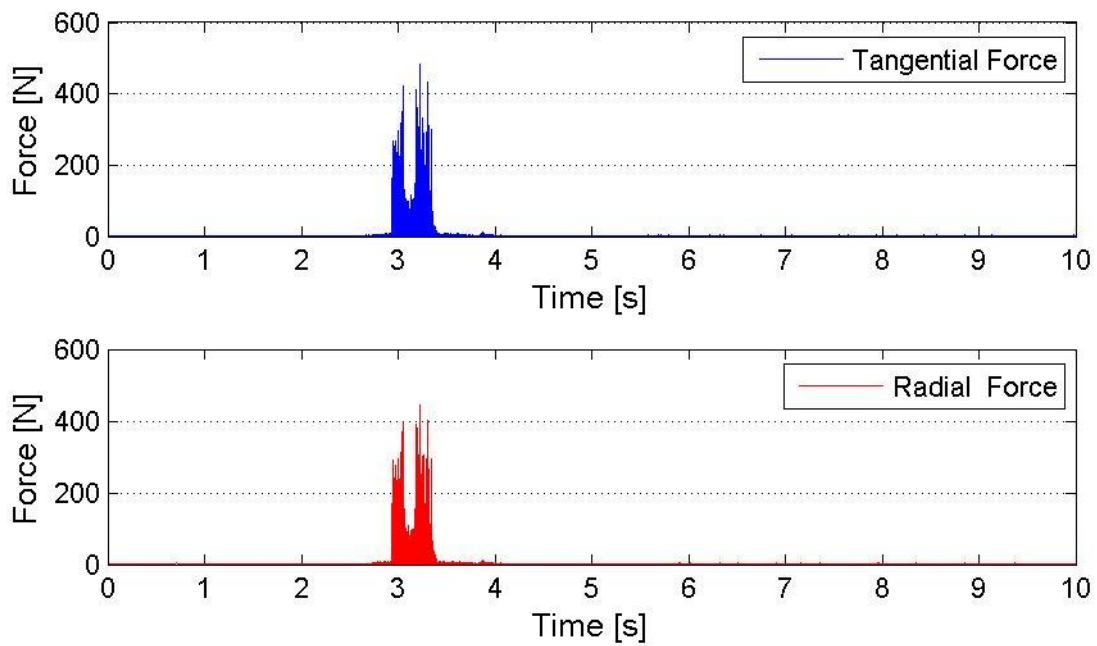


Figure E-46: Tangential and radial cutting force of CB1100 at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

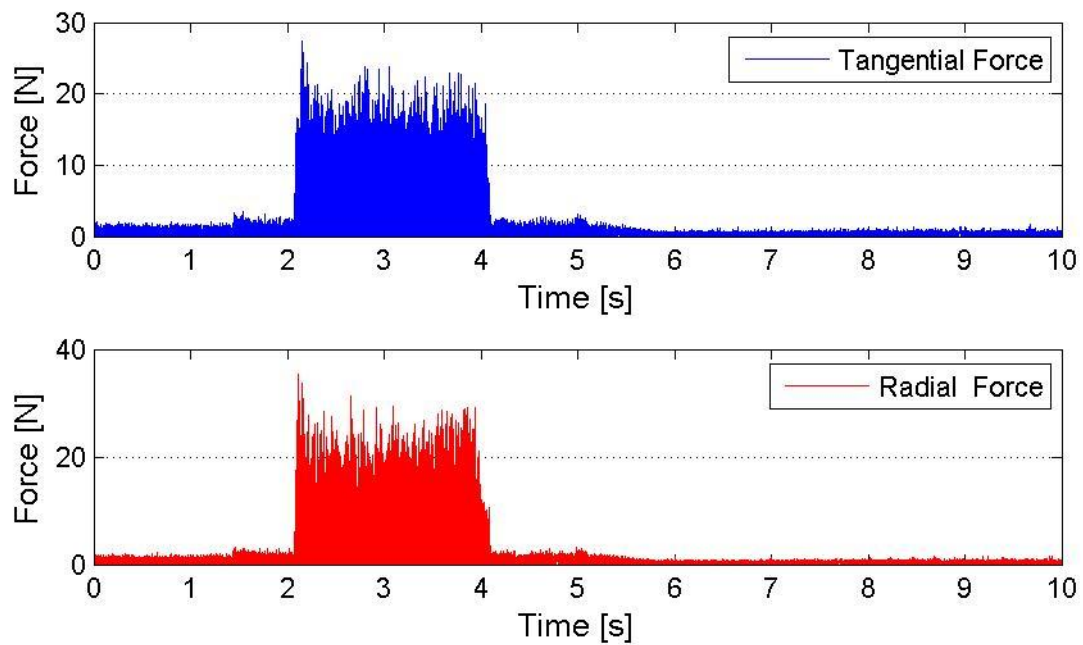


Figure E-47: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

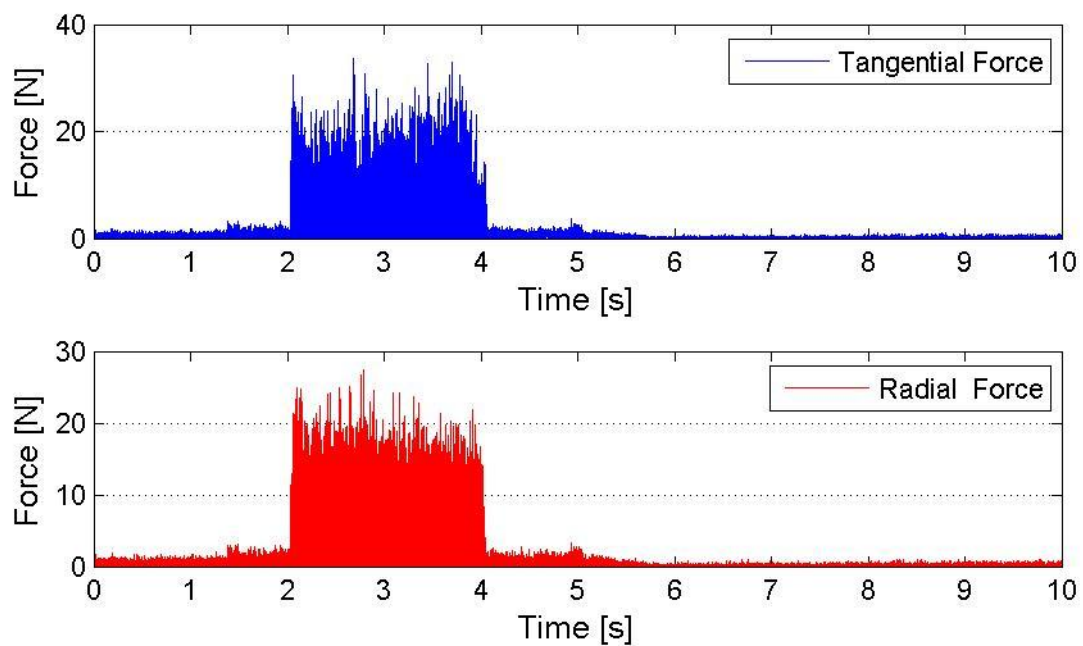


Figure E-48: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

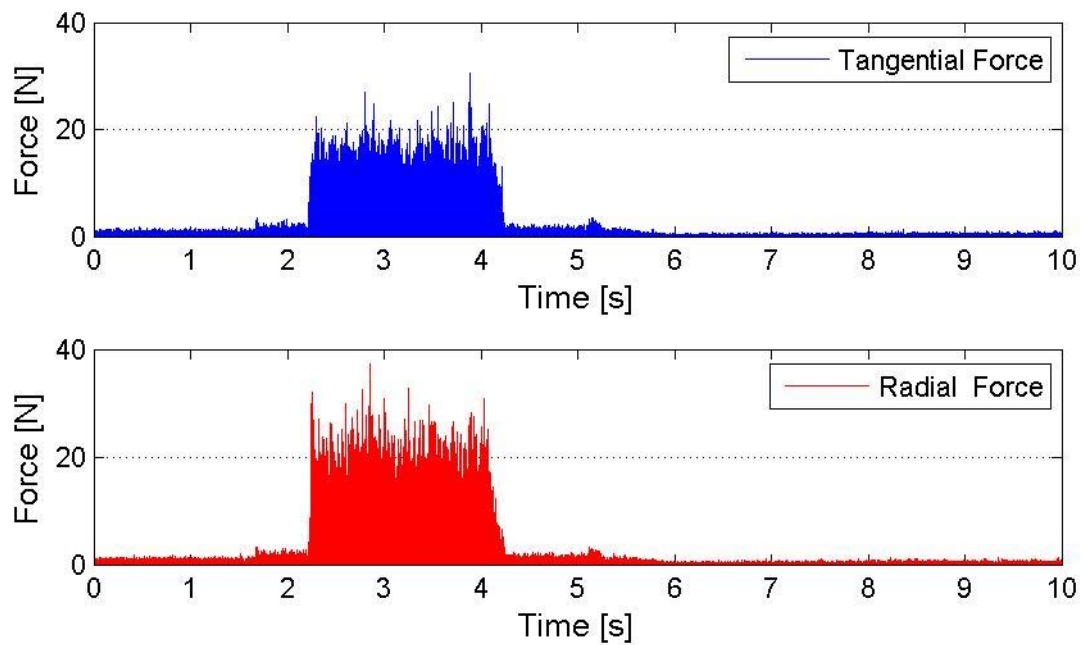


Figure E-49: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

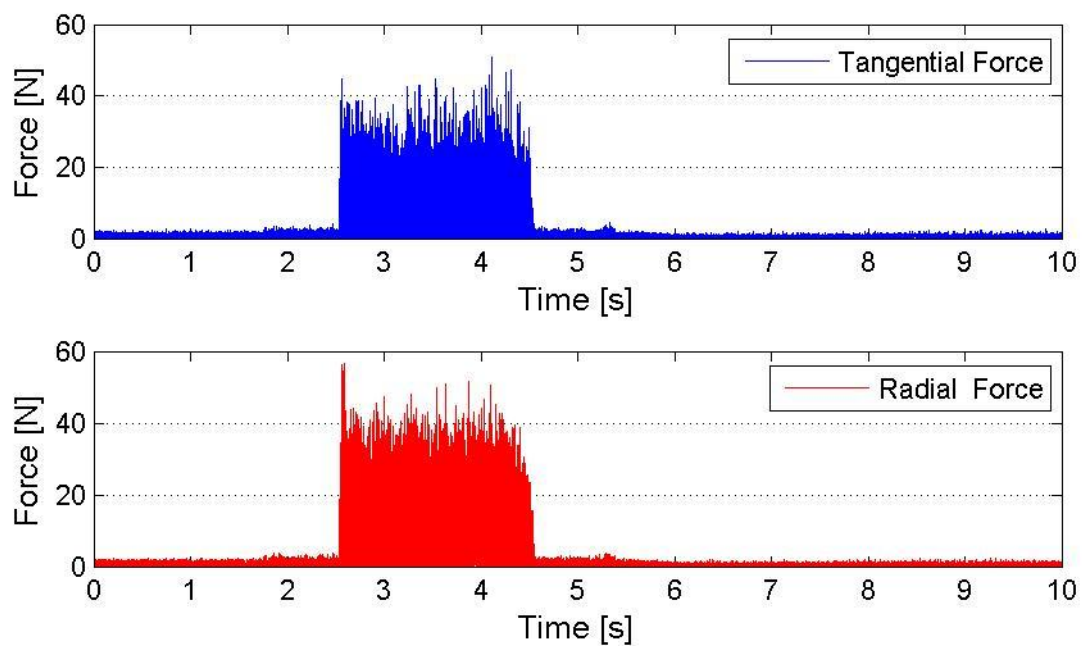


Figure E-50: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

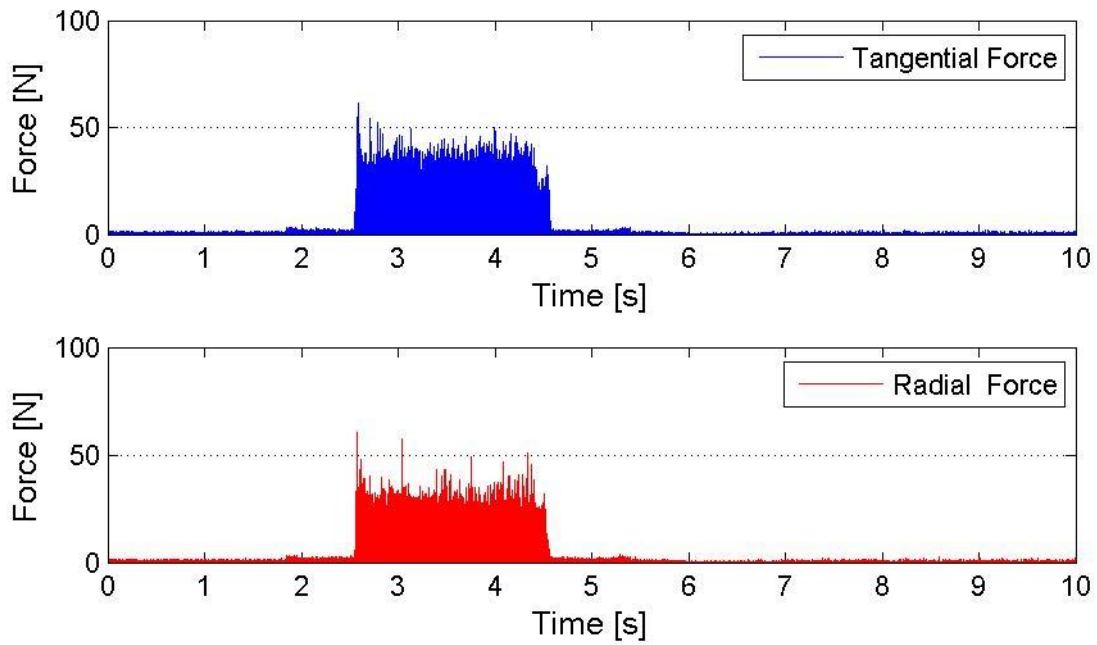


Figure E-51: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

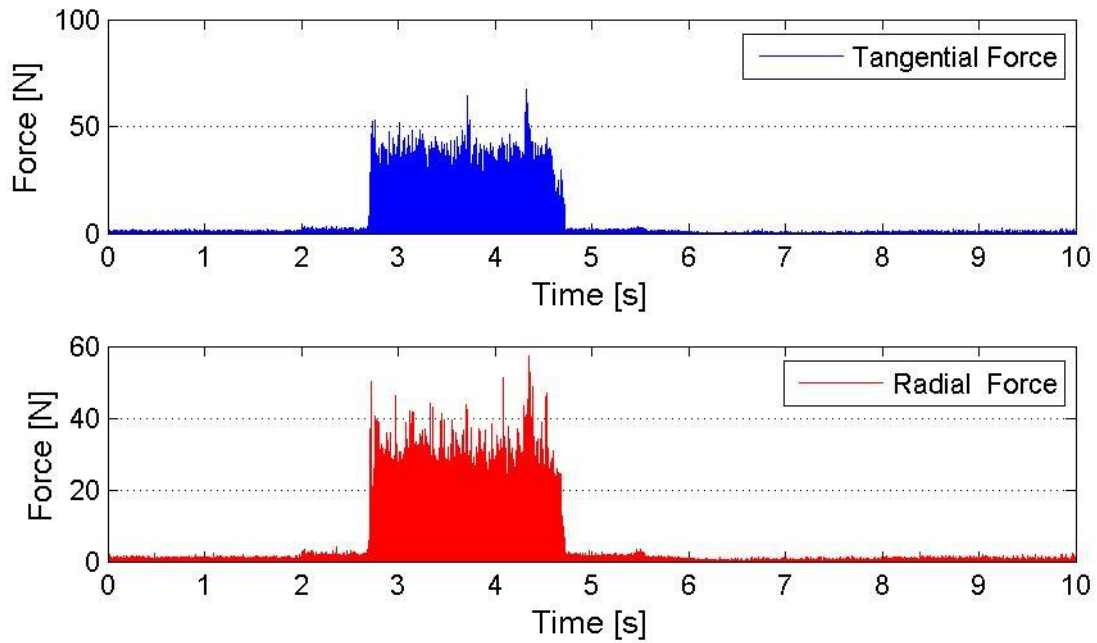


Figure E-52: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

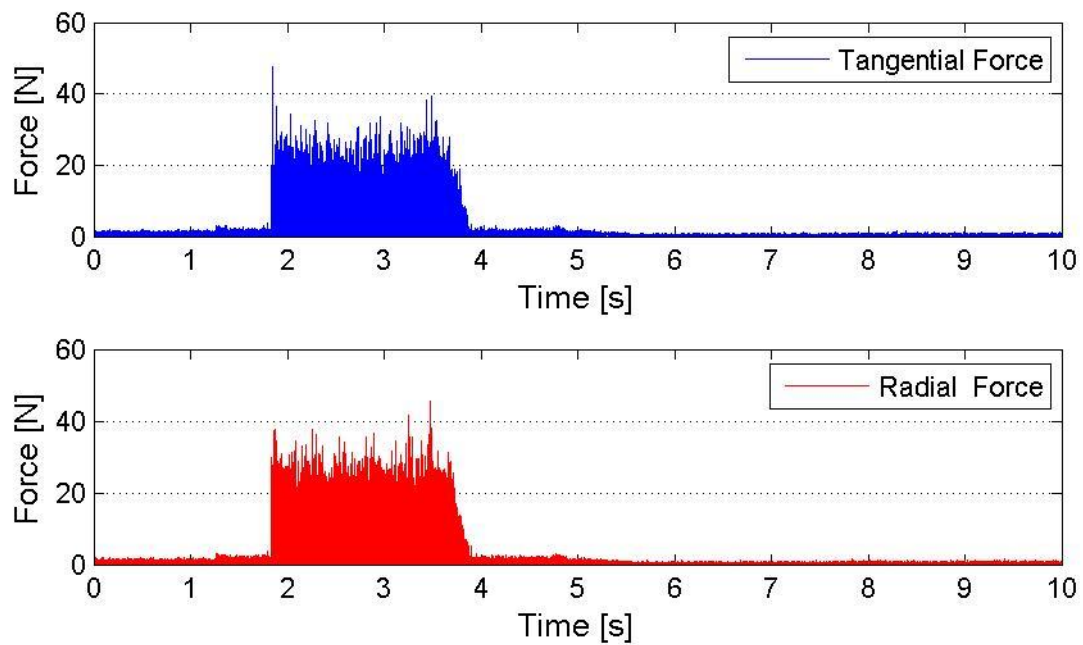


Figure E-53: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

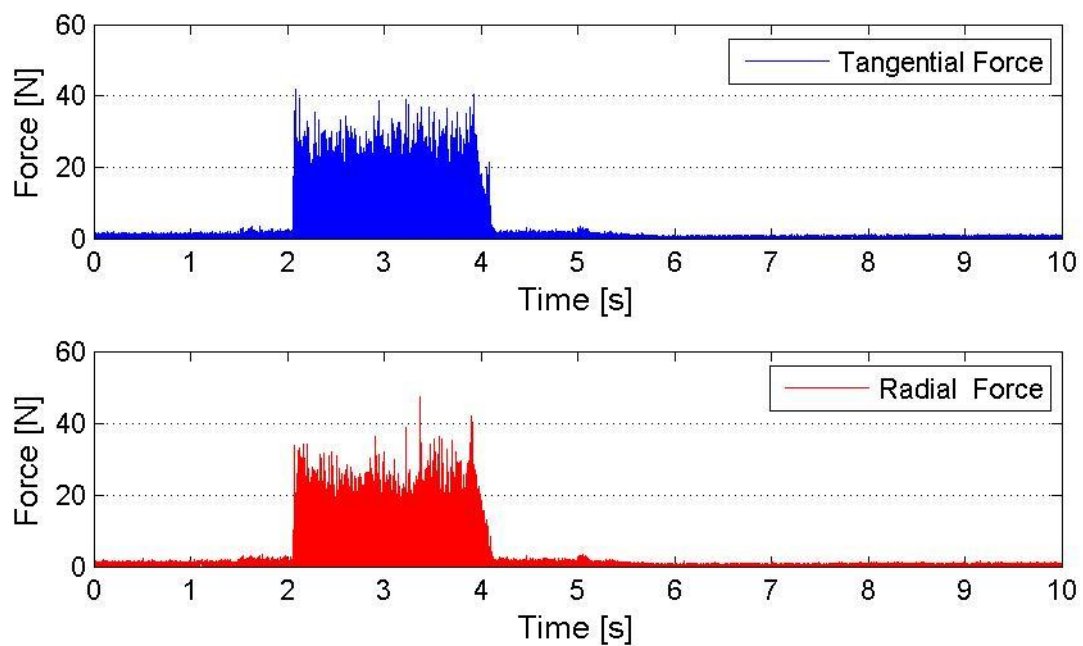


Figure E-54: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

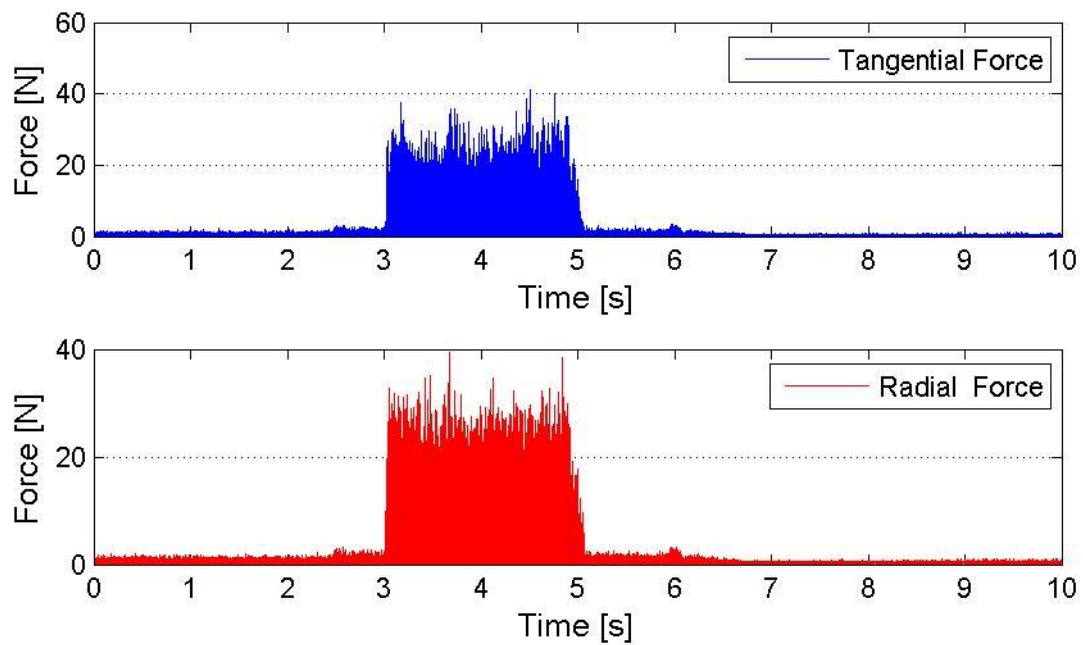


Figure E-55: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

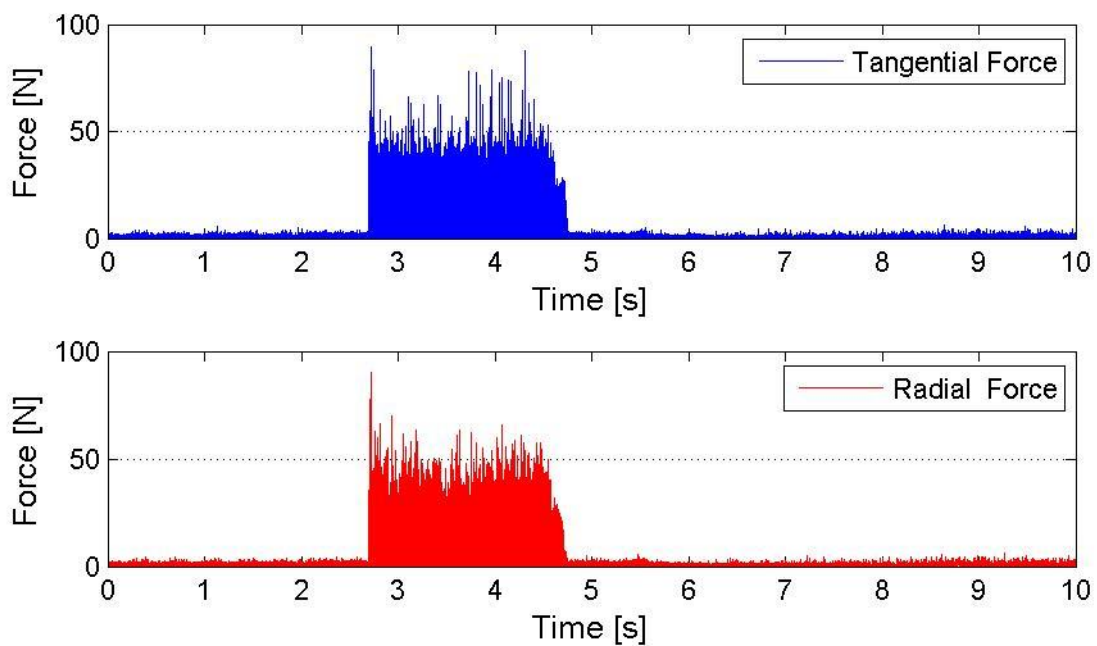


Figure E-56: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

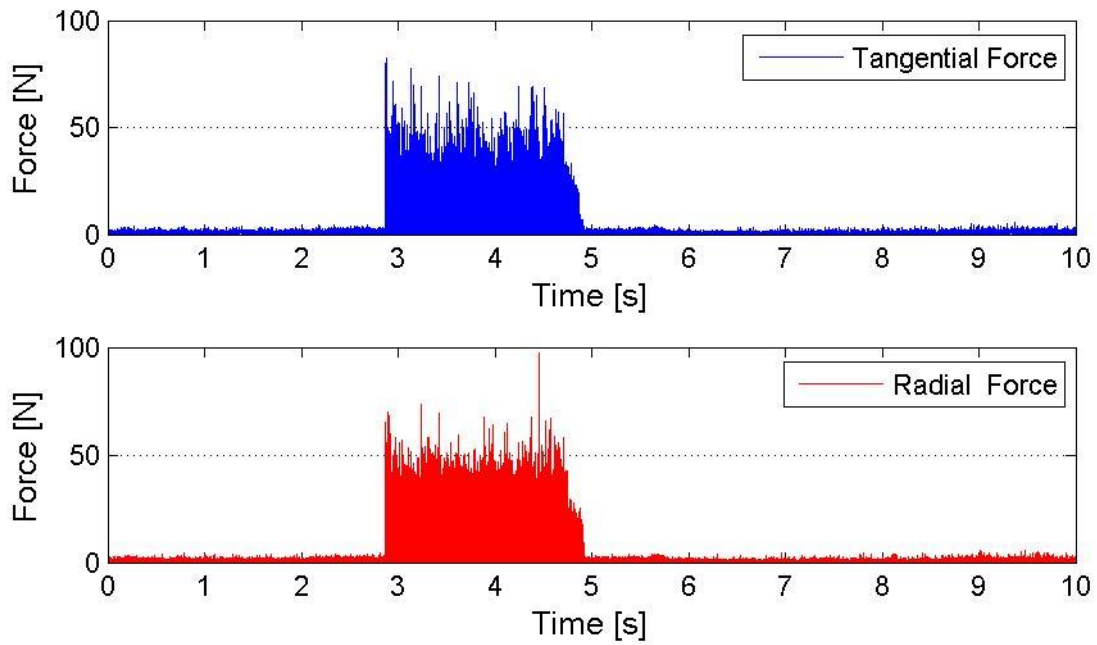


Figure E-57: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

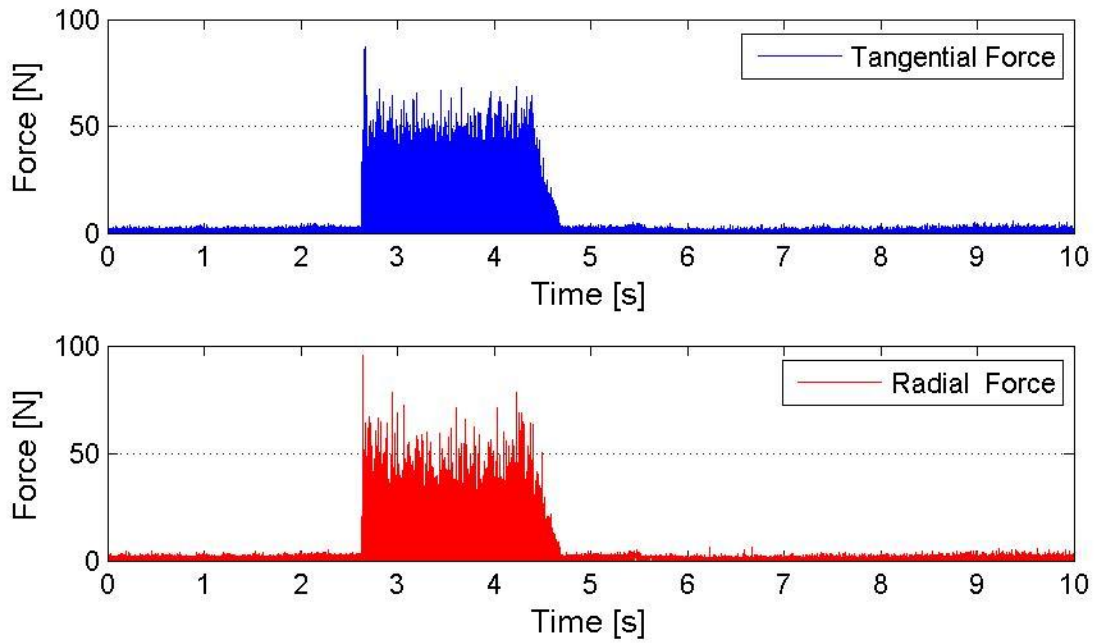


Figure E-58: Tangential and radial cutting force of CB1100 at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

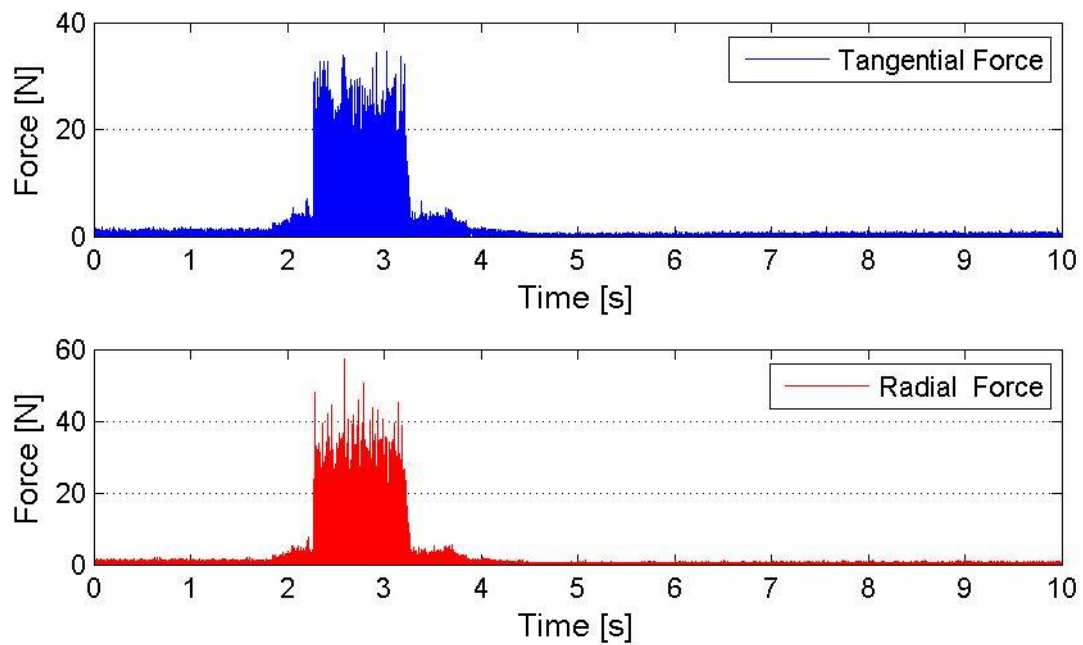


Figure E-59: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

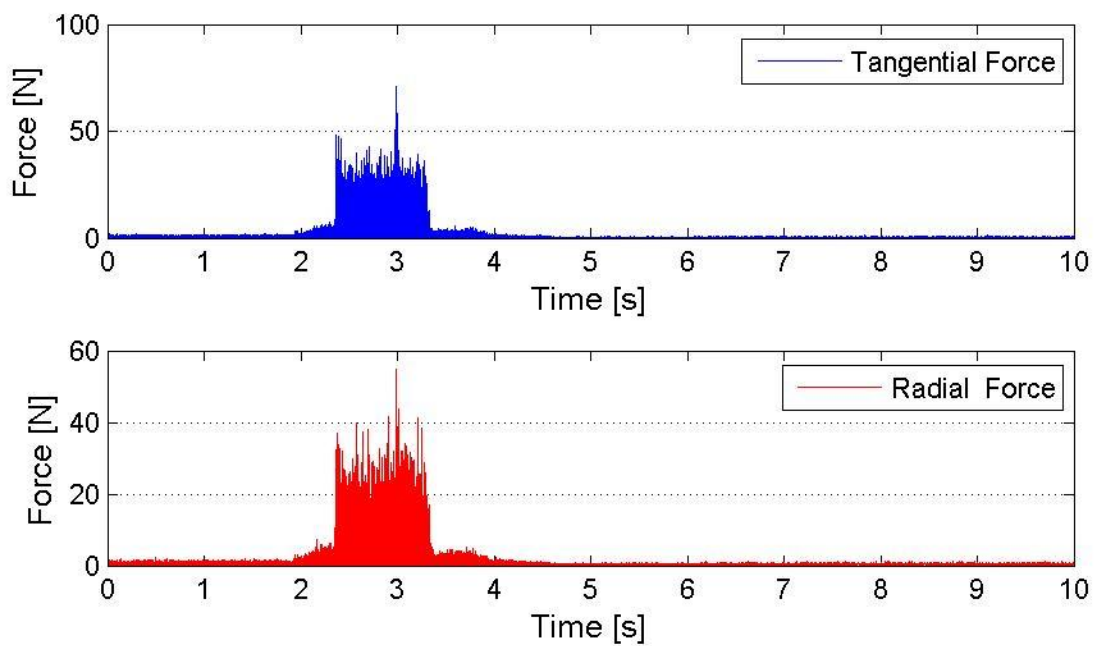


Figure E-60: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

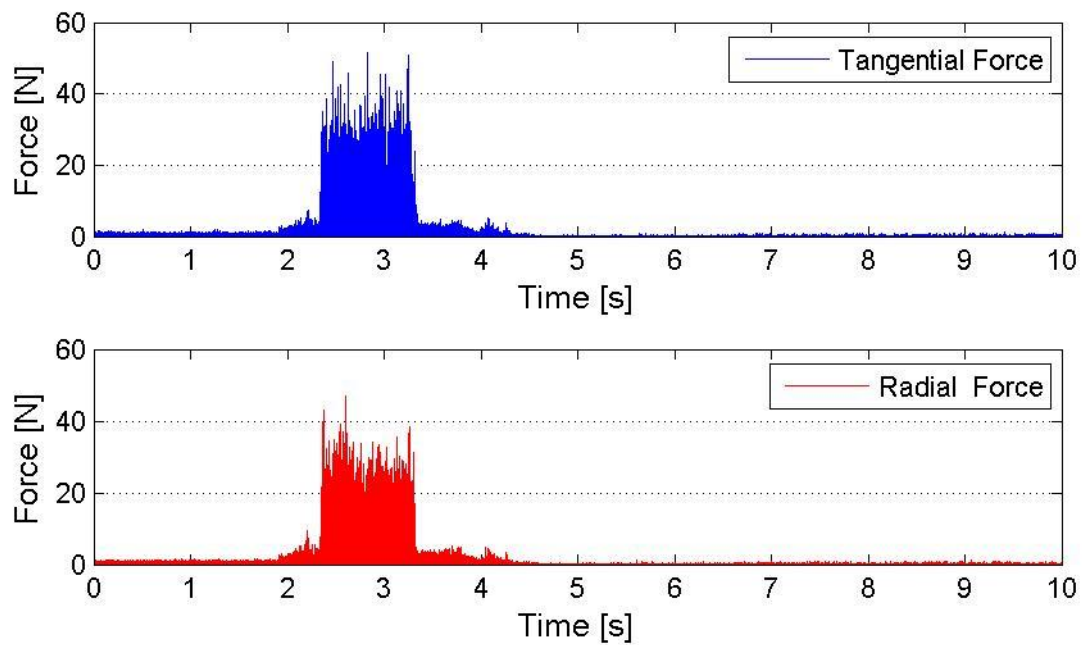


Figure E-61: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

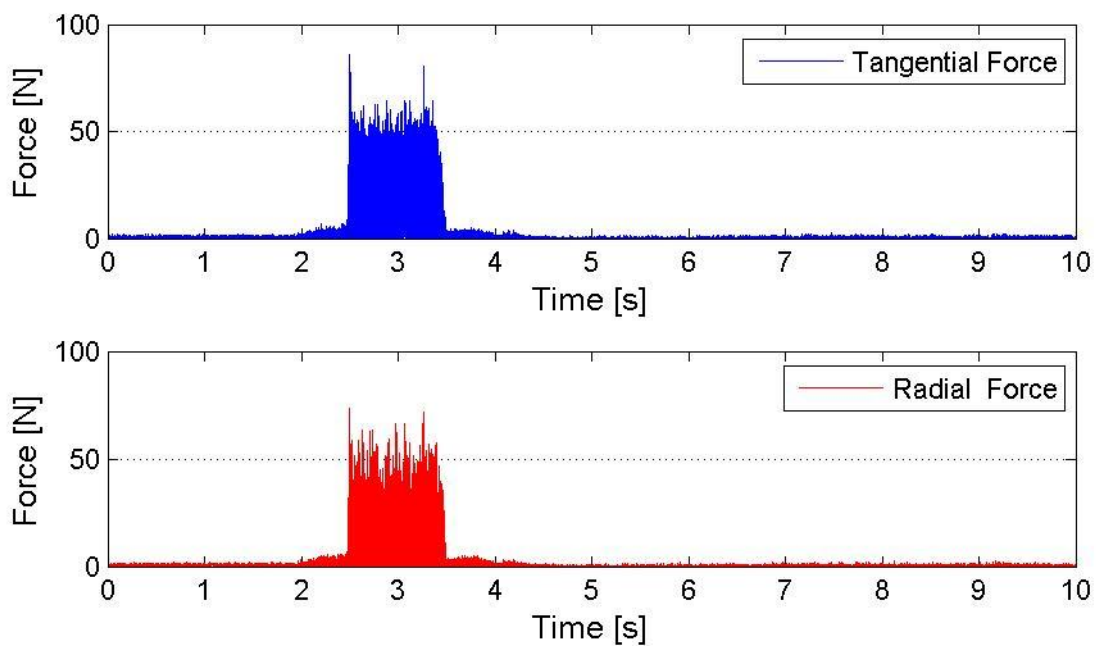


Figure E-62: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

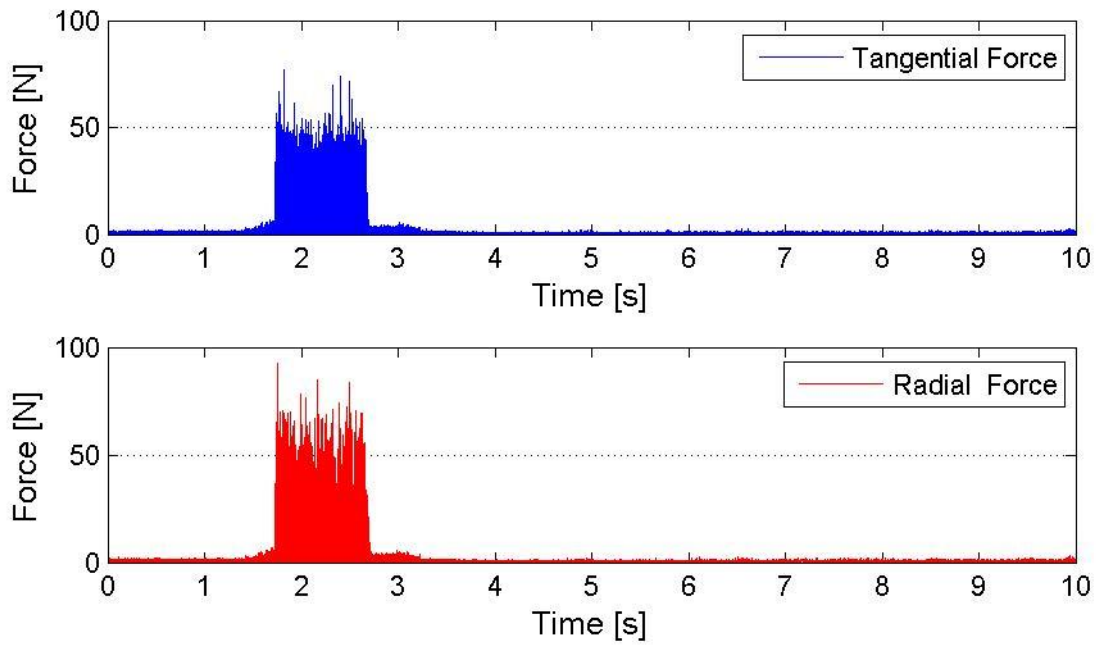


Figure E-63: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

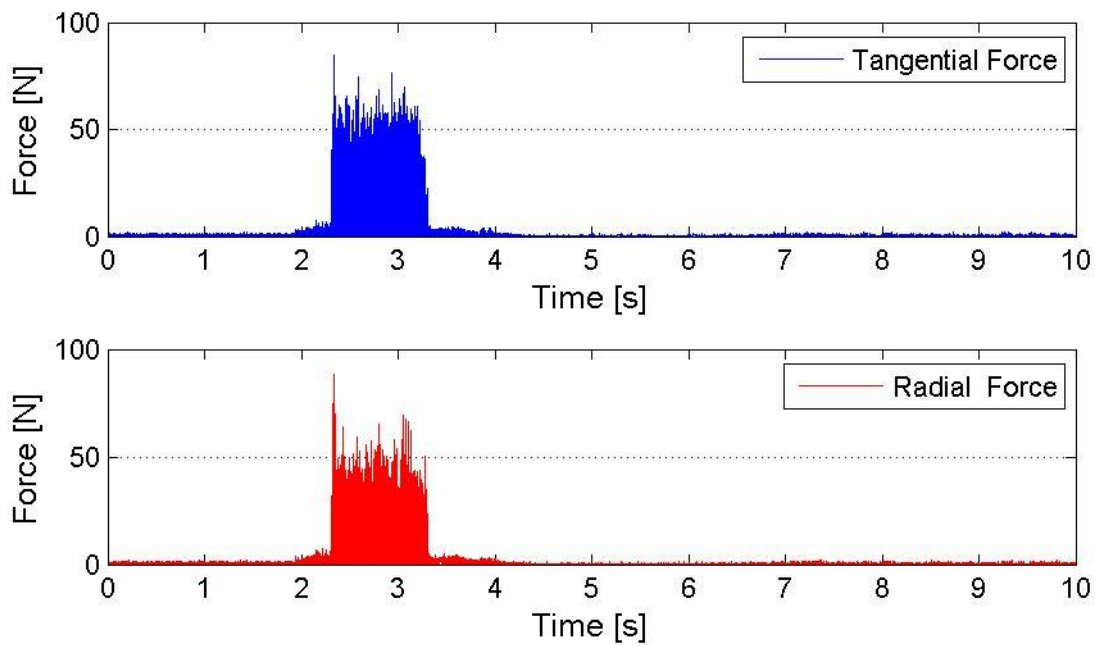


Figure E-64: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

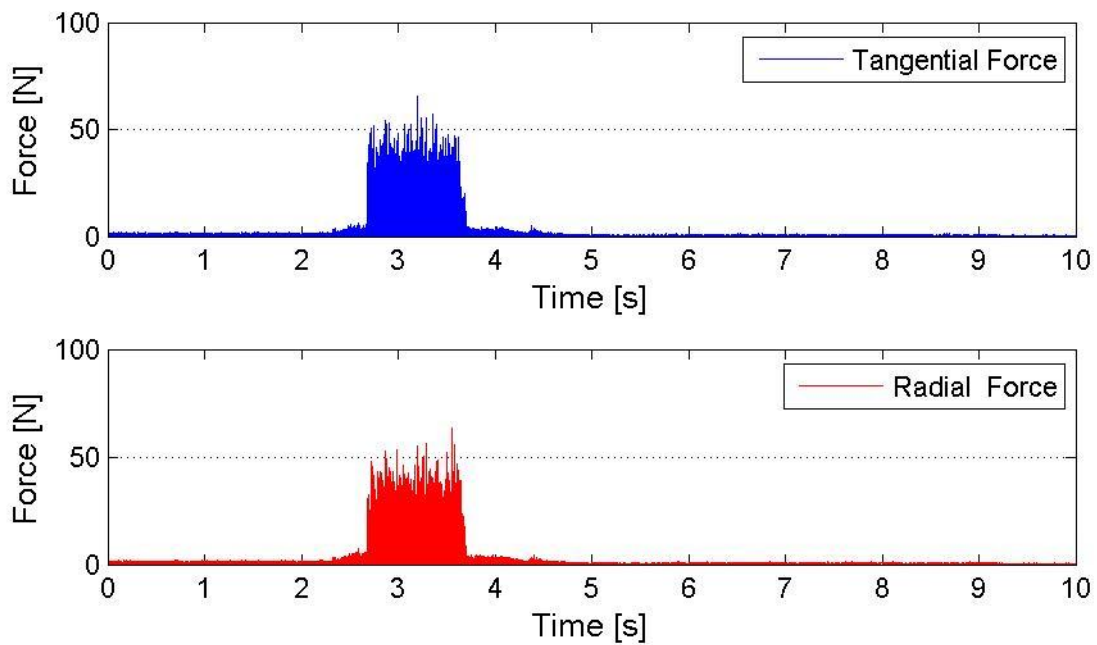


Figure E-65: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

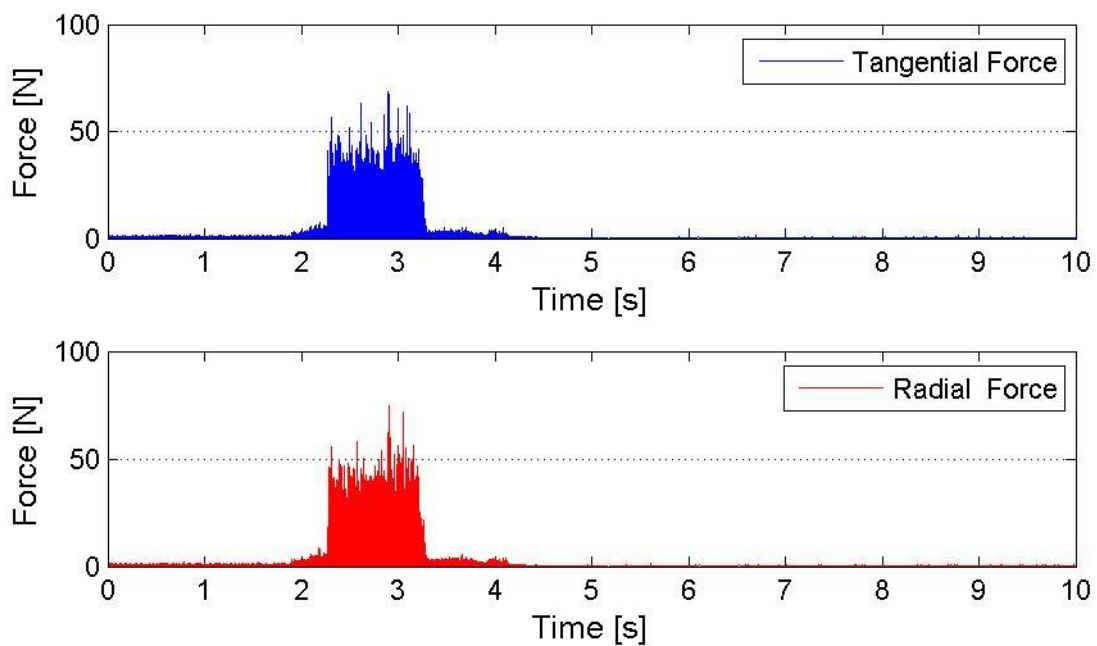


Figure E-66: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

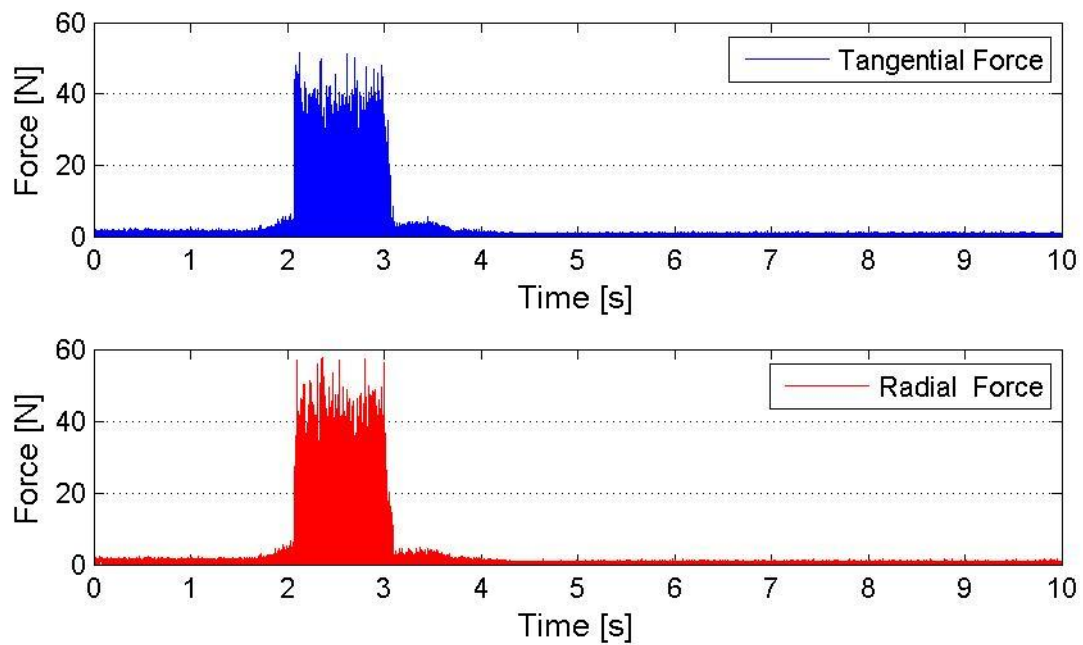


Figure E-67: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

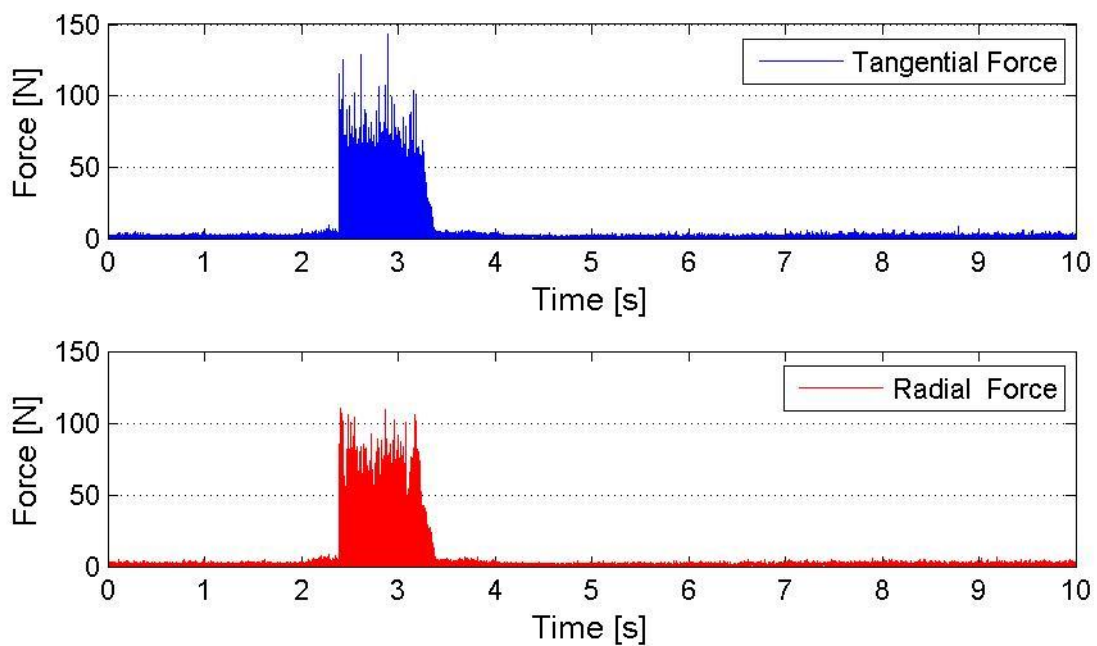


Figure E-68: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

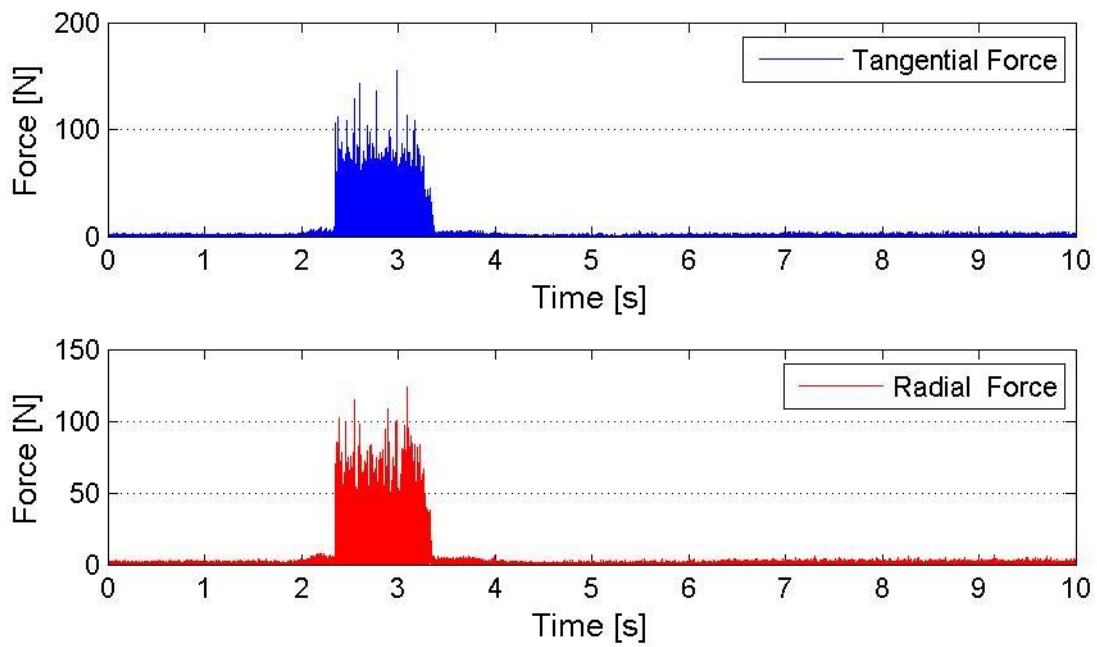


Figure E-69: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

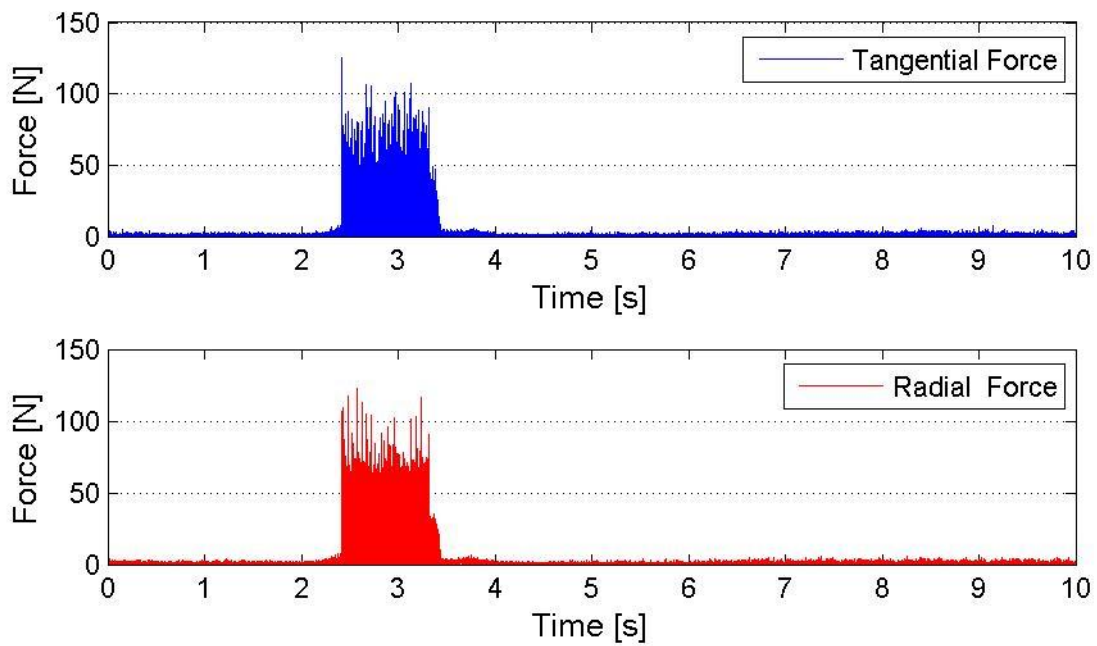


Figure E-70: Tangential and radial cutting force of CB1100 at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

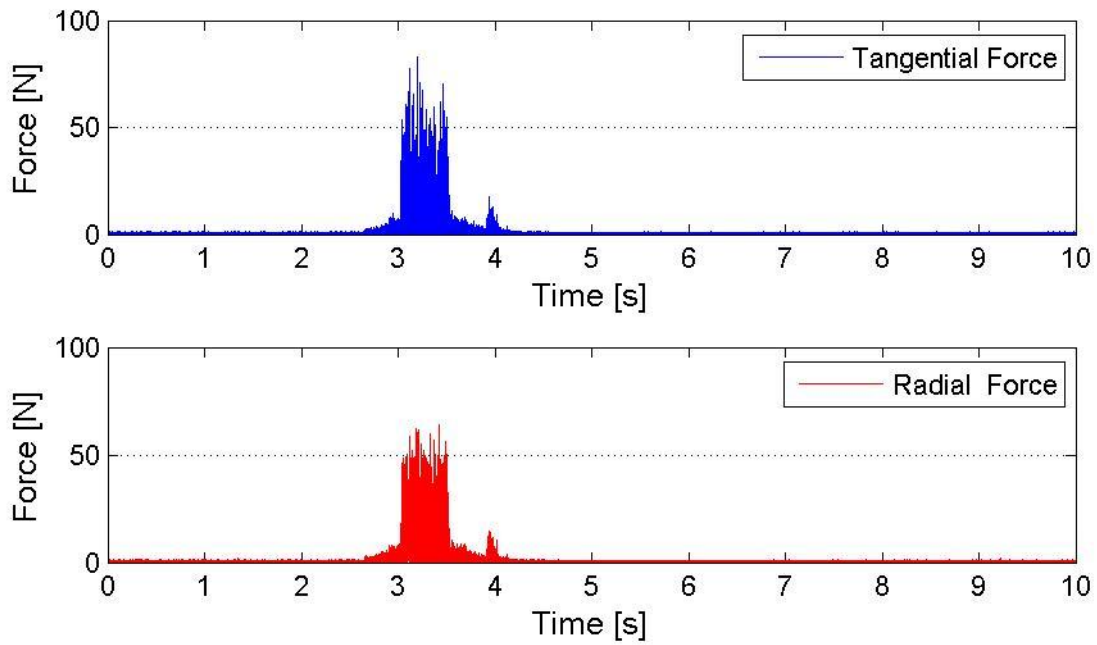


Figure E-71: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

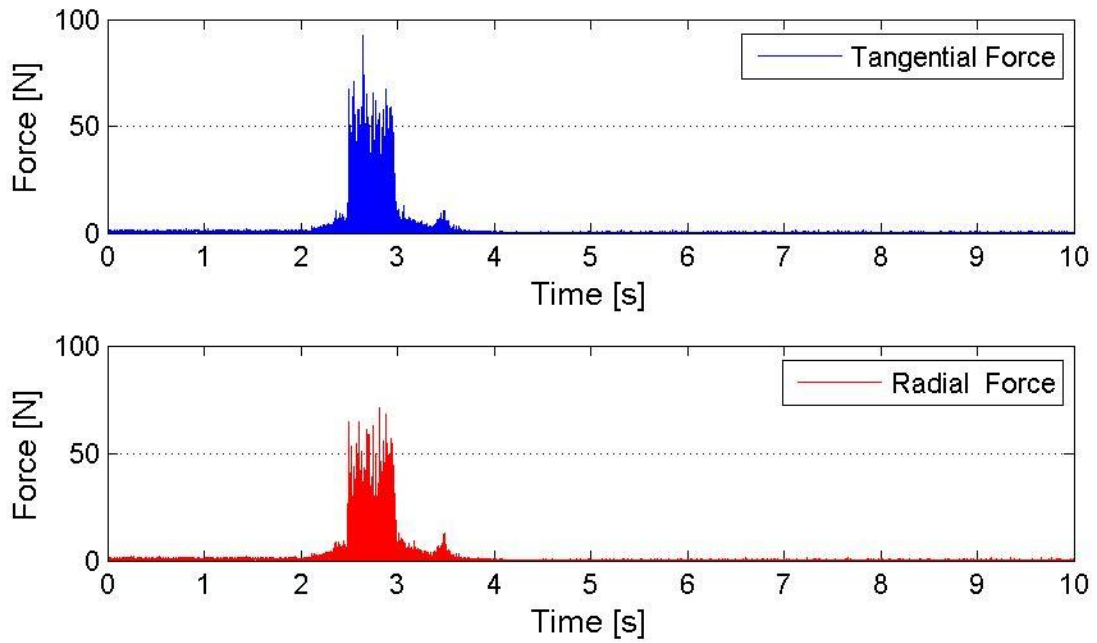


Figure E-72: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

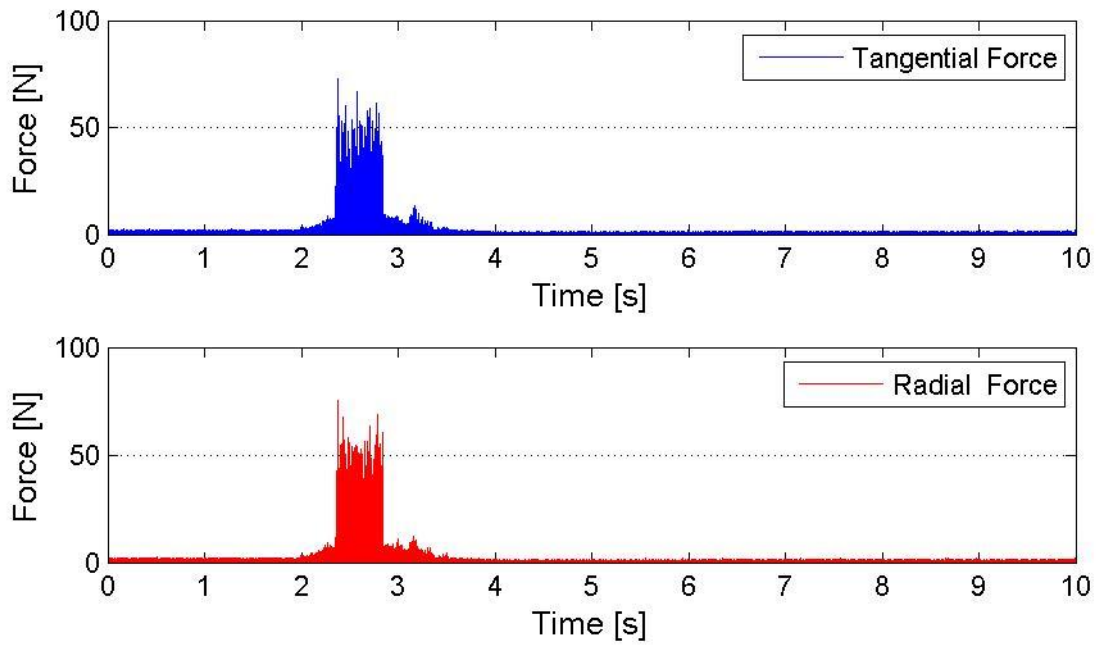


Figure E-73: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

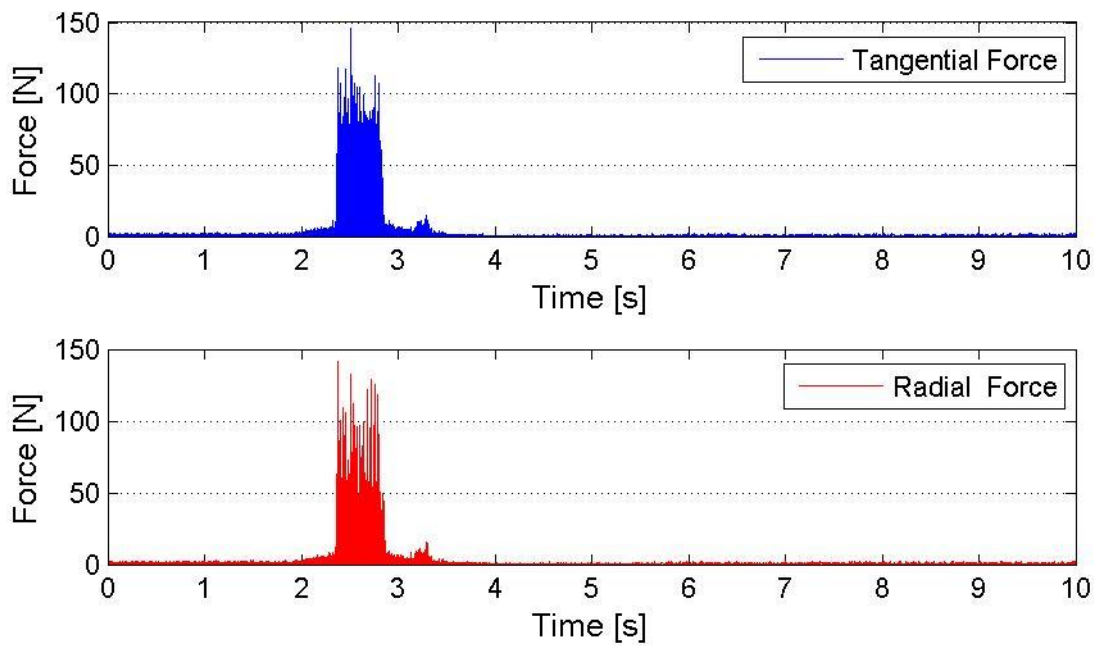


Figure E-74: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

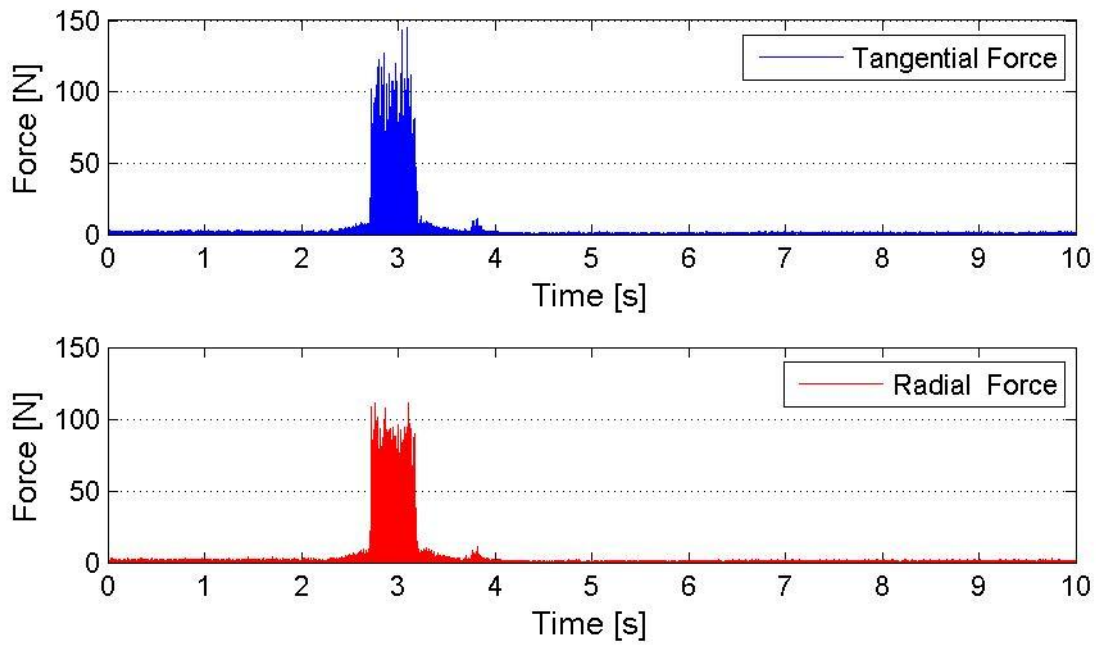


Figure E-75: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

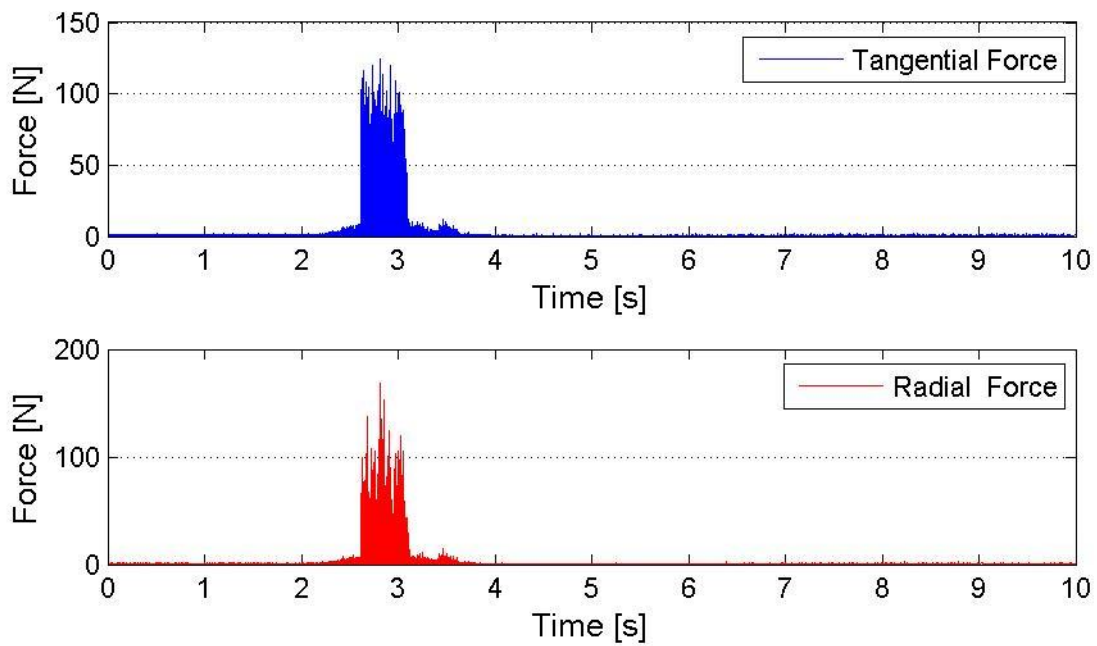


Figure E-76: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

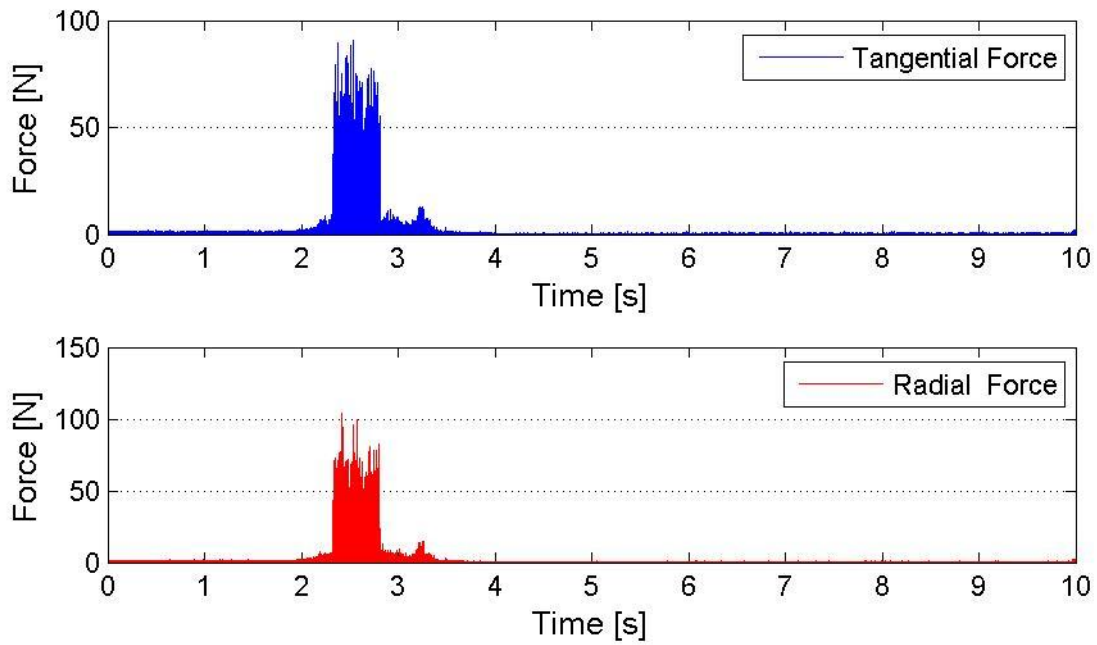


Figure E-77: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

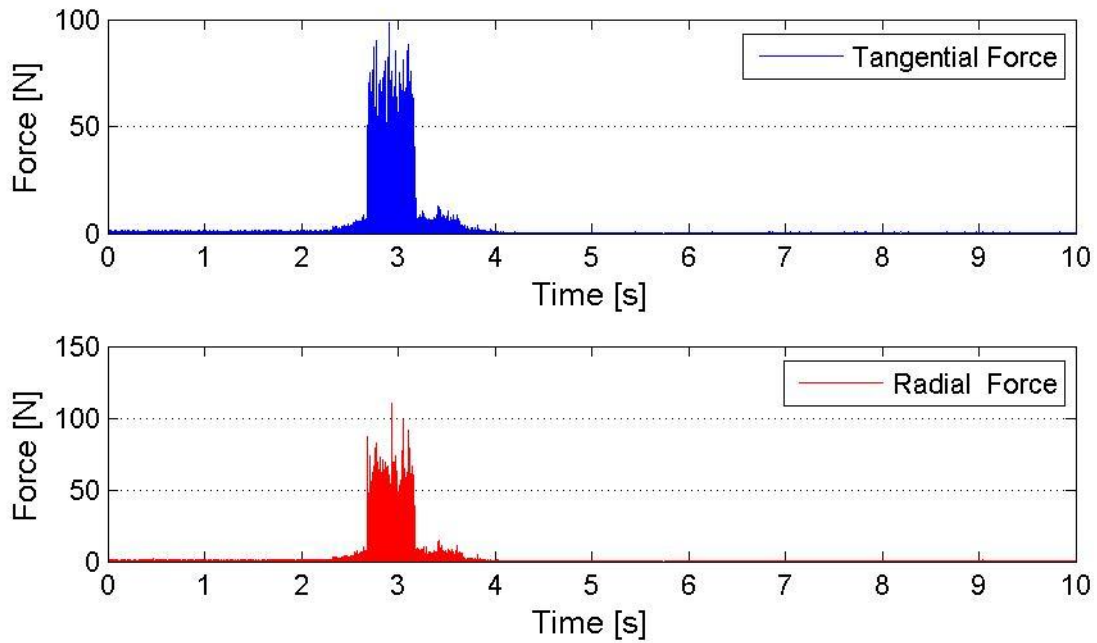


Figure E-78: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

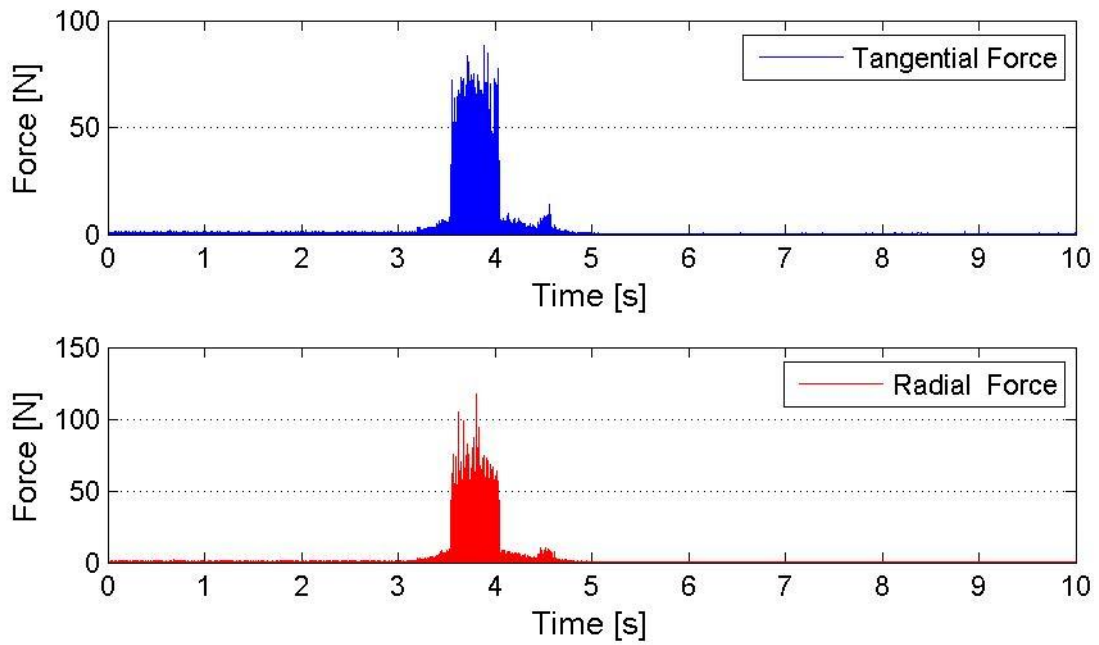


Figure E-79: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

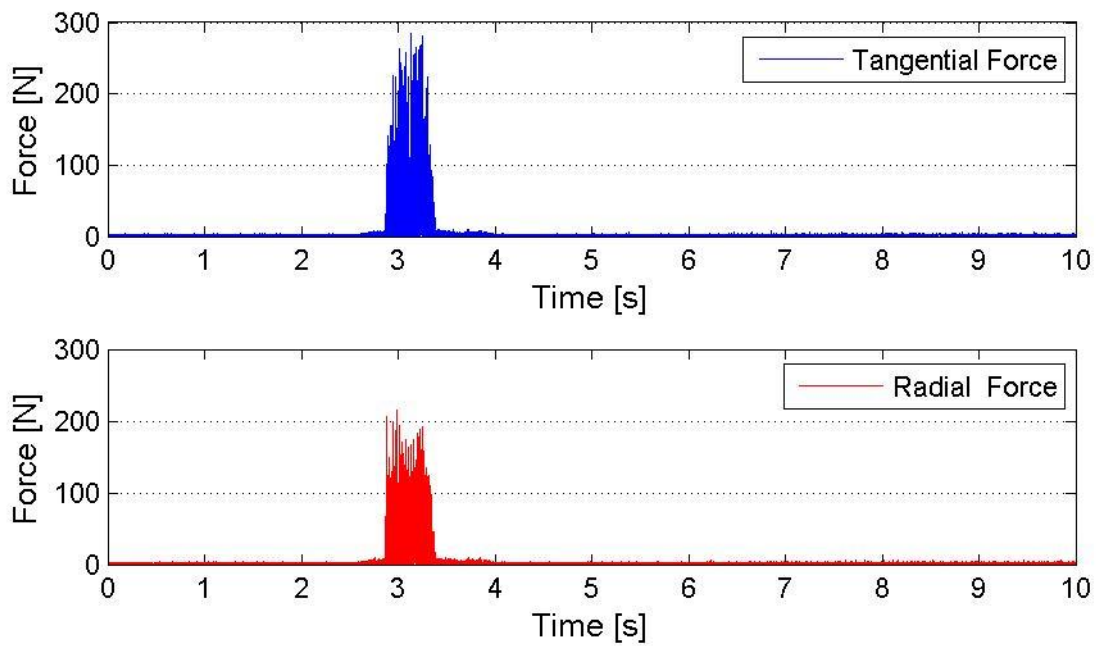


Figure E-80: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

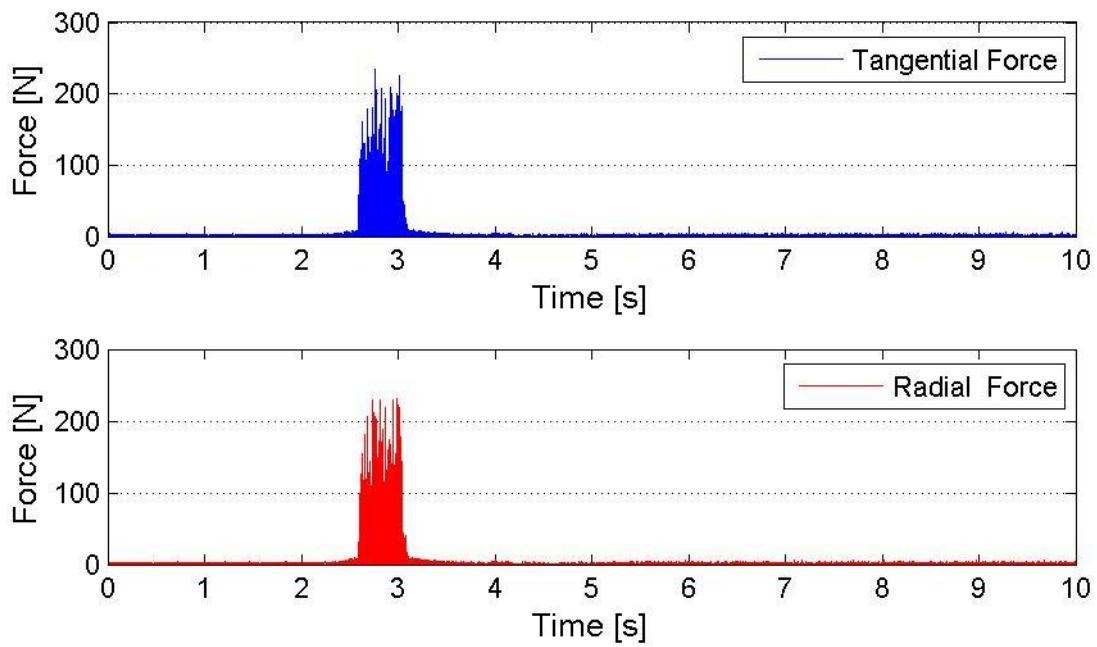


Figure E-81: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

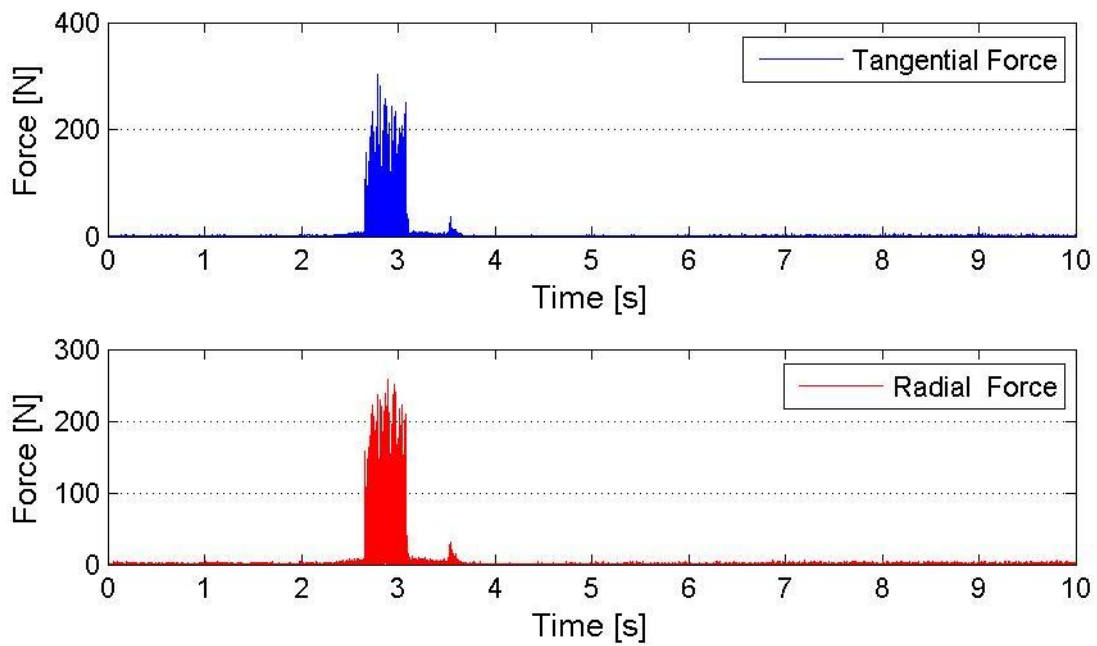


Figure E-82: Tangential and radial cutting force of CB1100 at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

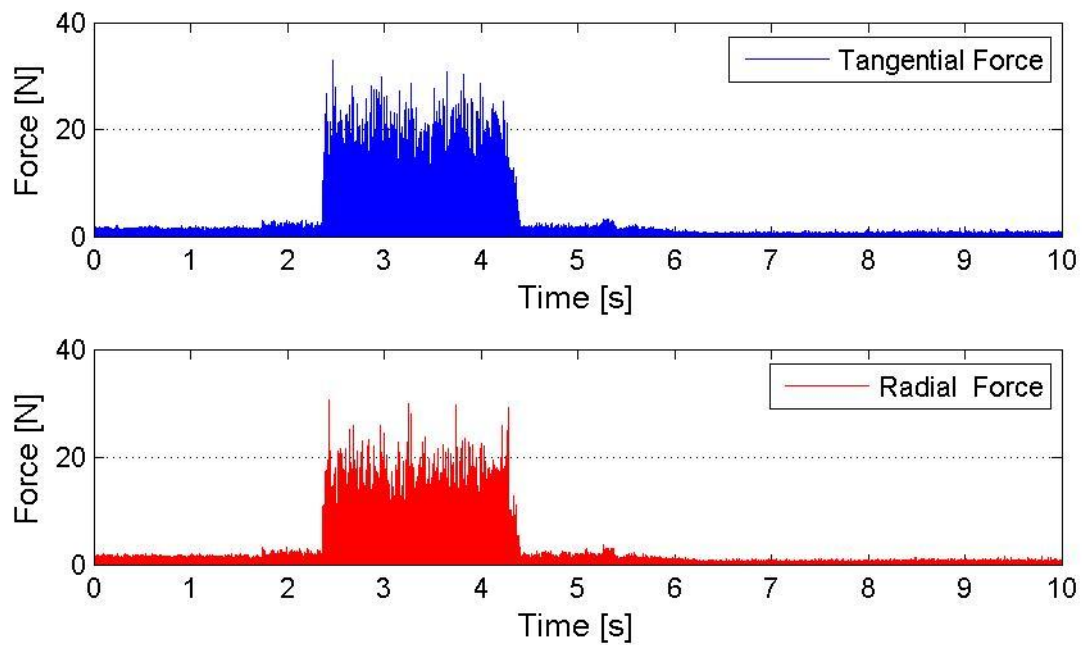


Figure E-83: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

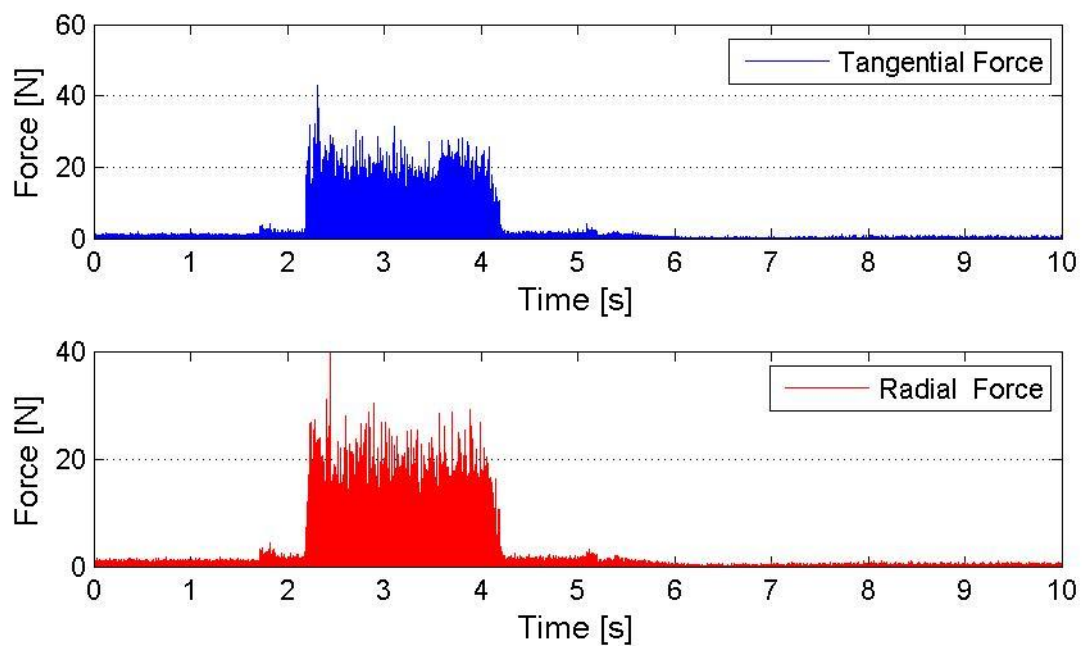


Figure E-84: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

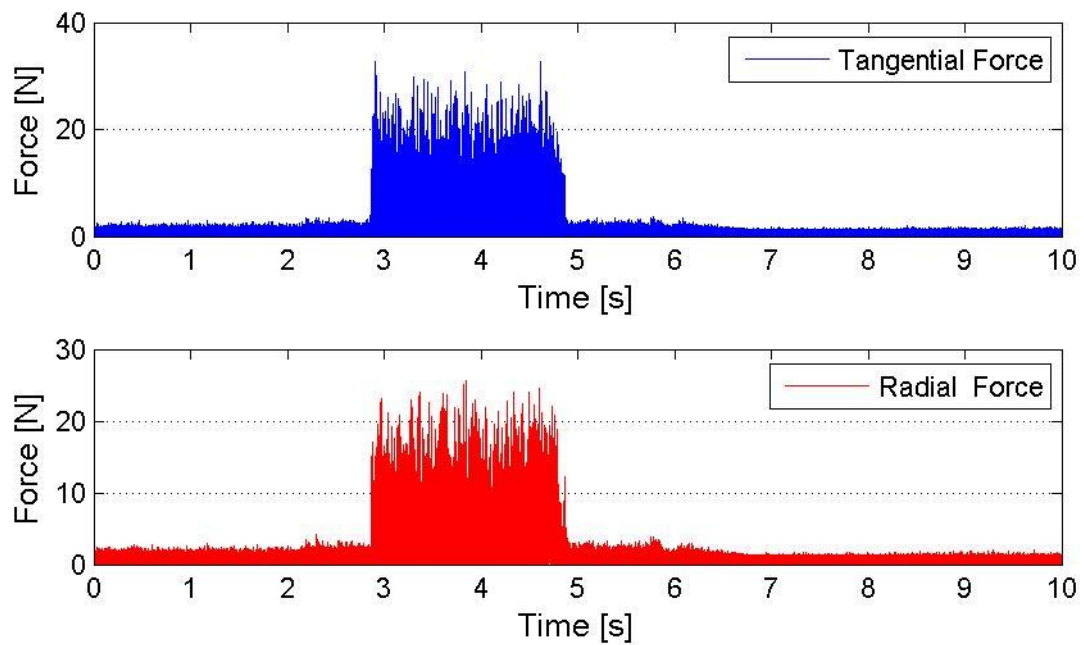


Figure E-85: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

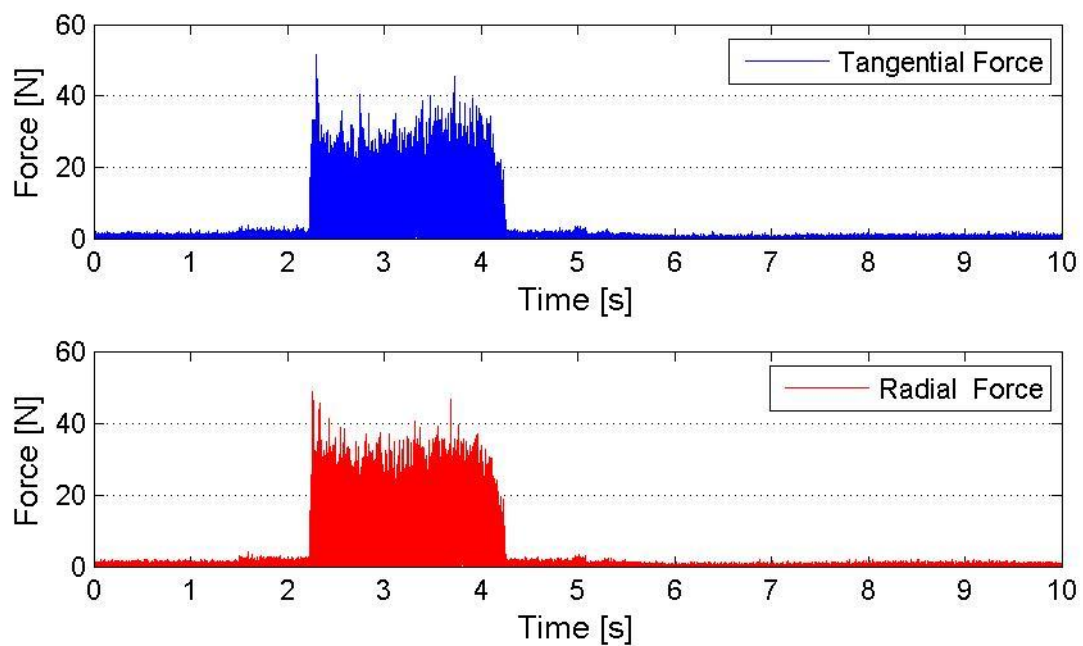


Figure E-86: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

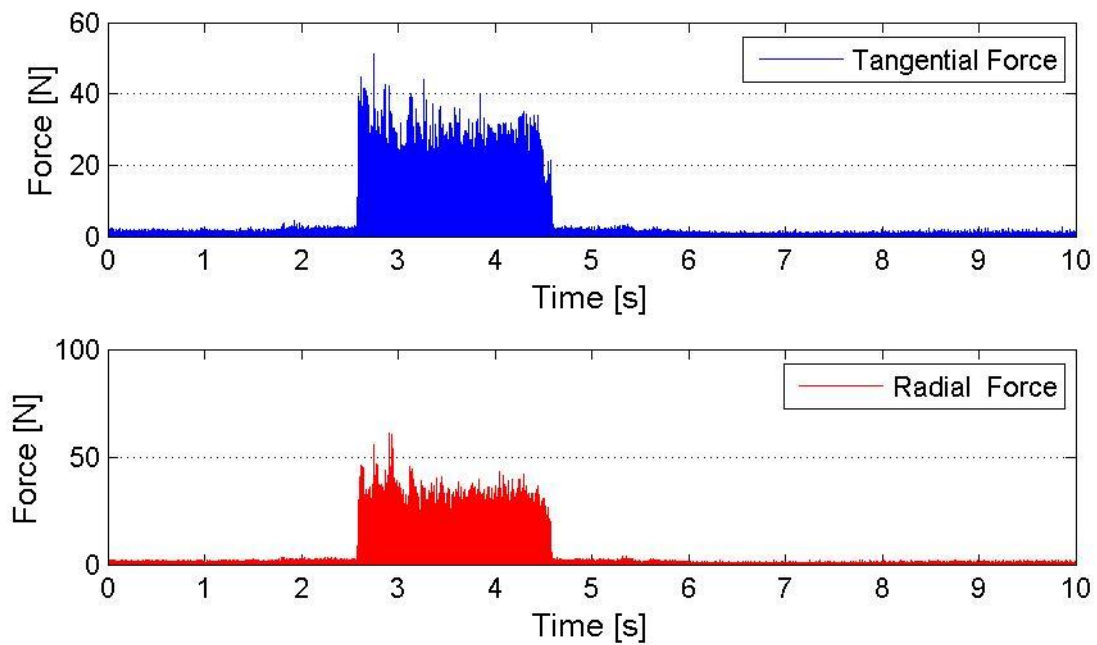


Figure E-87: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

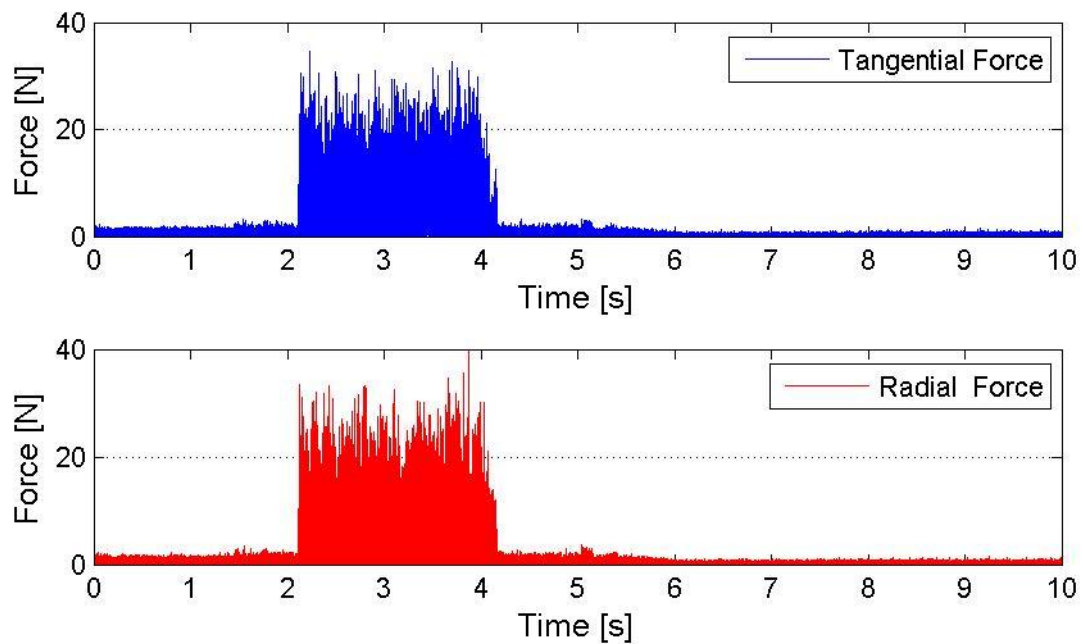


Figure E-88: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

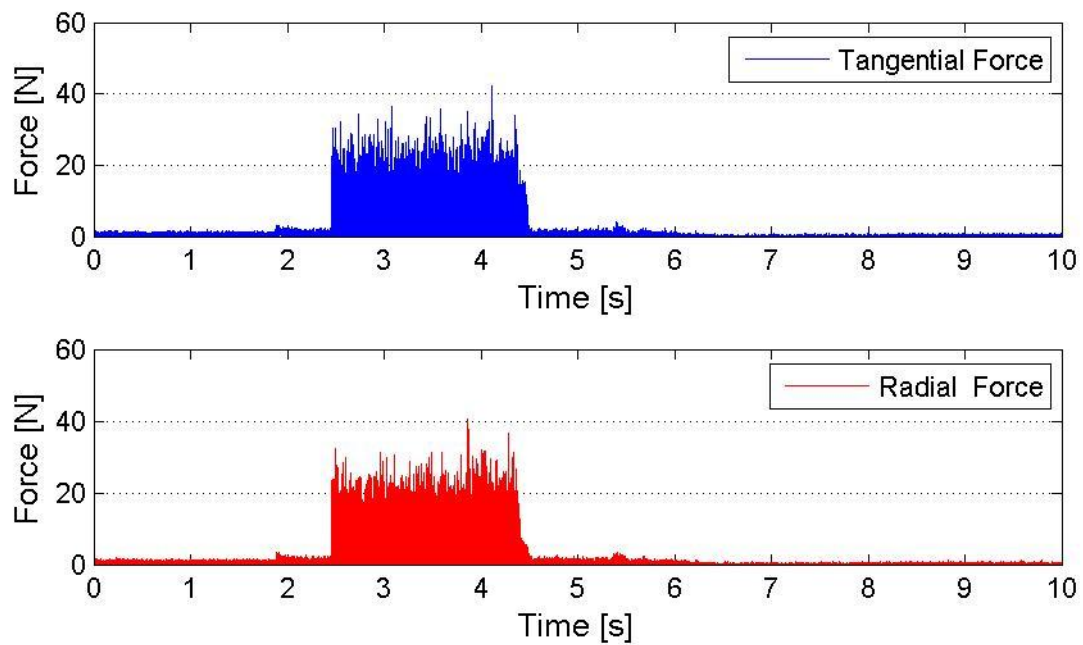


Figure E-89: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

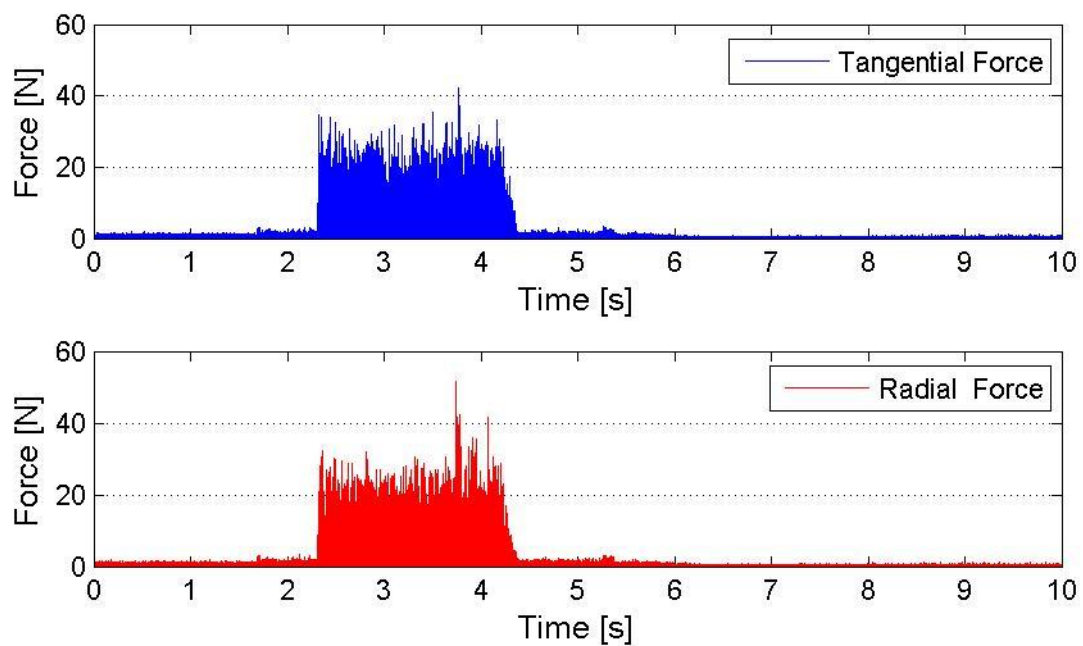


Figure E-90: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

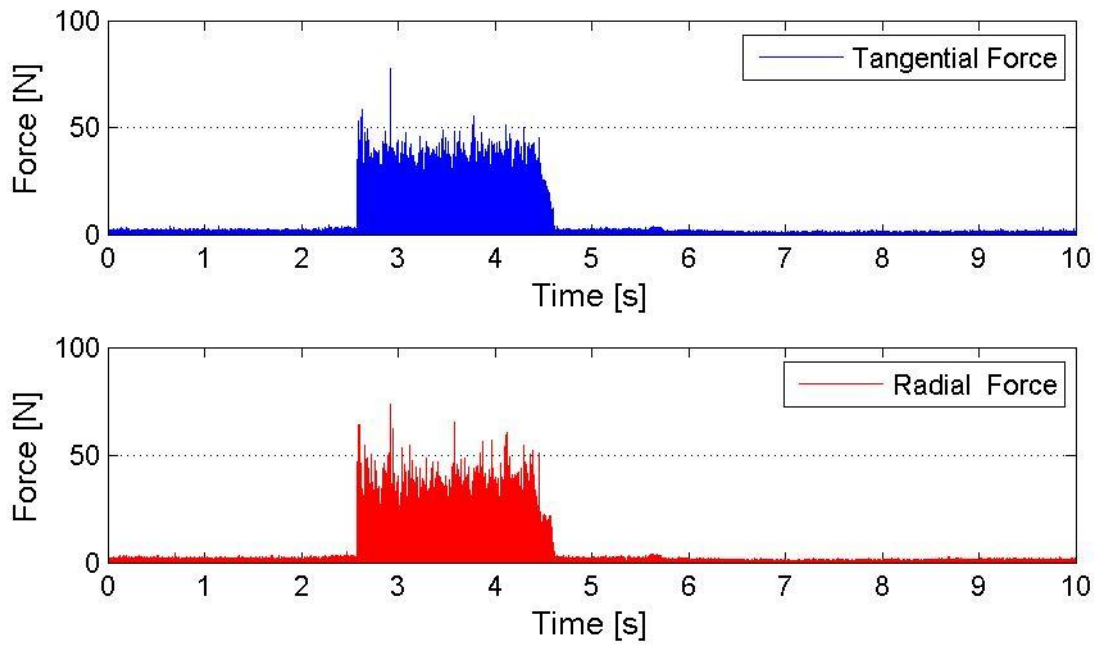


Figure E-91: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

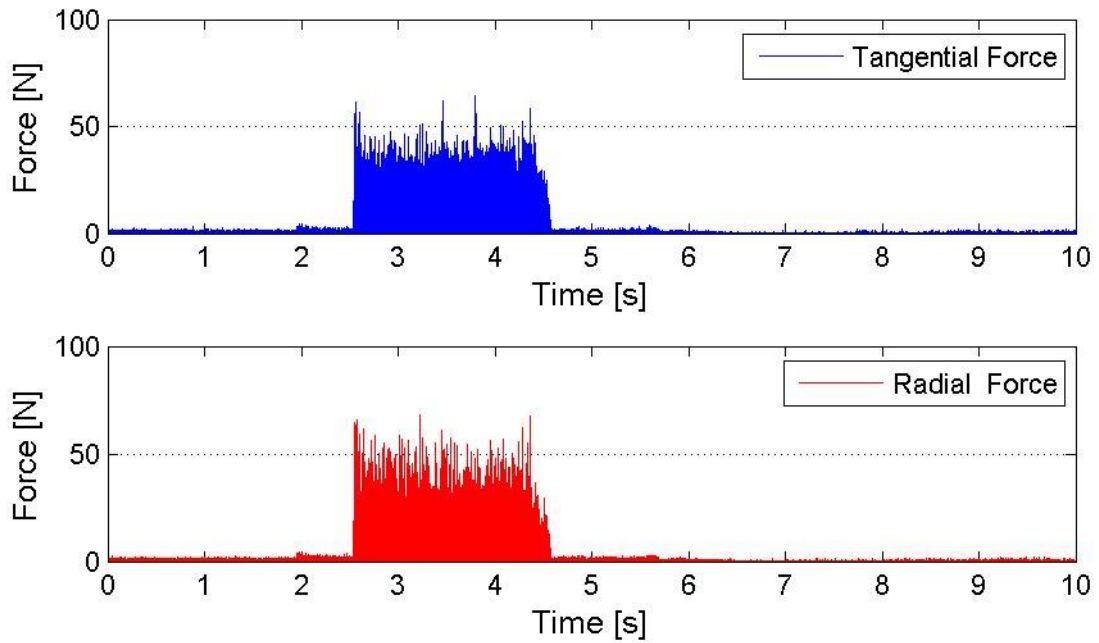


Figure E-92: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

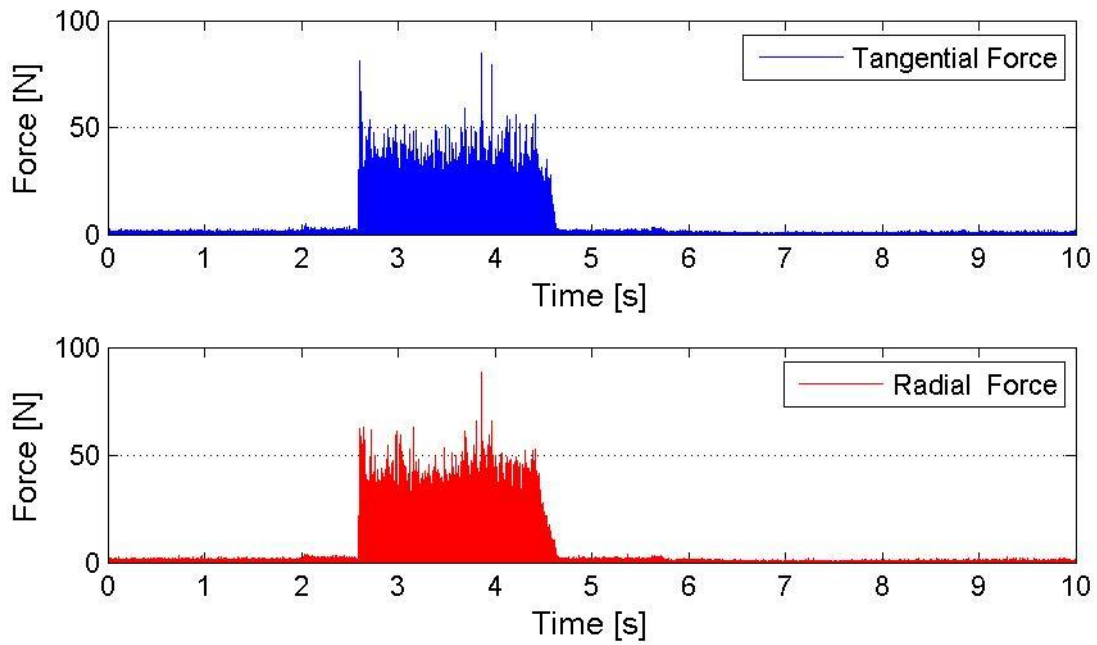


Figure E-93: Tangential and radial cutting force of CB1100 at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

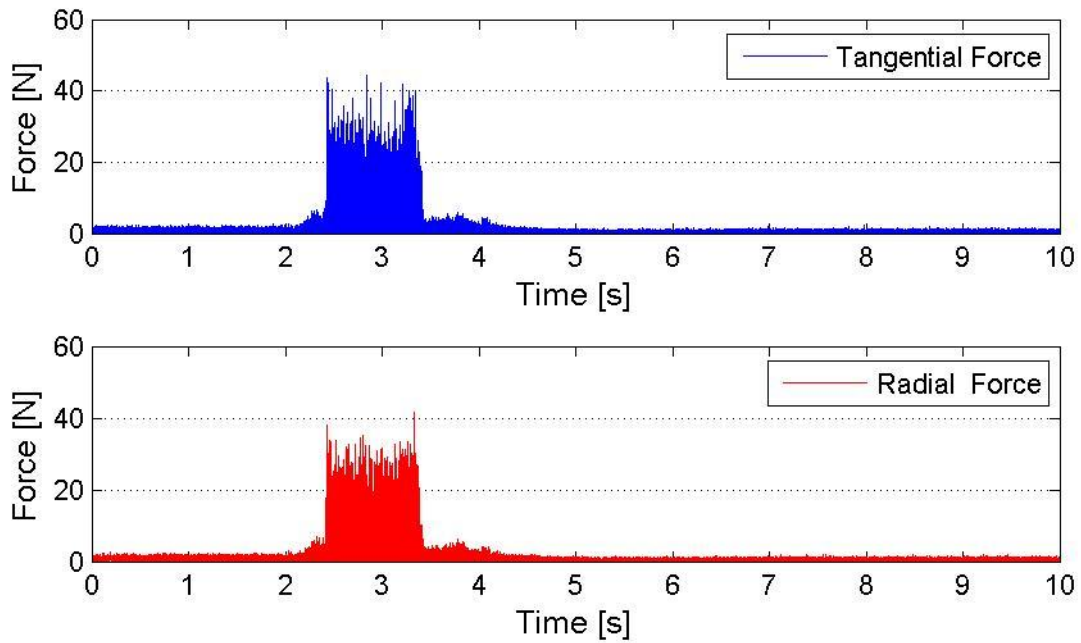


Figure E-94: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

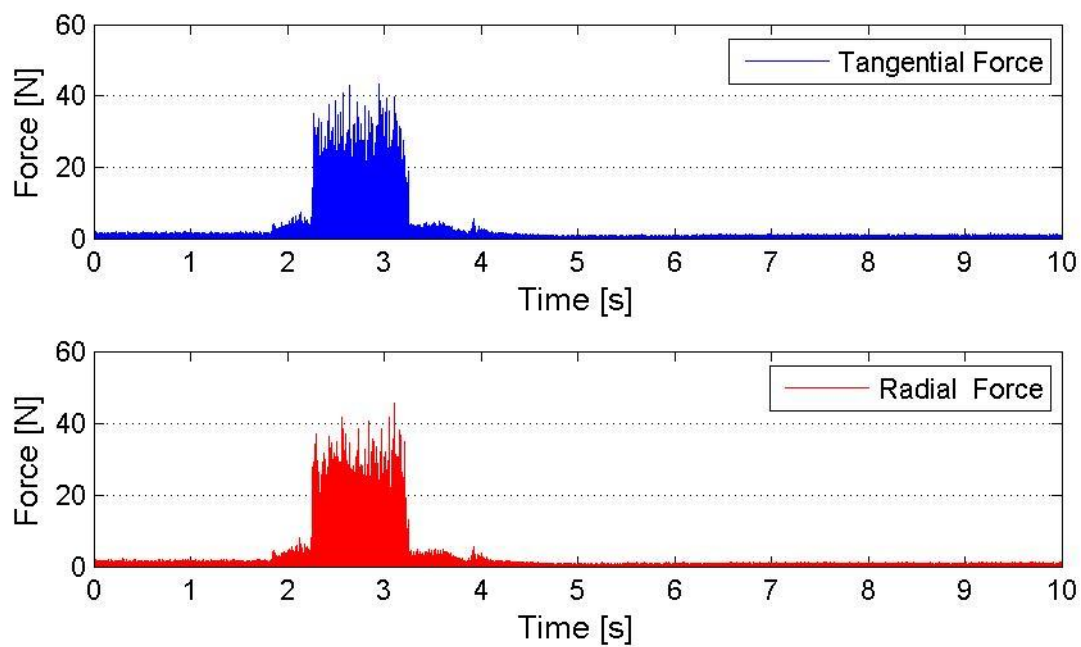


Figure E-95: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

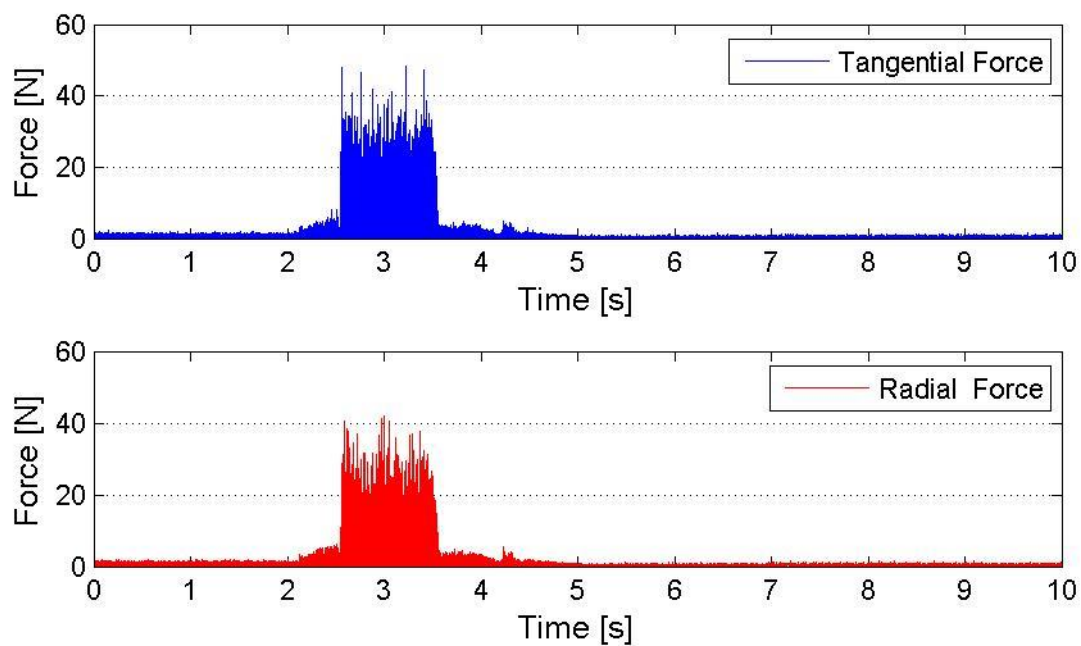


Figure E-96: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

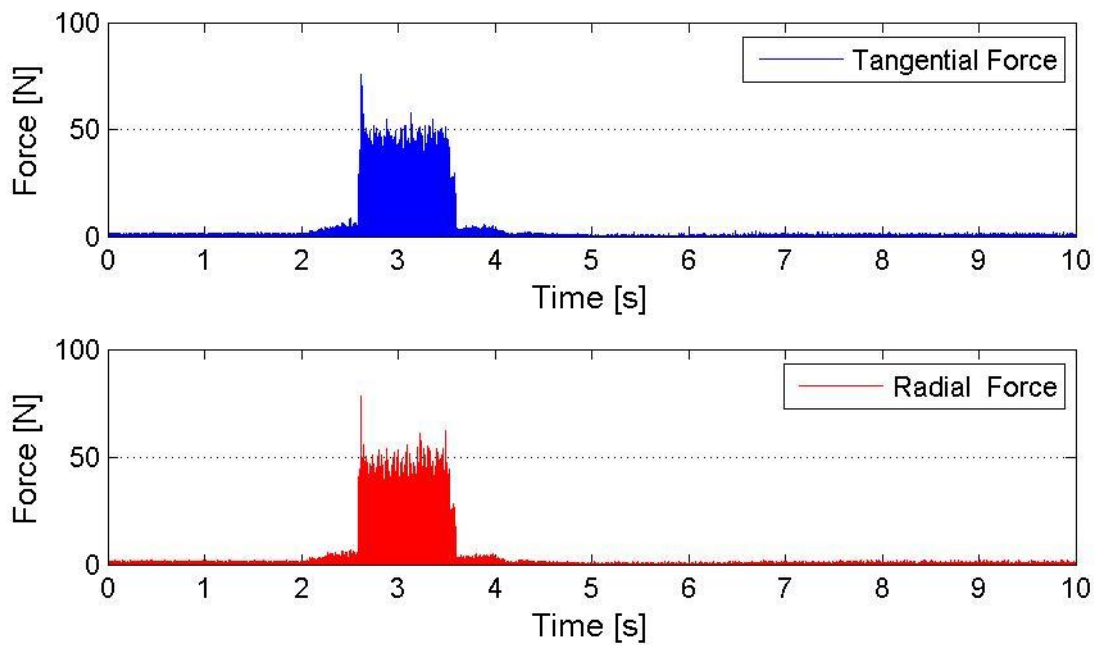


Figure E-97: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

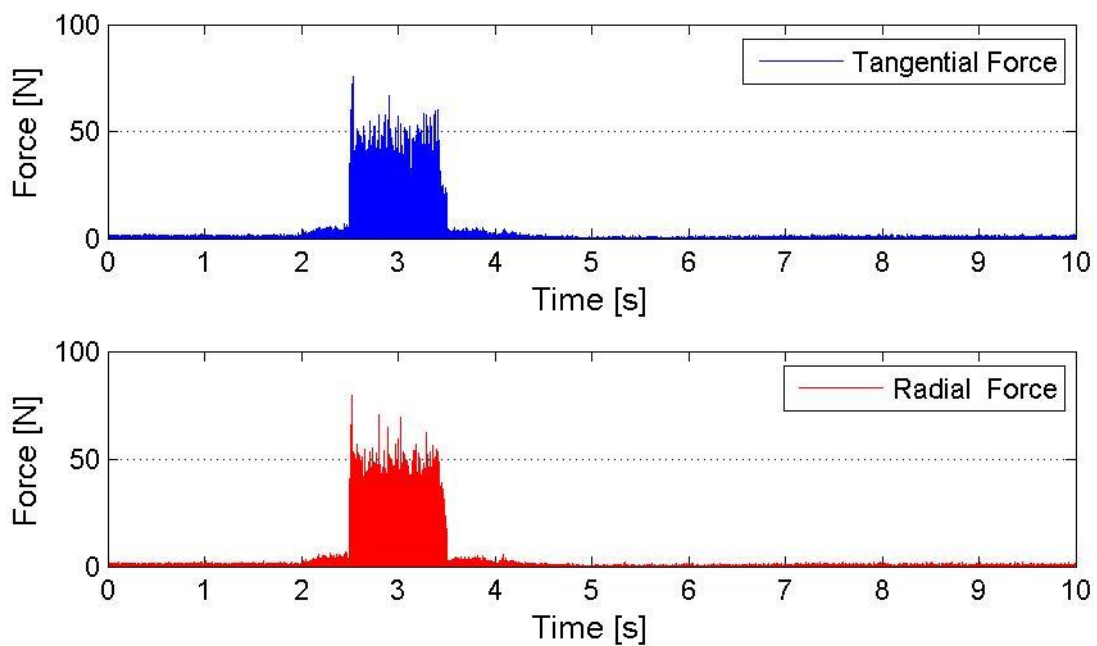


Figure E-98: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

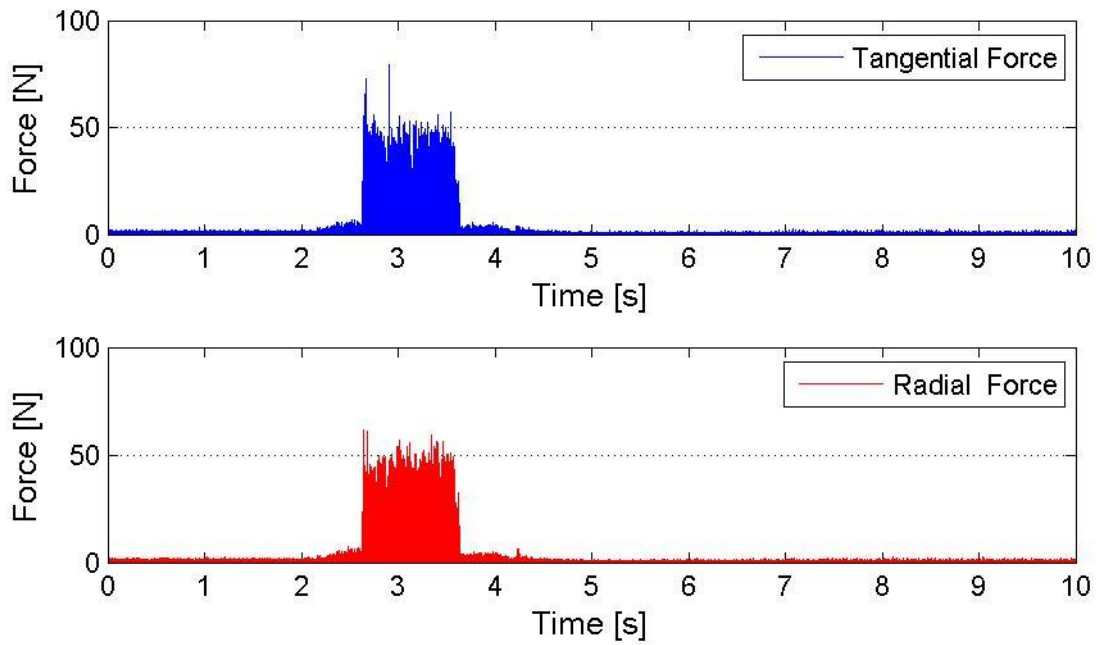


Figure E-99: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

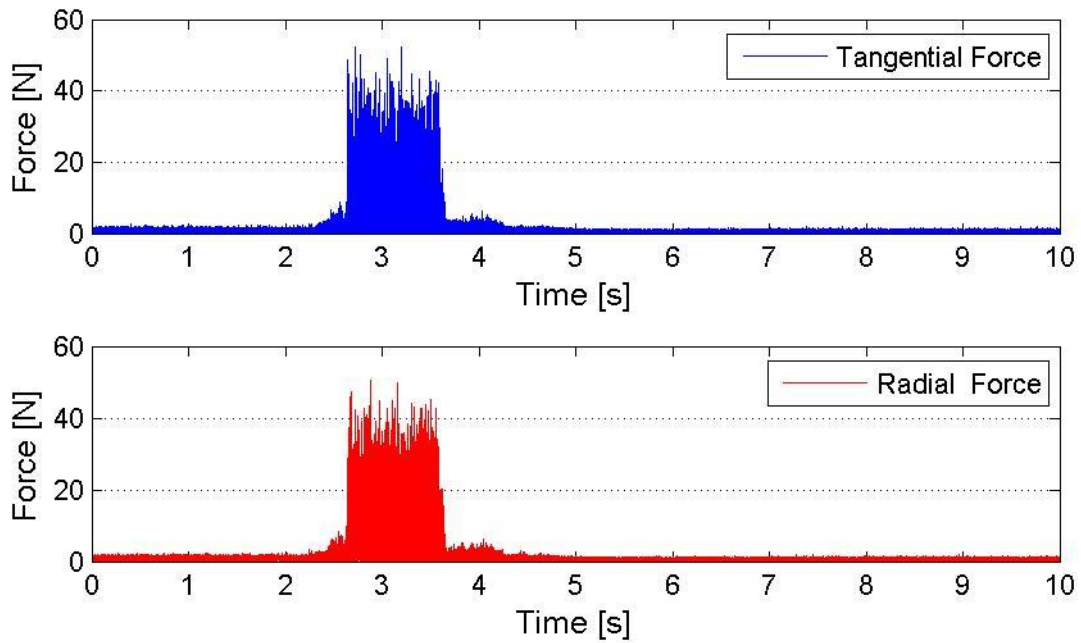


Figure E-100: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

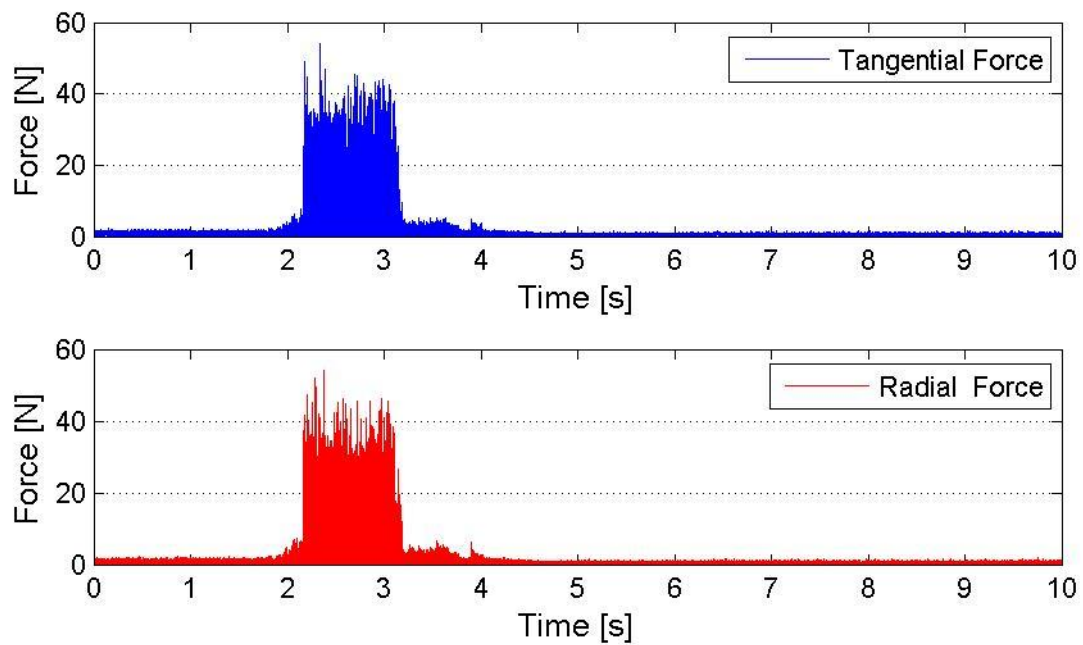


Figure E-101: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

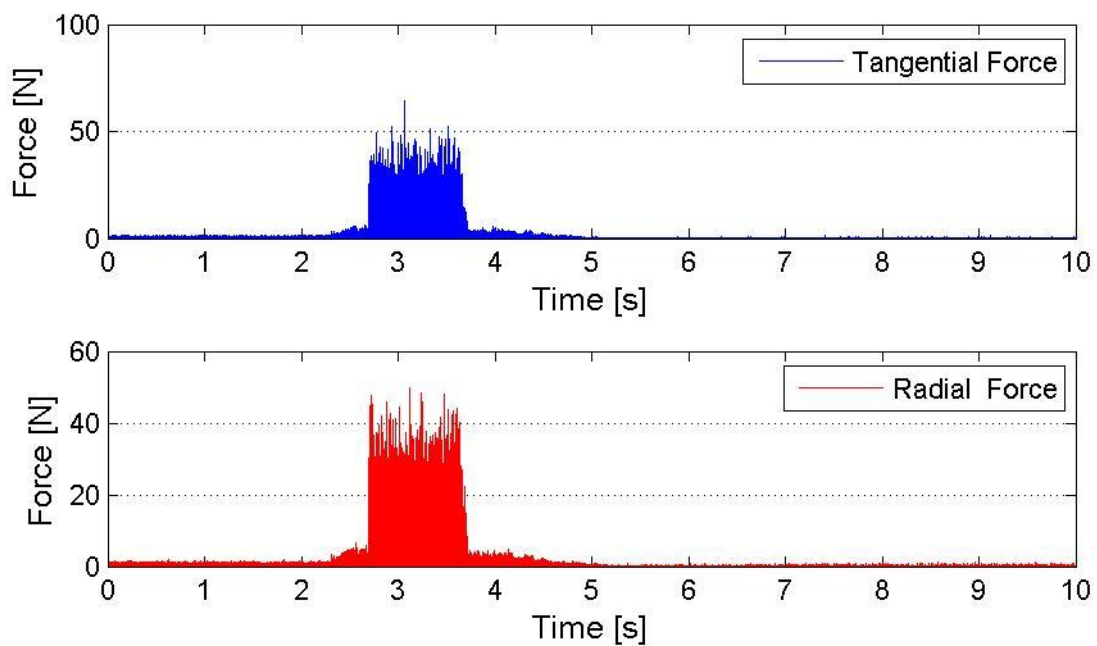


Figure E-102: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

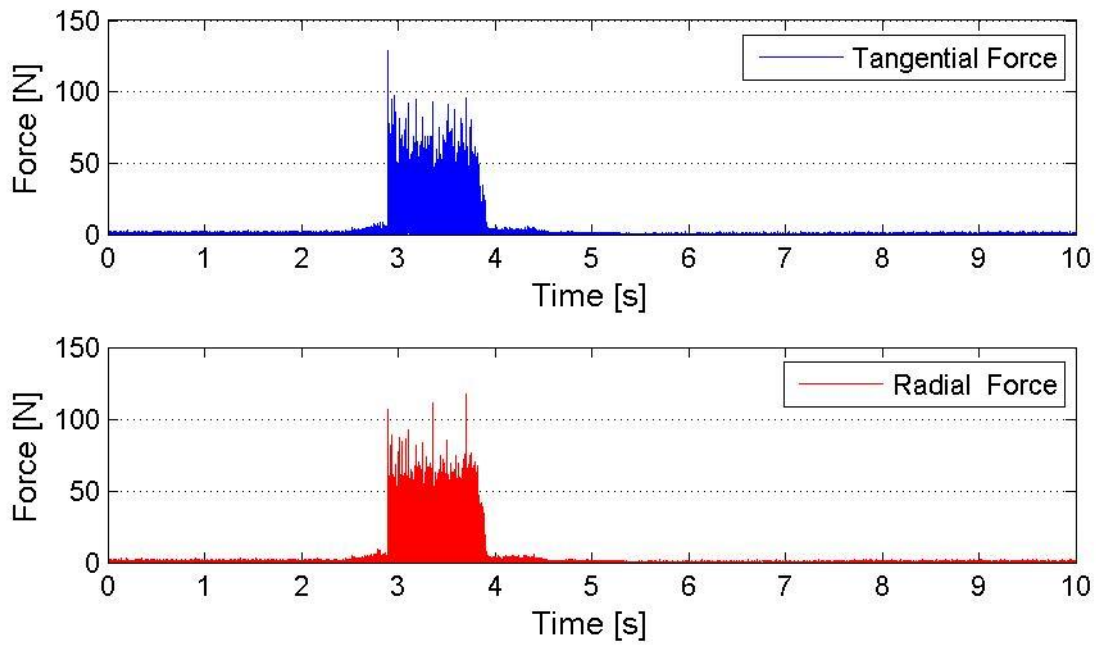


Figure E-103: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

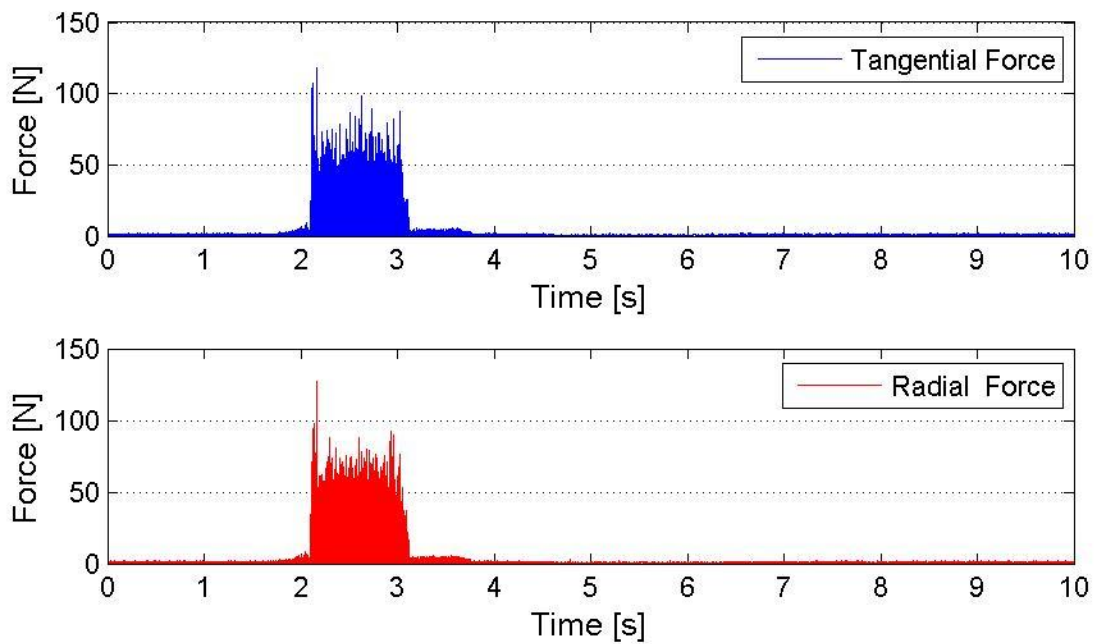


Figure E-104: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

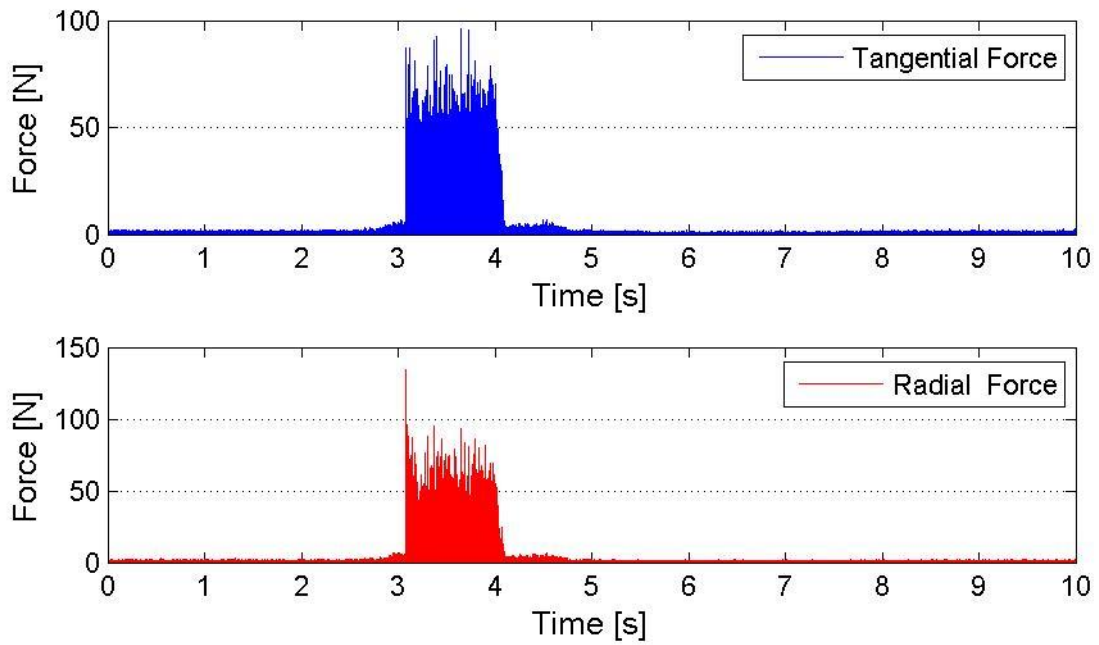


Figure E-105: Tangential and radial cutting force of CB1100 at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

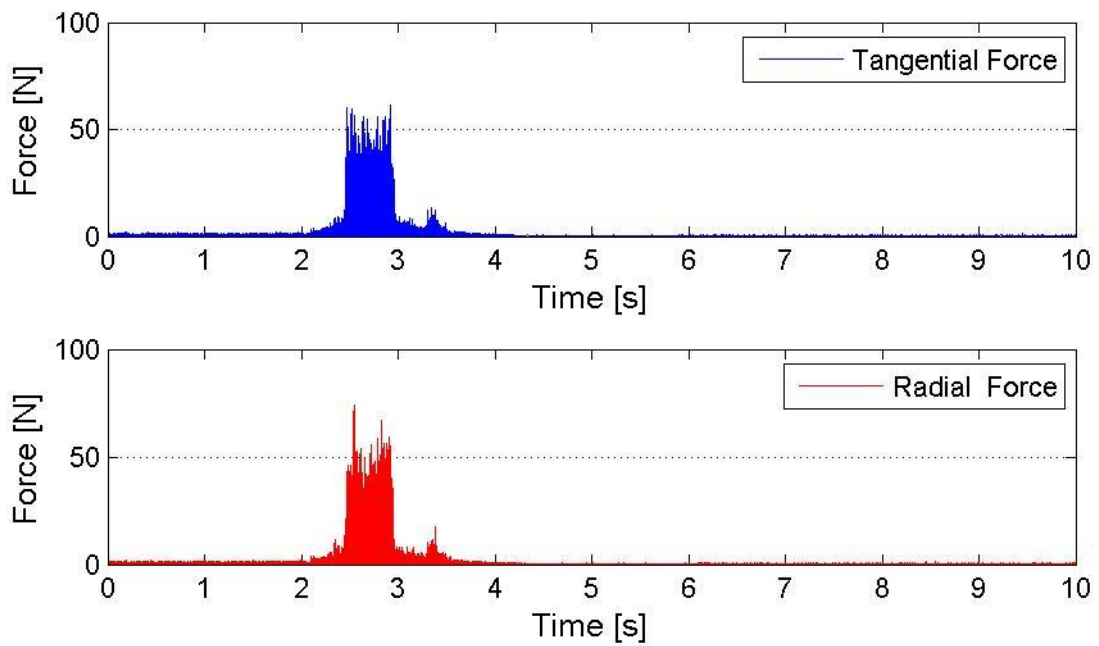


Figure E-106: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

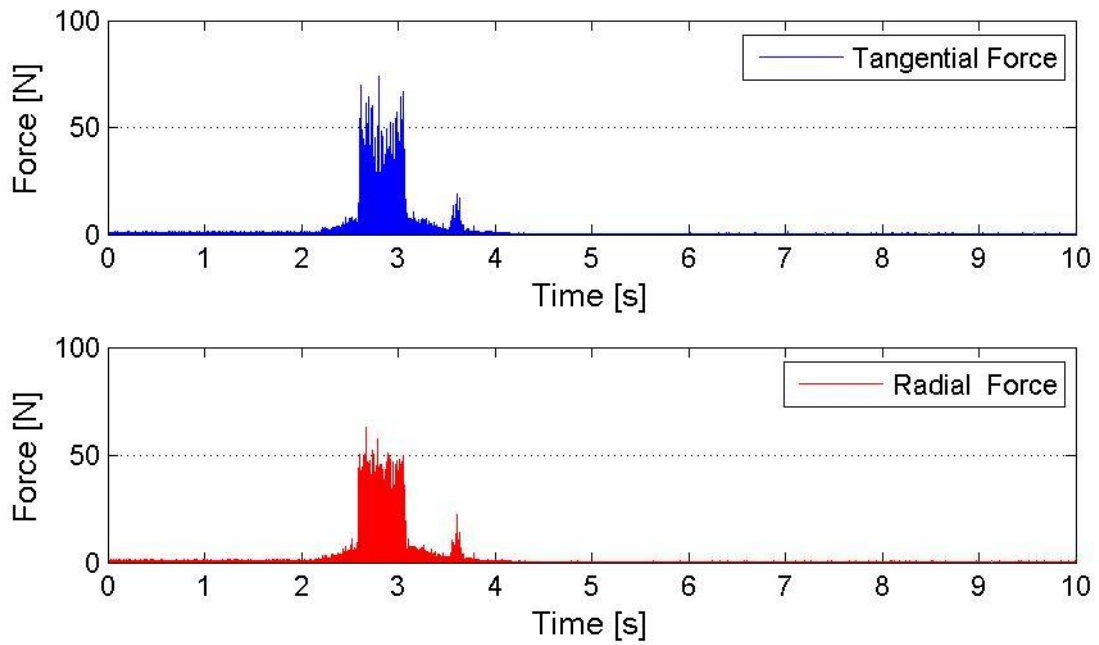


Figure E-107: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

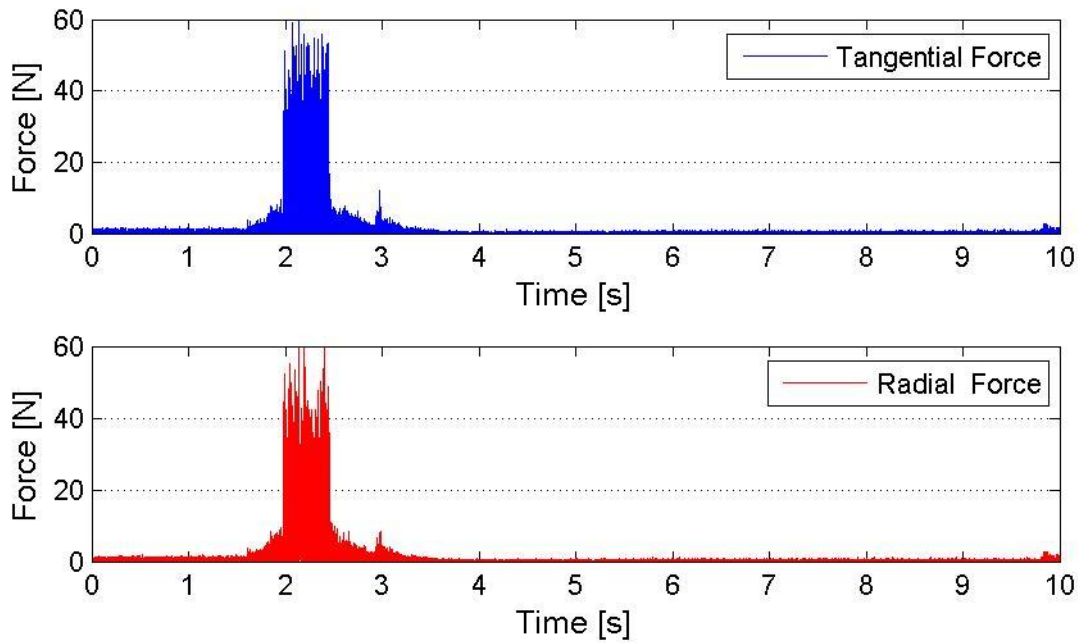


Figure E-108: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

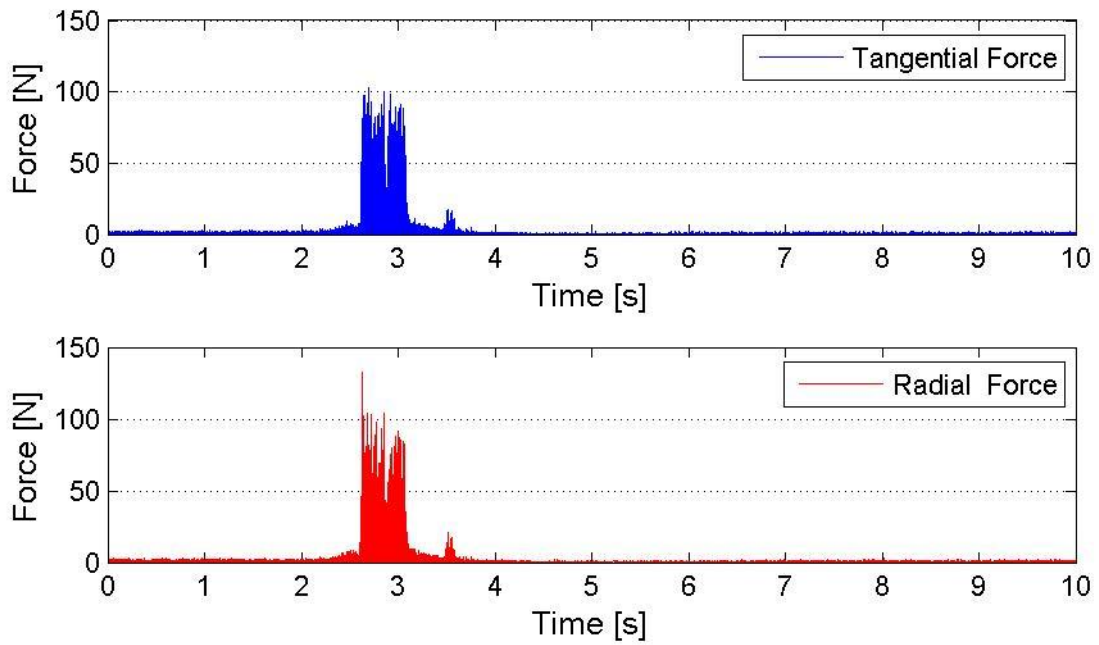


Figure E-109: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

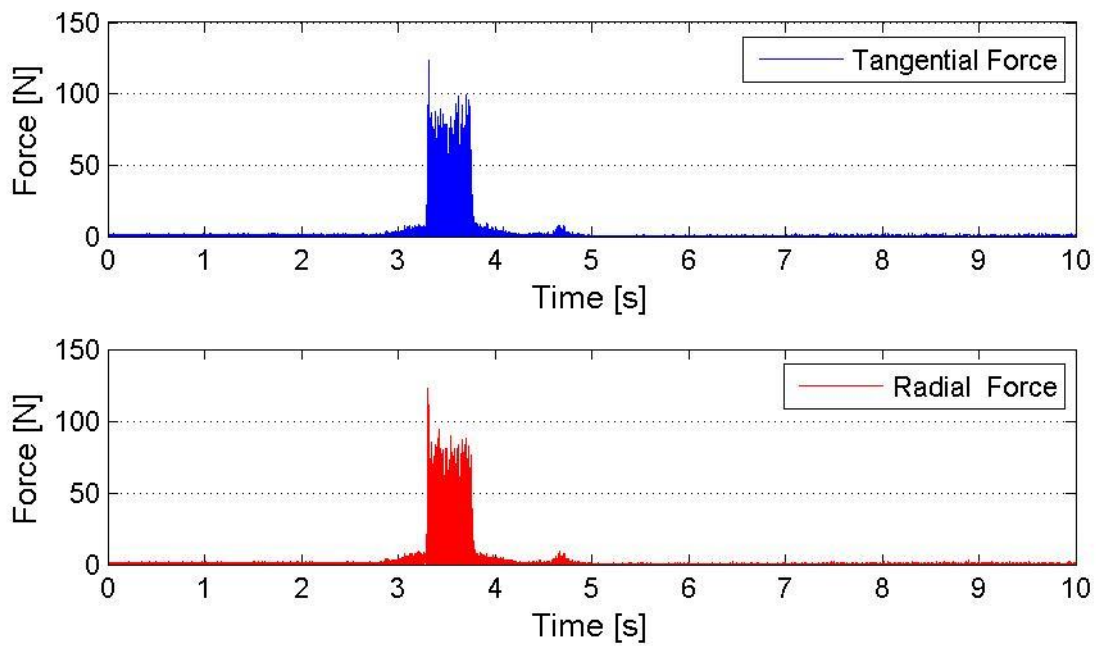


Figure E-110: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

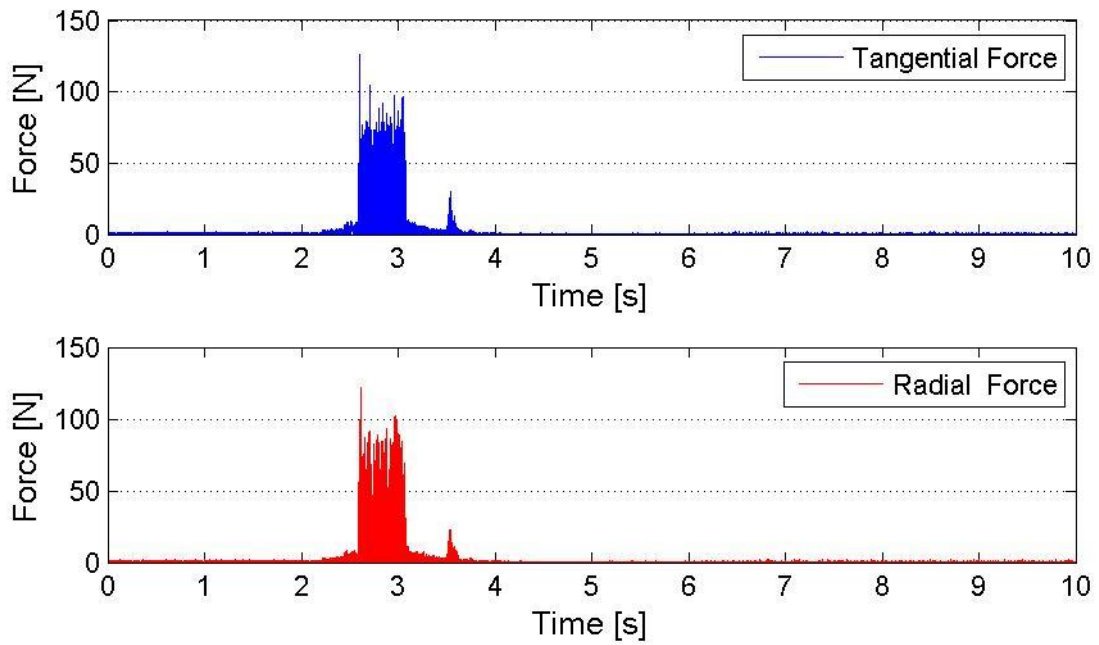


Figure E-111: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

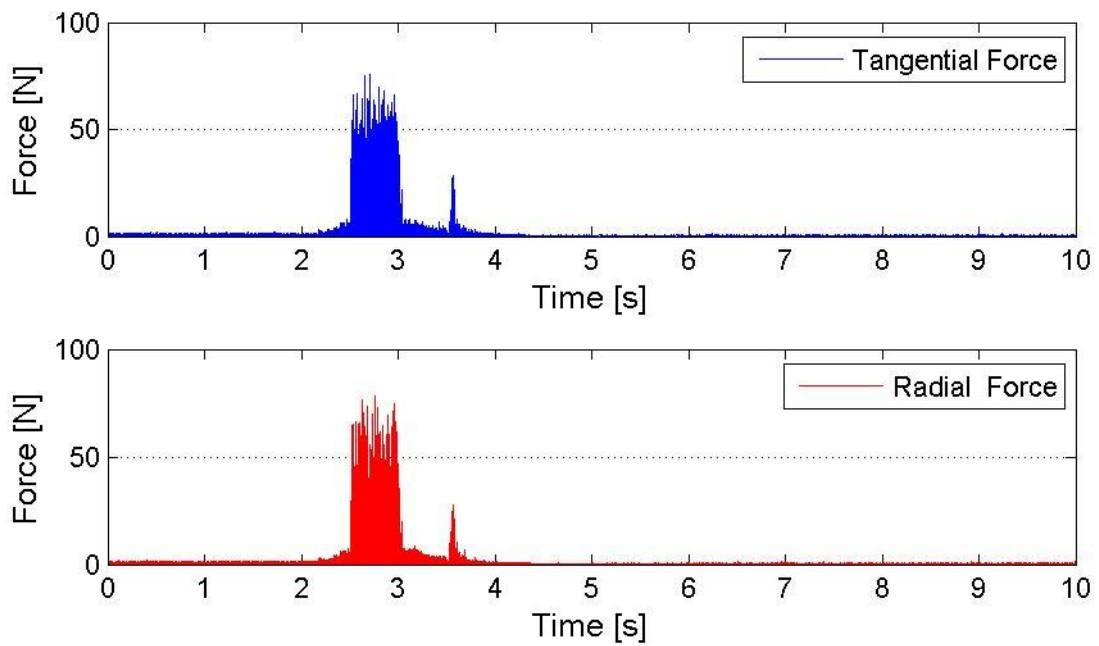


Figure E-112: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

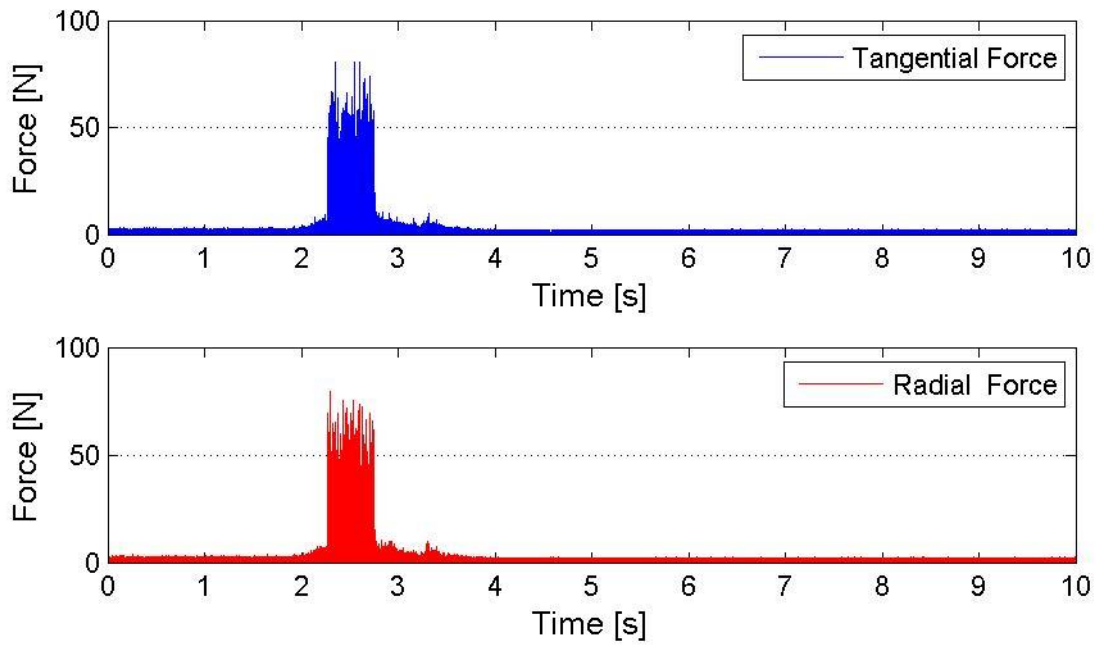


Figure E-113: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

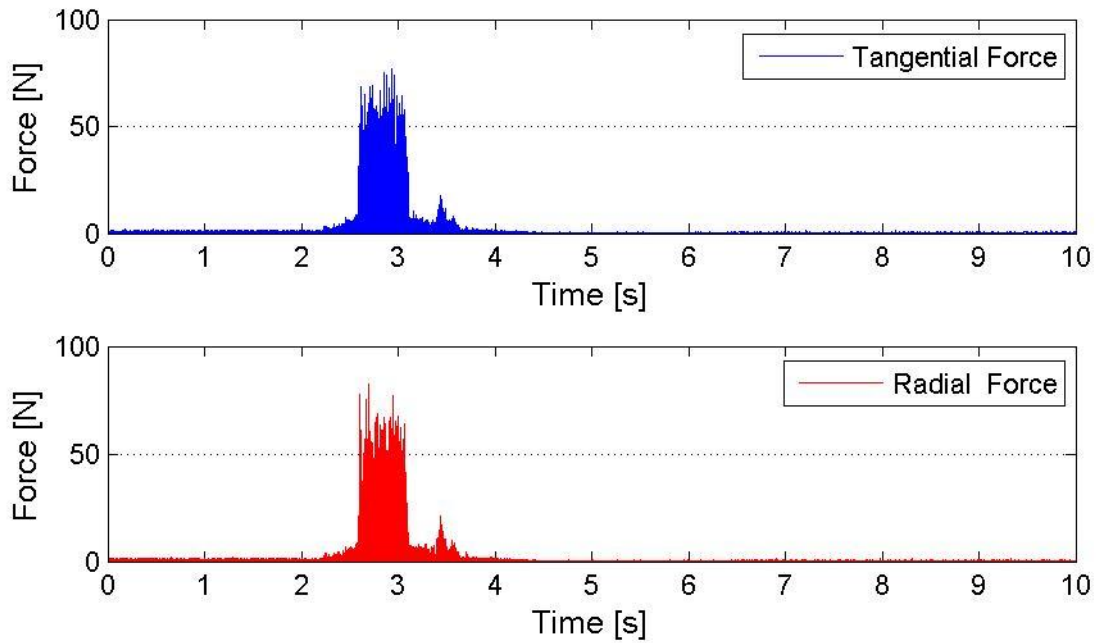


Figure E-114: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

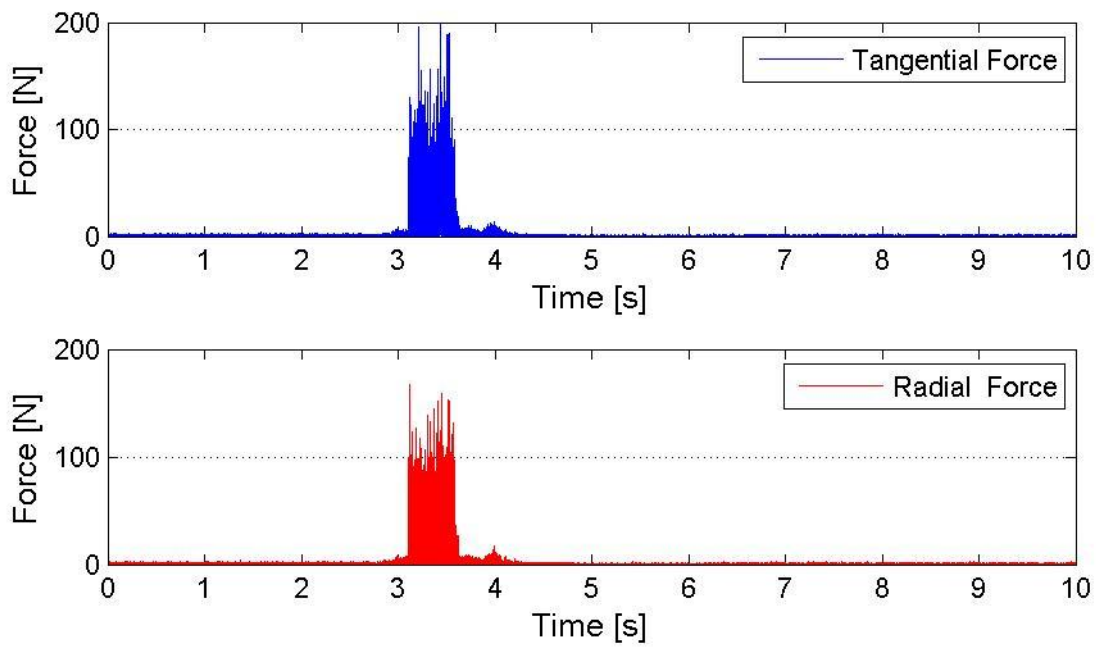


Figure E-115: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

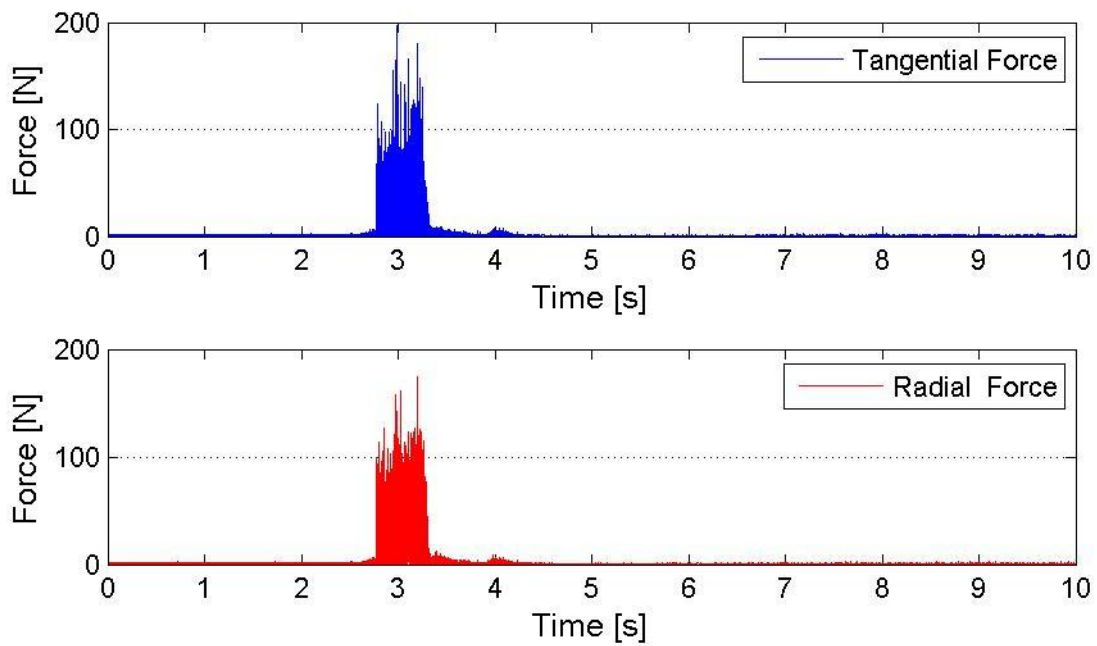


Figure E-116: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

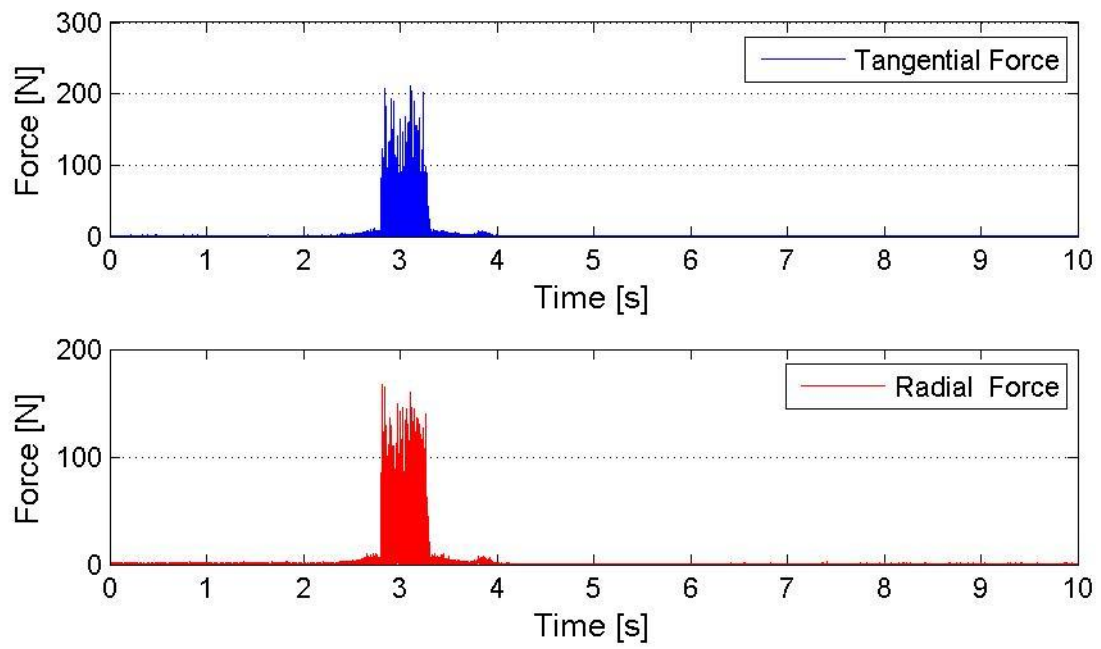


Figure E-117: Tangential and radial cutting force of CB1100 at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

Appendix: F. AAC cutting force DOE results

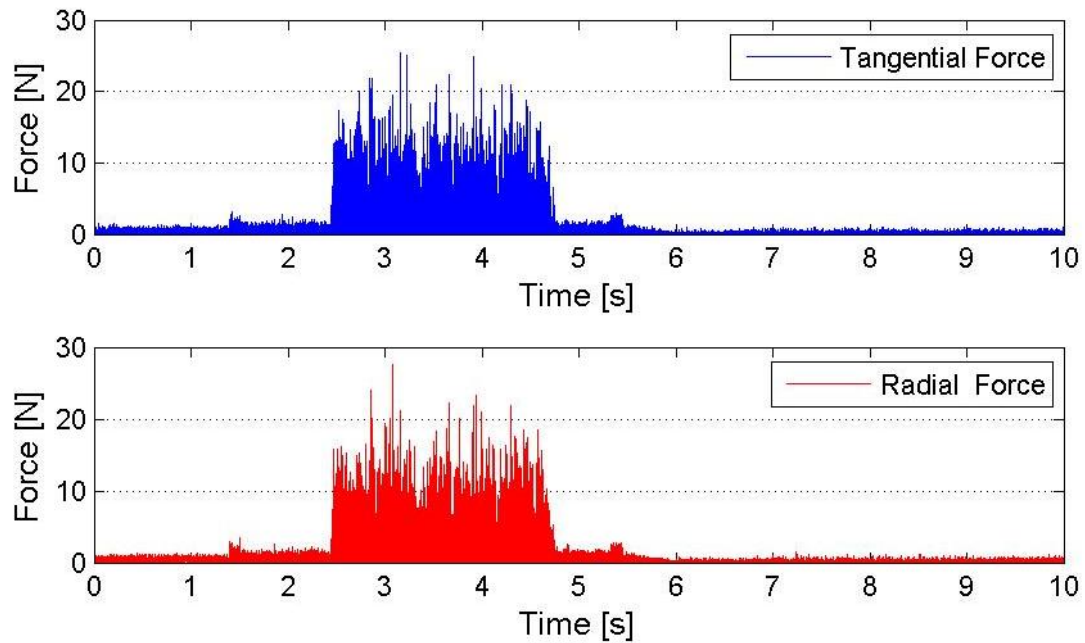


Figure F-118: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

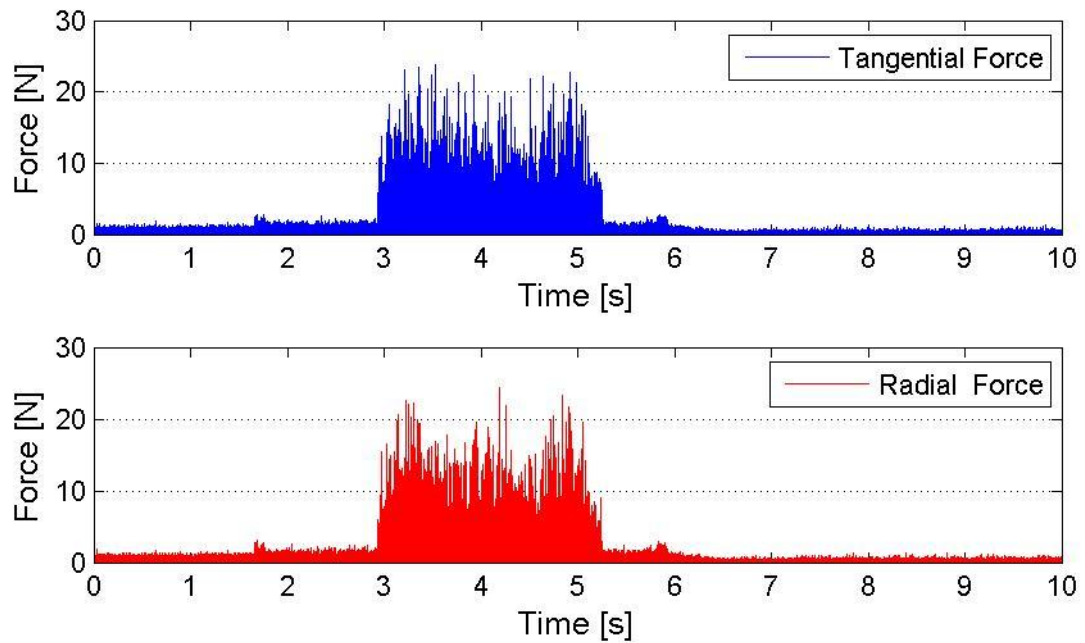


Figure F-119: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

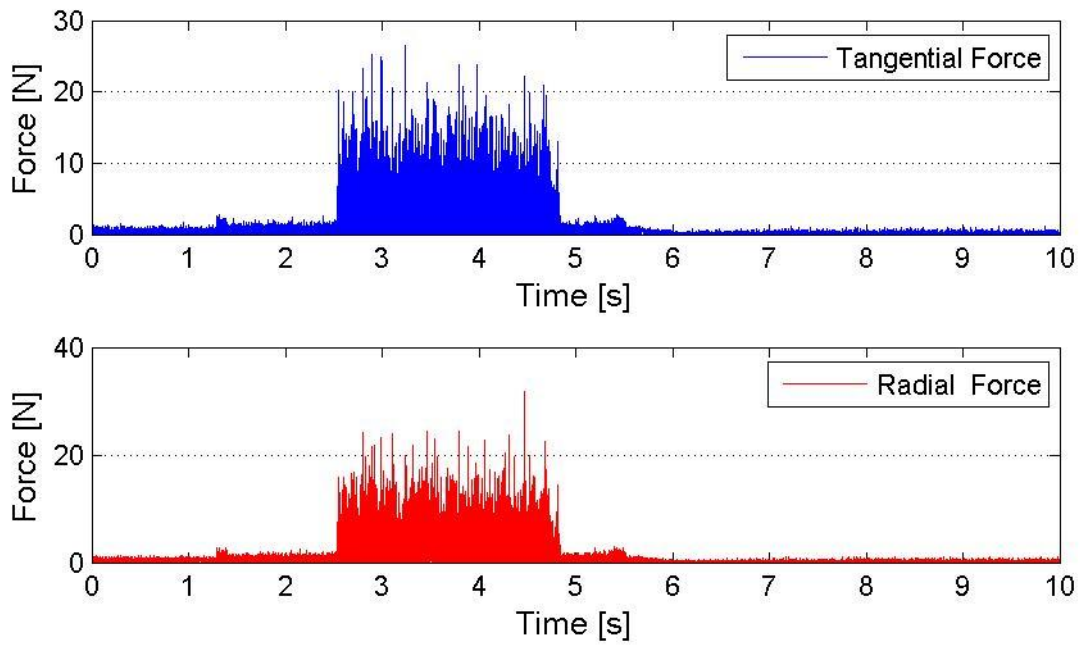


Figure F-120: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

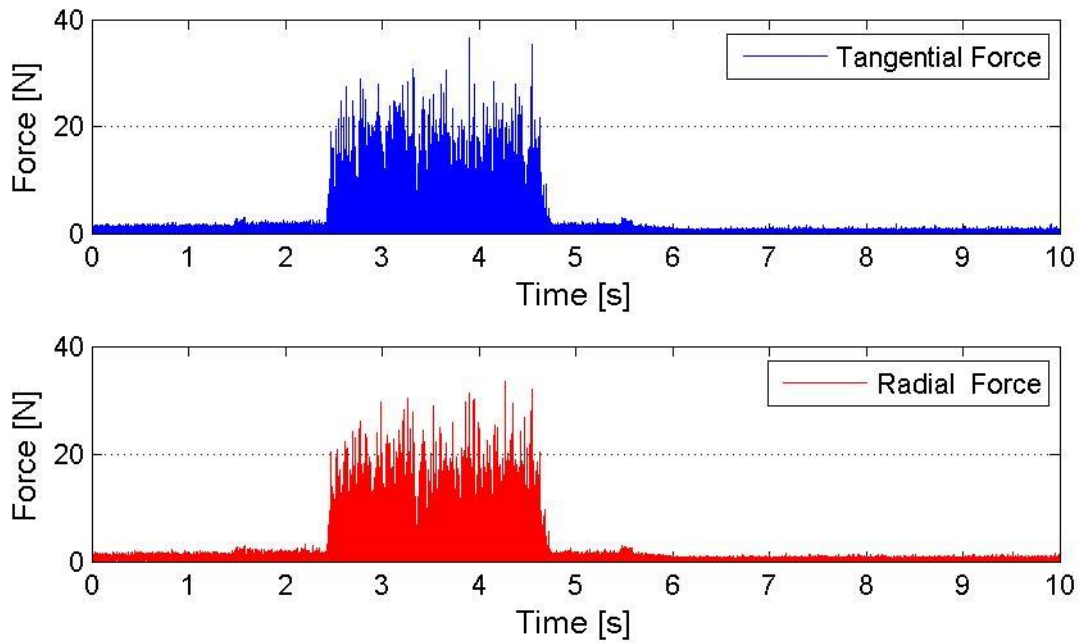


Figure F-121: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

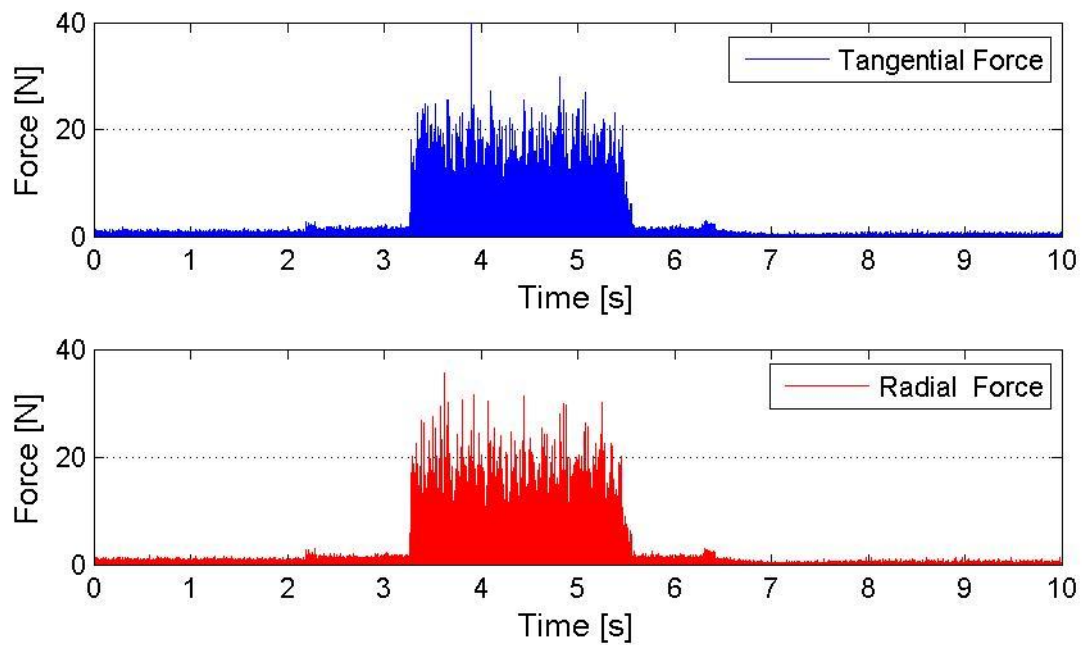


Figure F-122: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

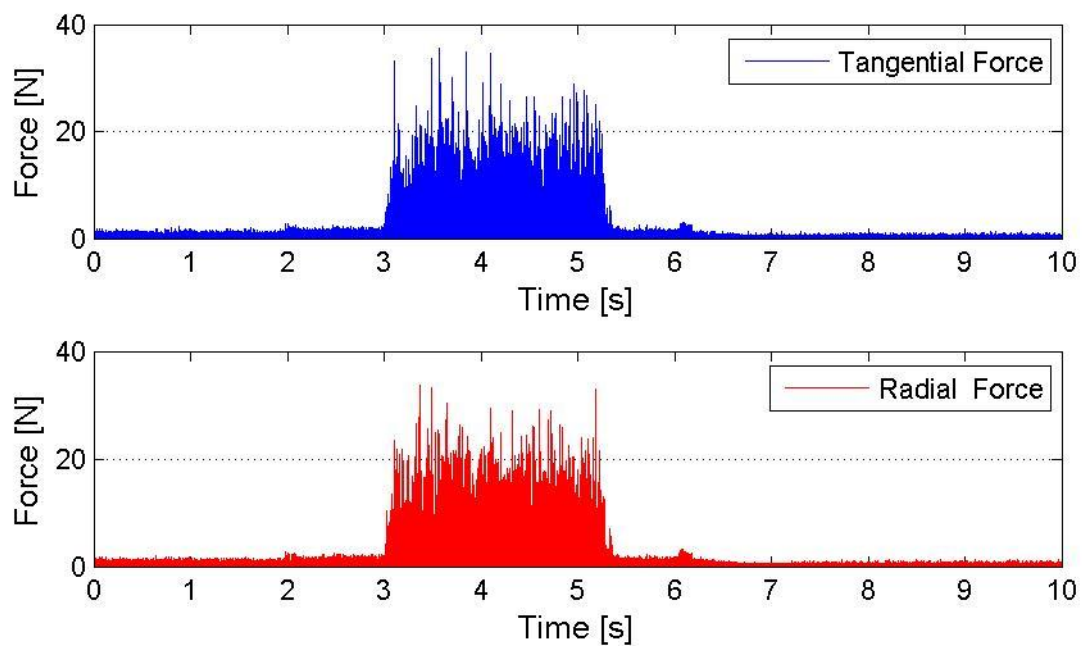


Figure F-123: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

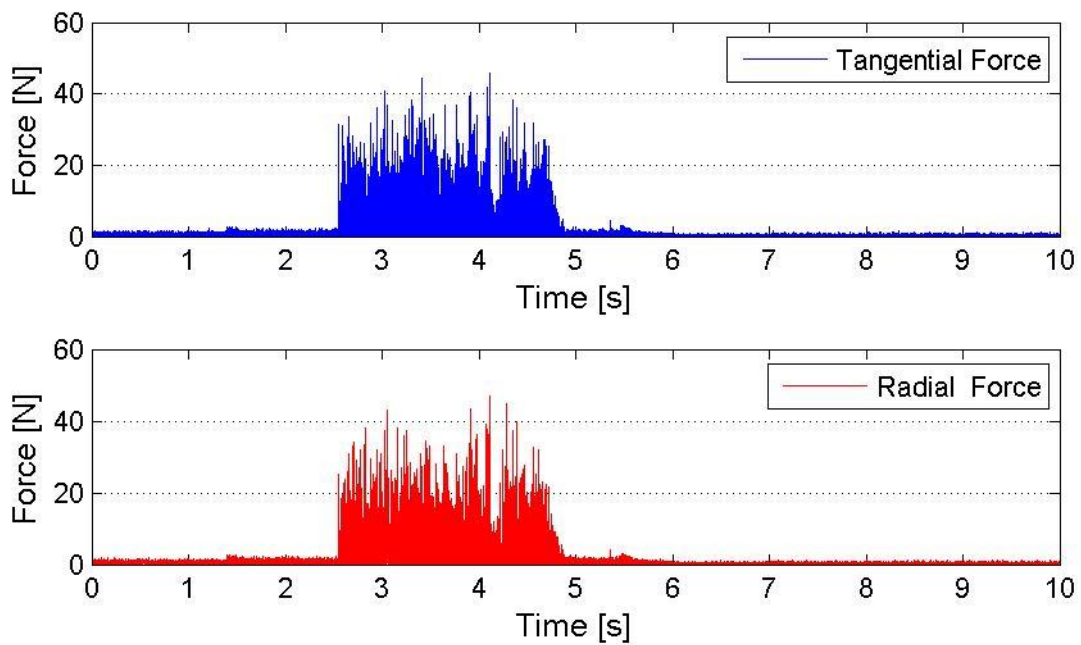


Figure F-124: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

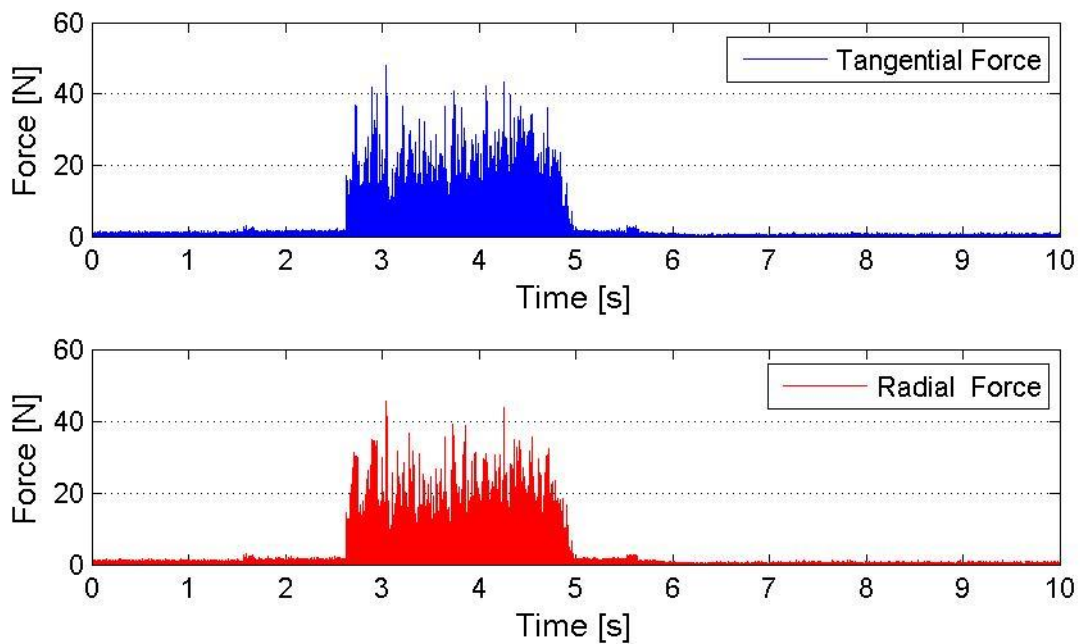


Figure F-125: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

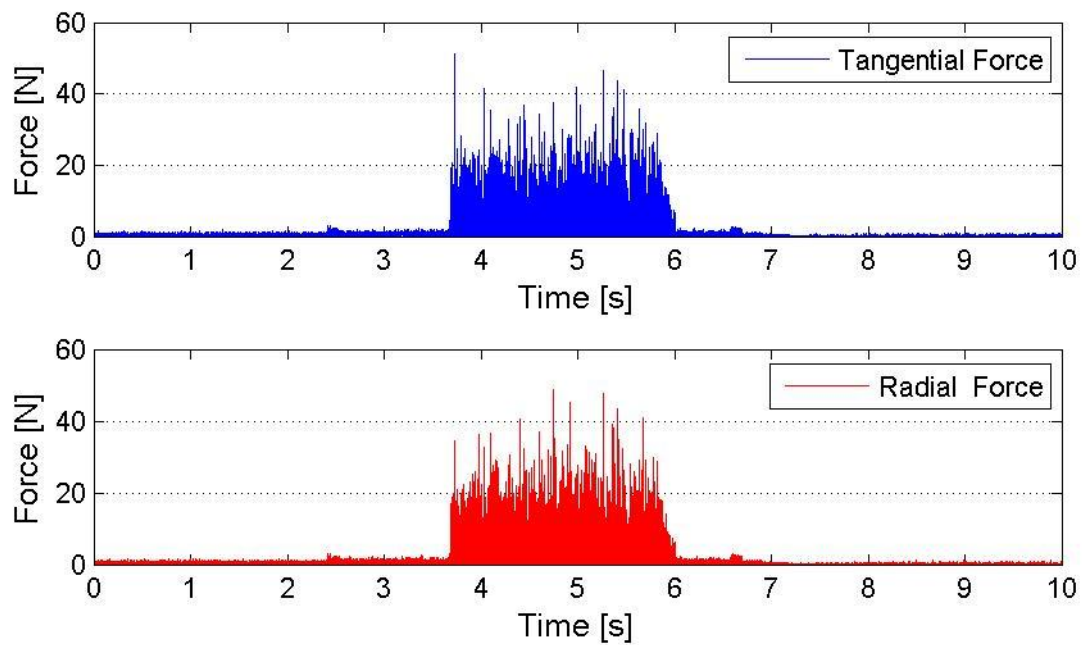


Figure F-126: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

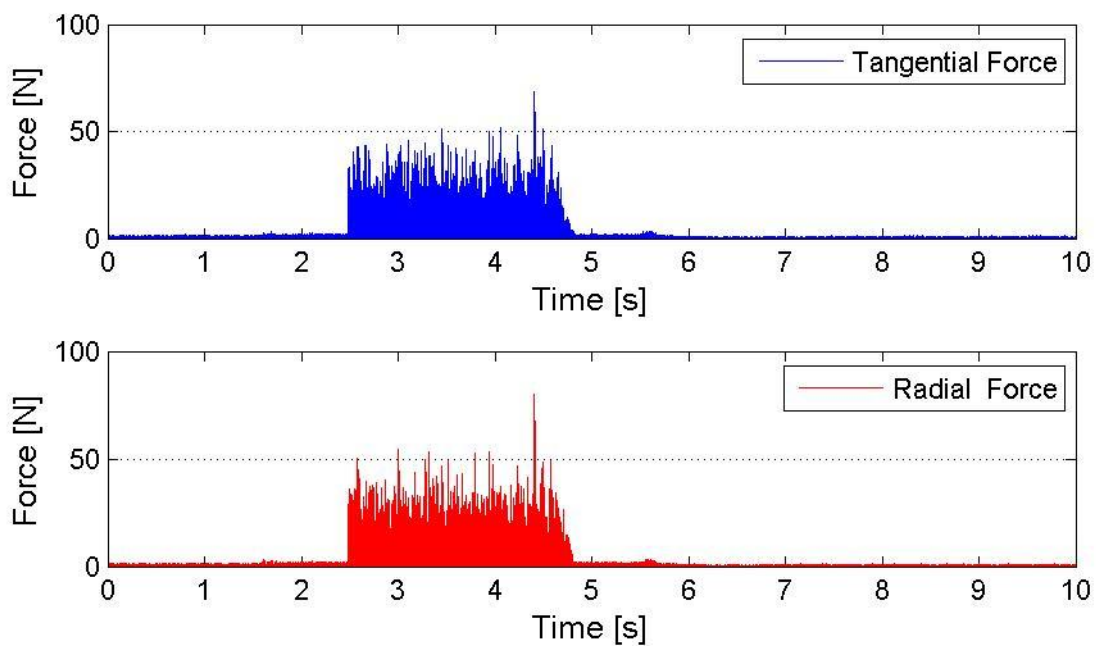


Figure F-127: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

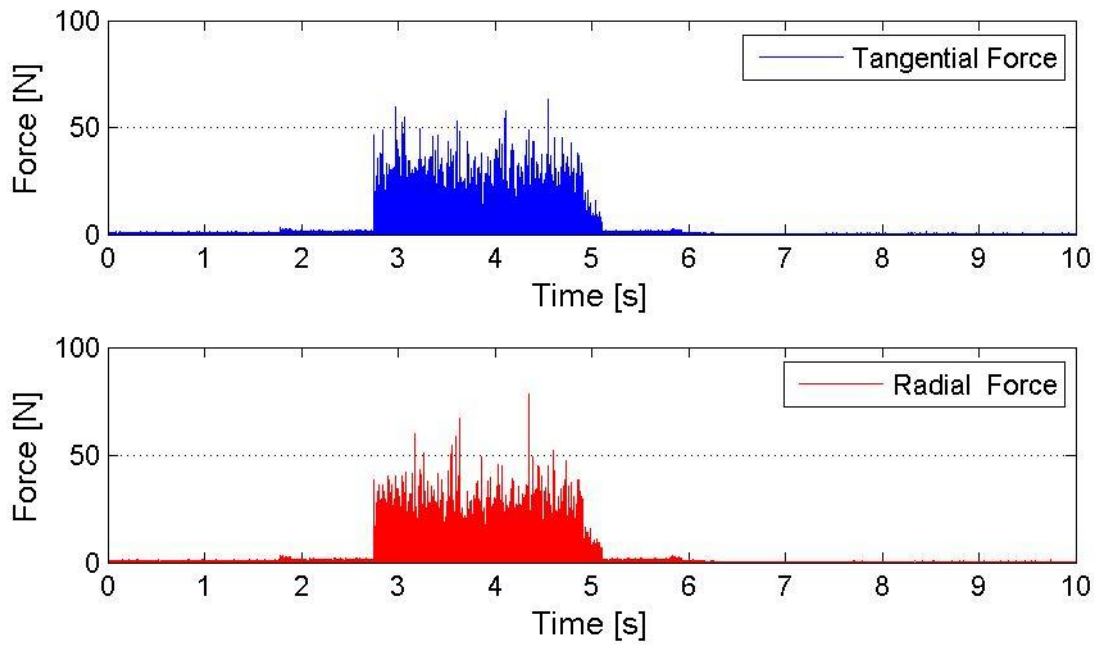


Figure F-128: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

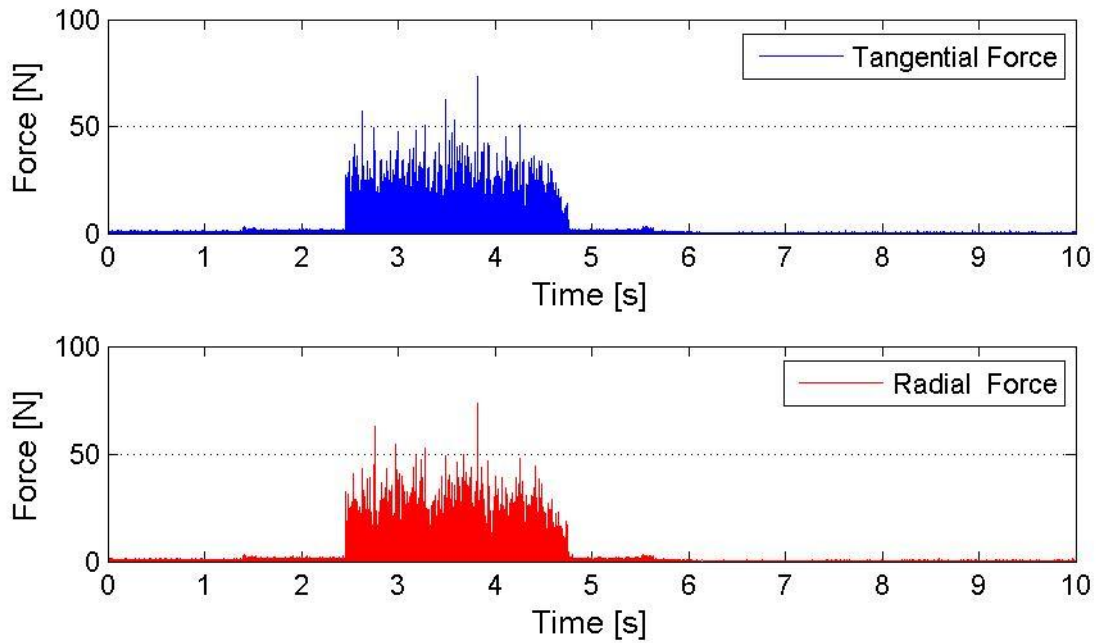


Figure F-129: Tangential and radial cutting force of AAC at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

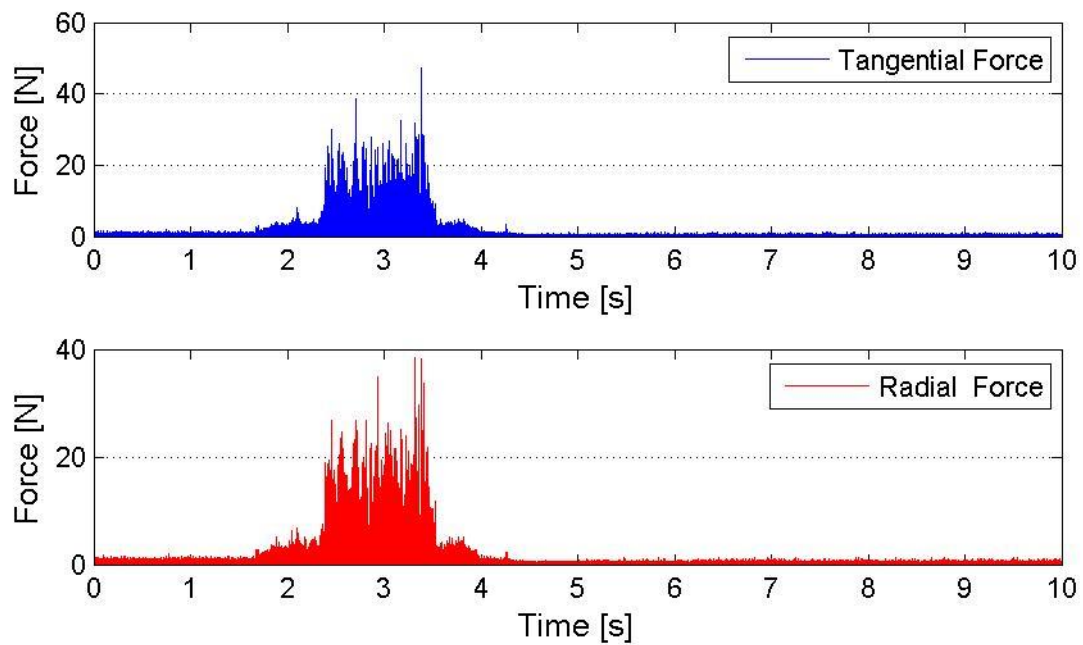


Figure F-130: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

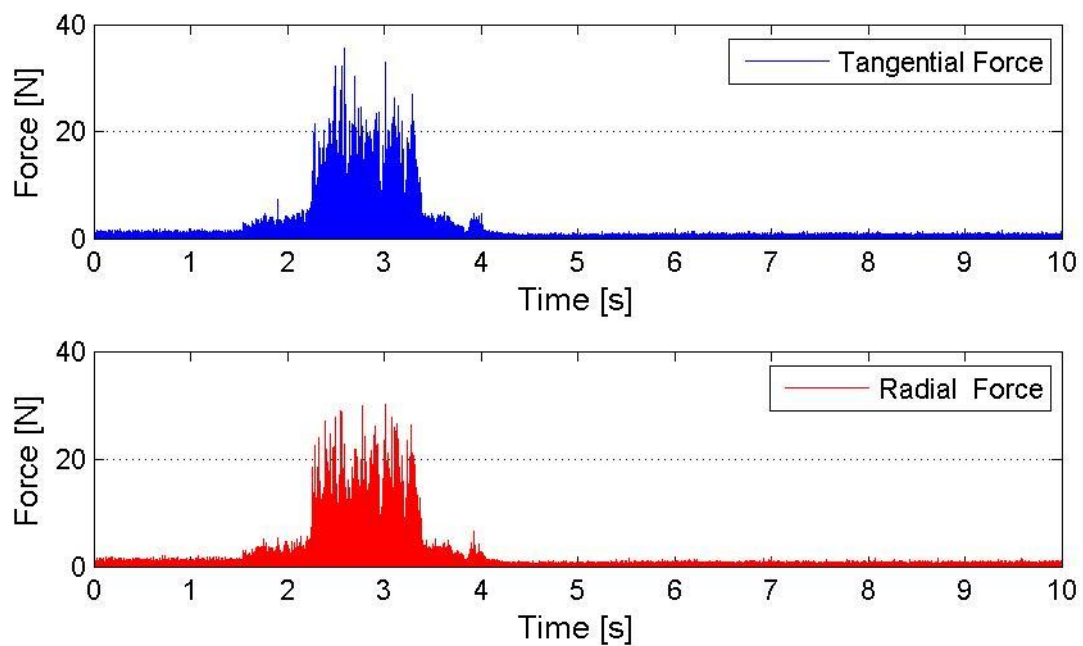


Figure F-131: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

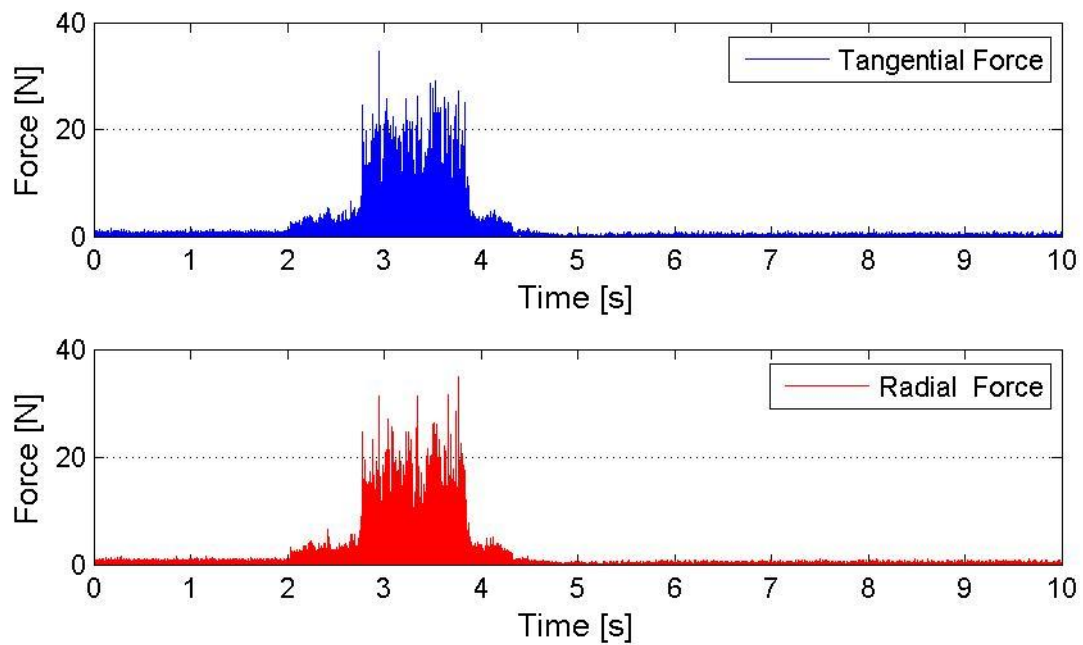


Figure F-132: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

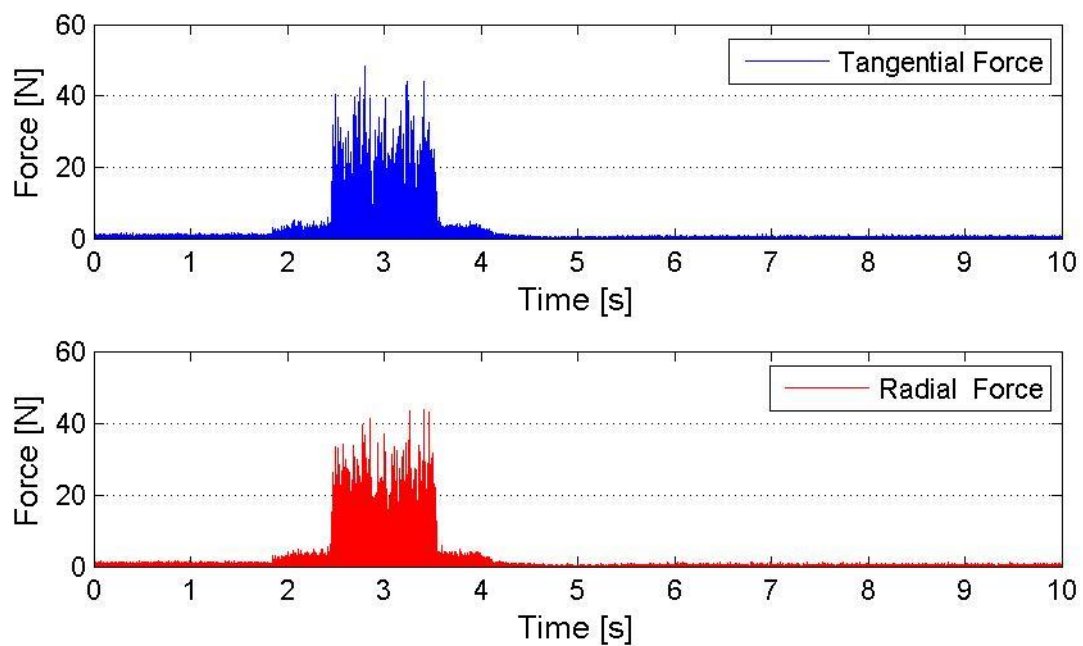


Figure F-133: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

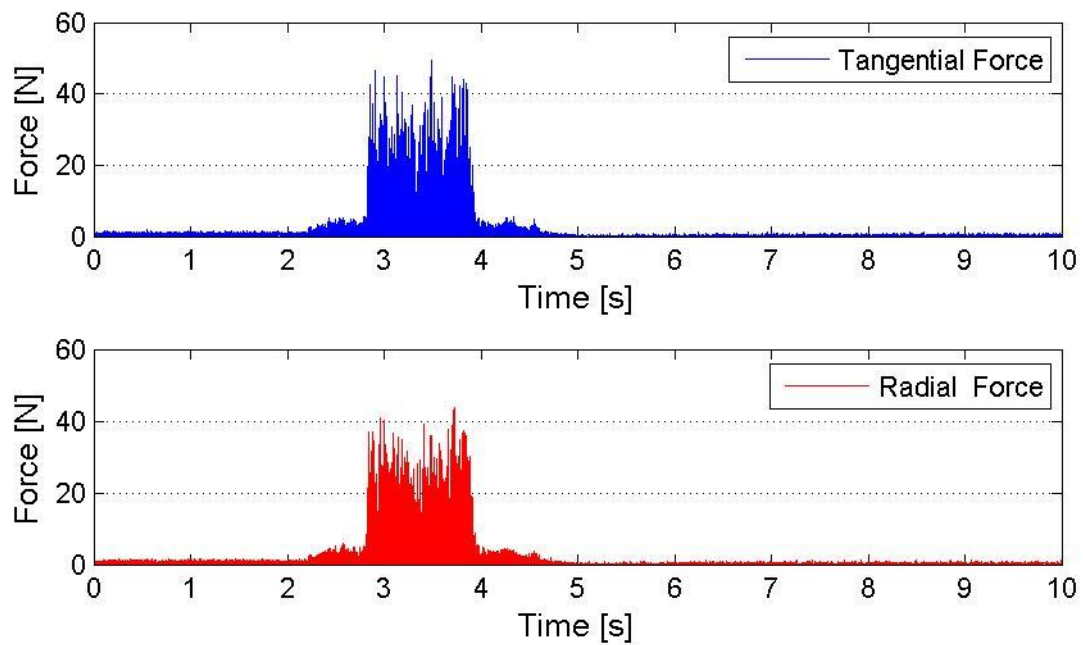


Figure F-134: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

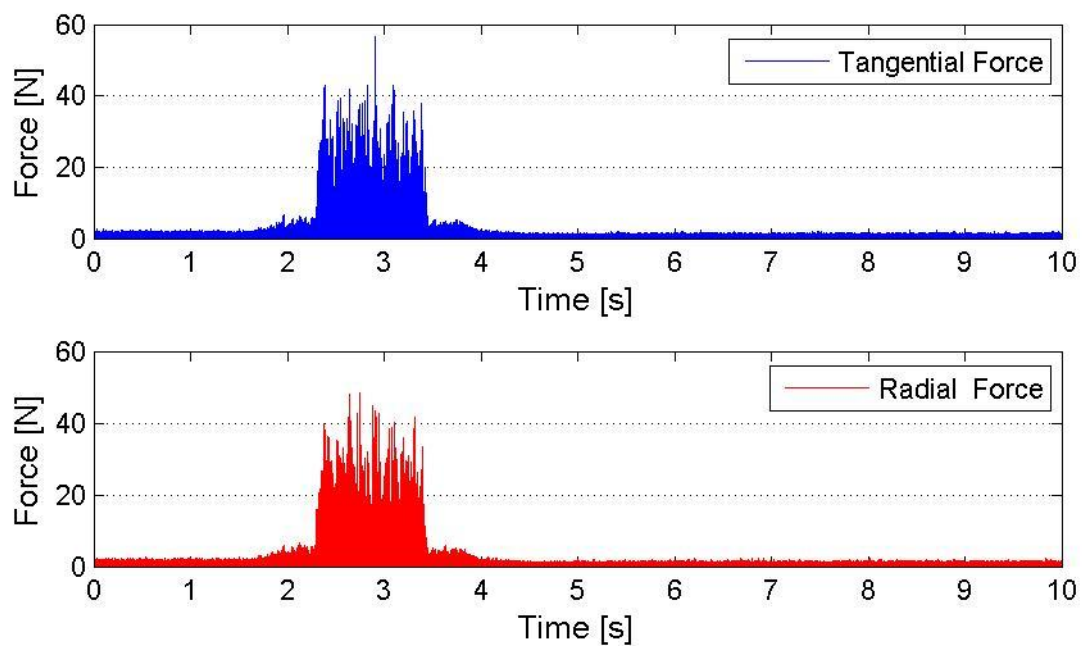


Figure F-135: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

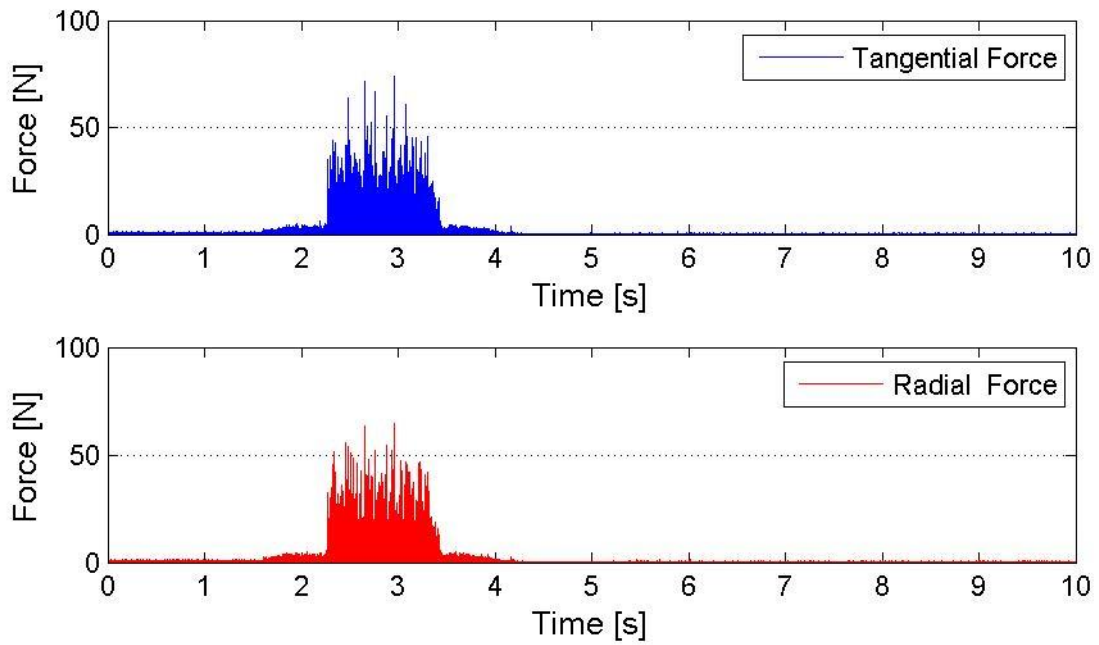


Figure F-136: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

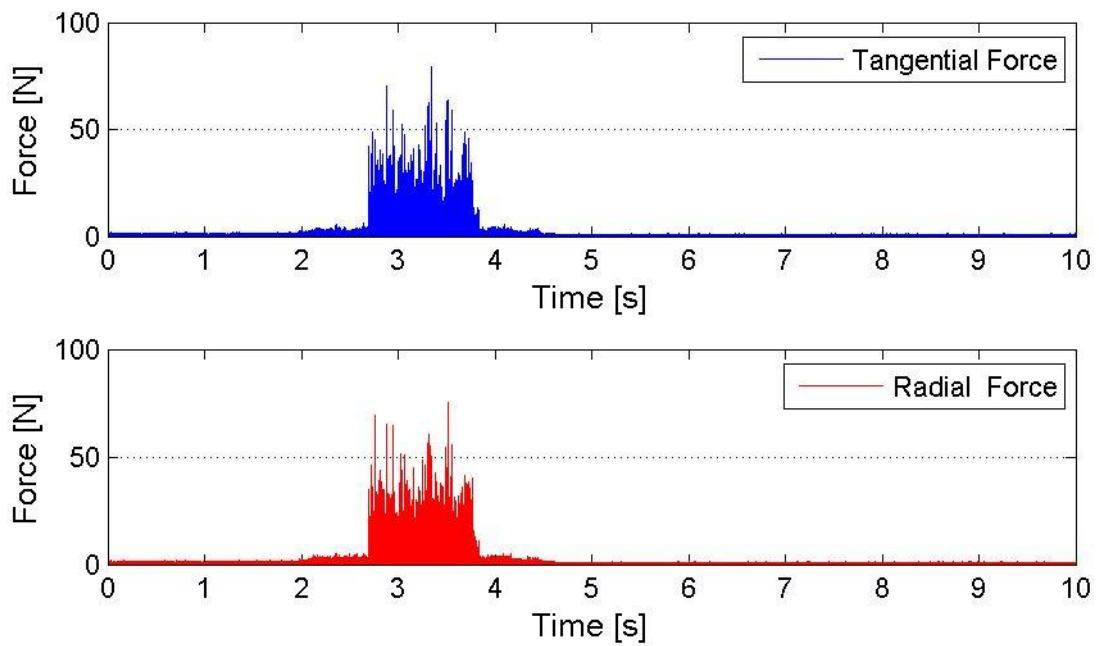


Figure F-137: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

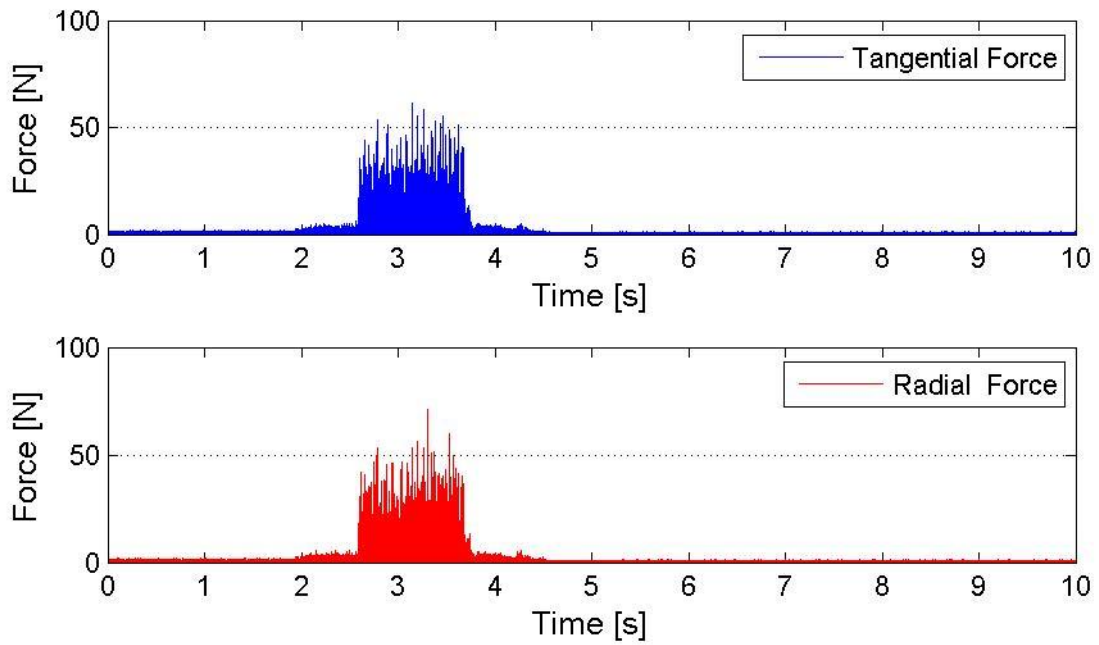


Figure F-138: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

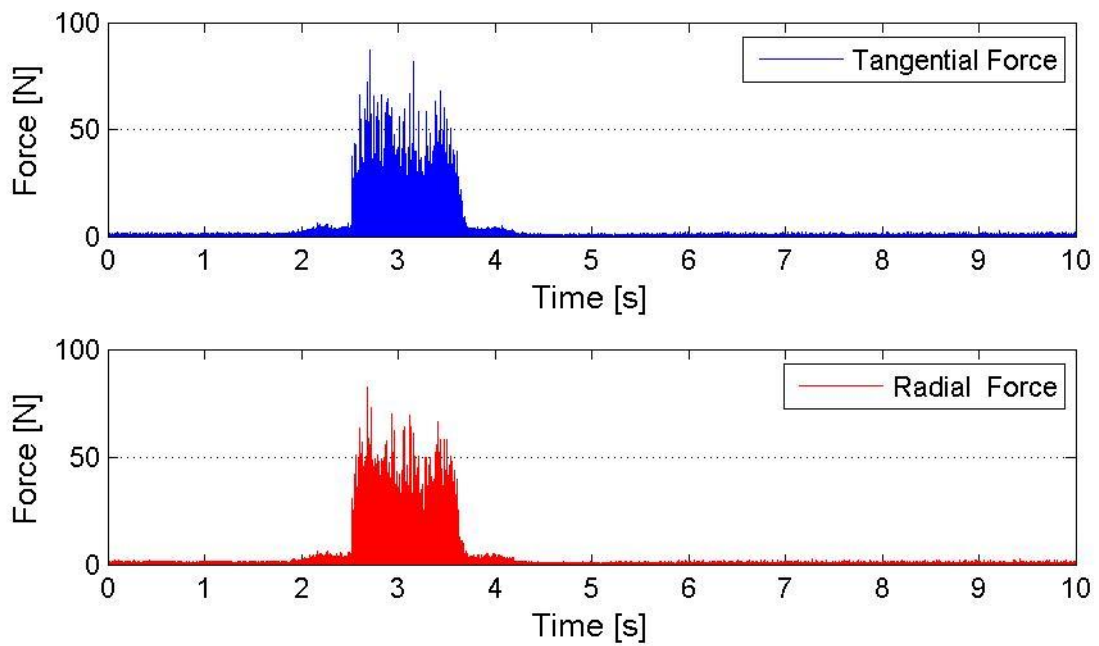


Figure F-139: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

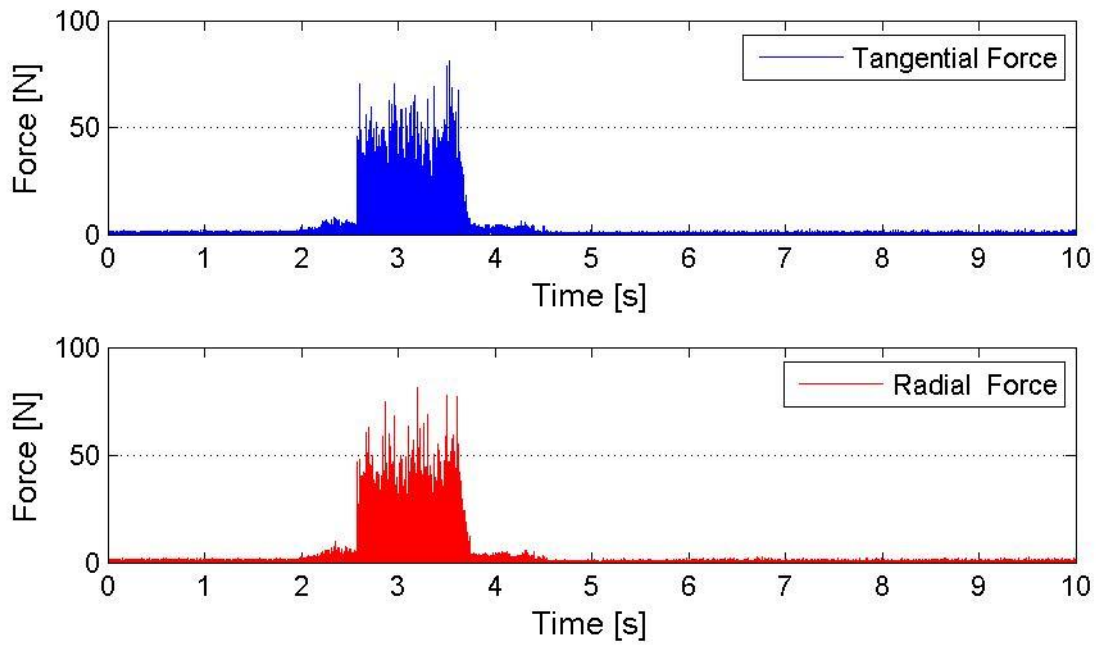


Figure F-140: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

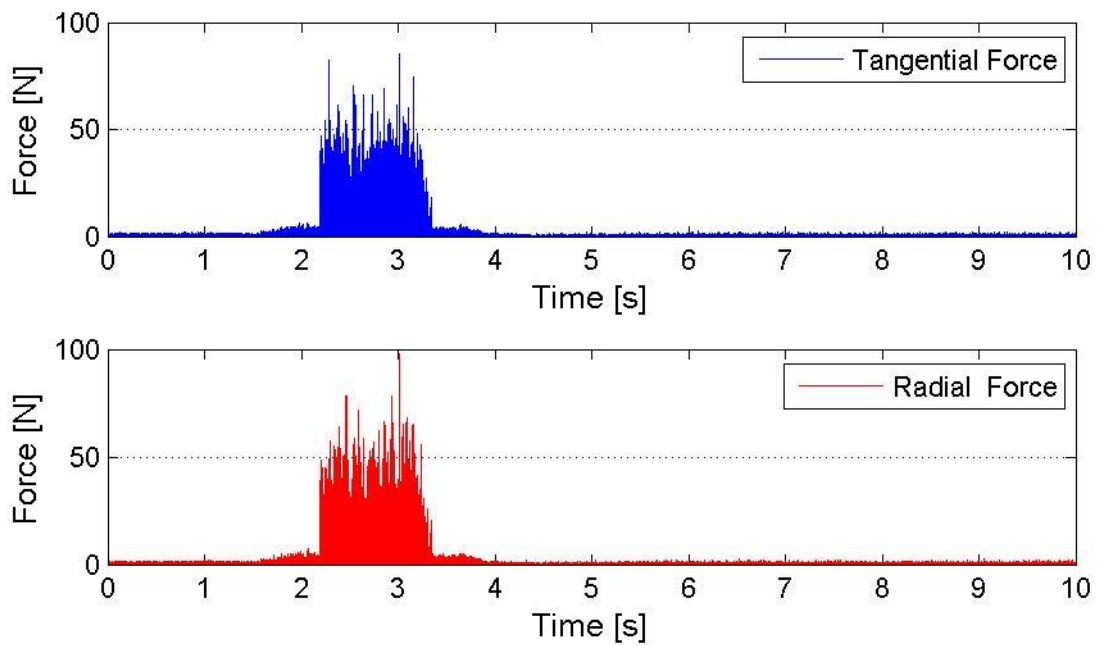


Figure F -141: Tangential and radial cutting force of AAC at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

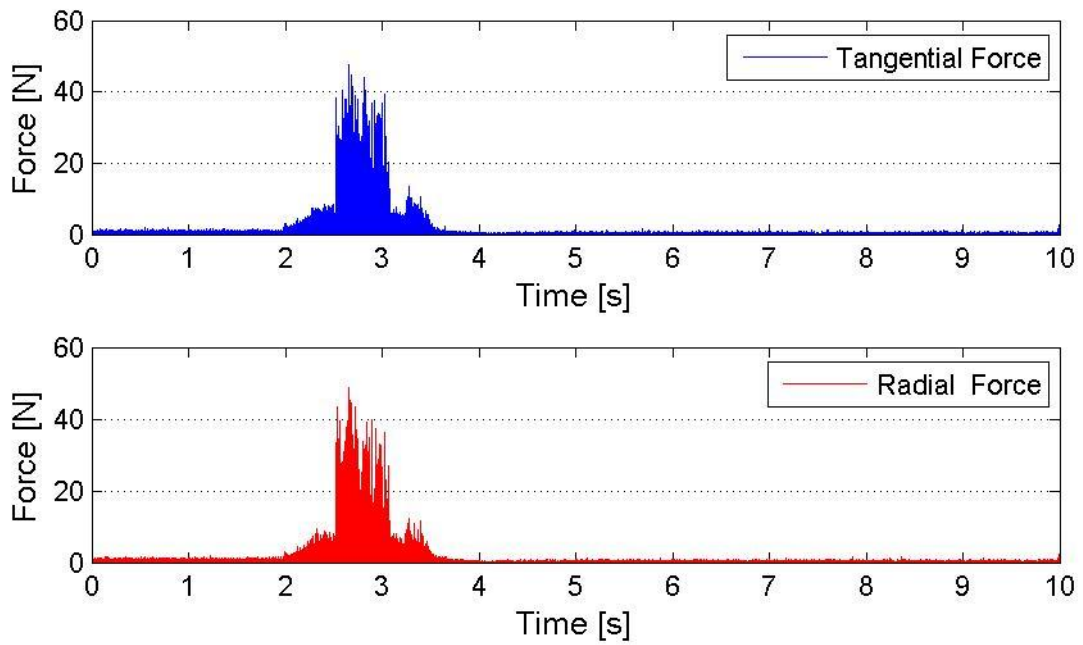


Figure F-142: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

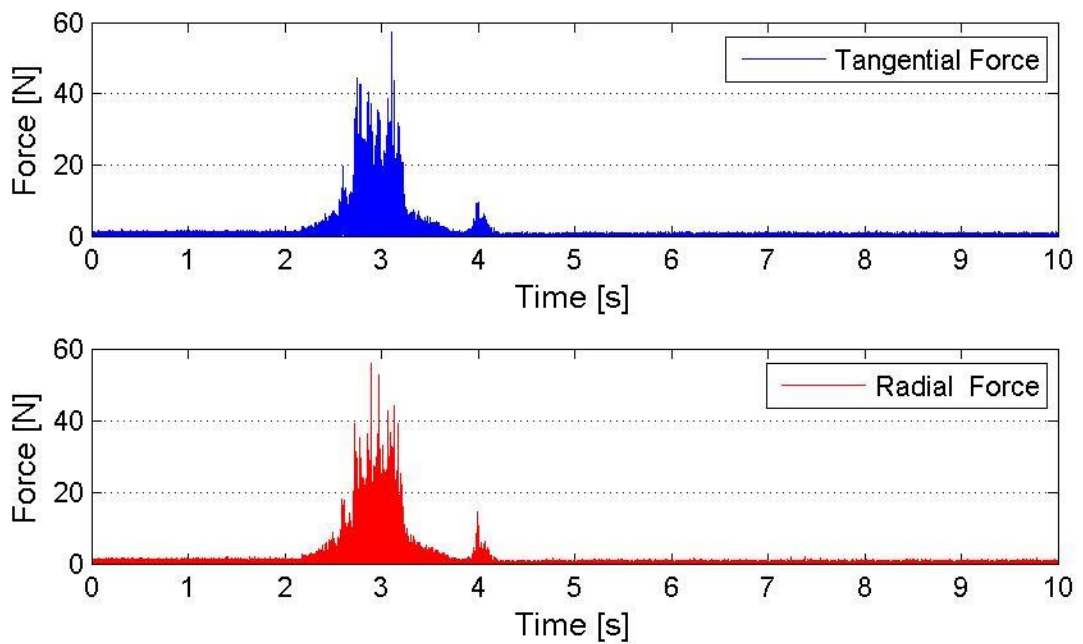


Figure F-143: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

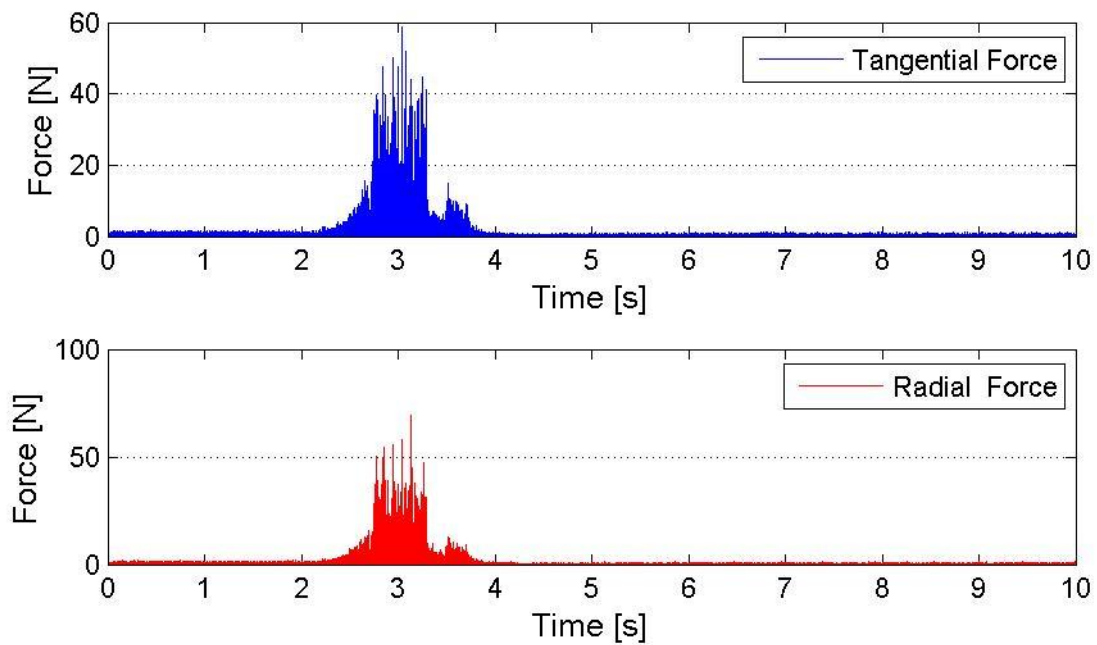


Figure F-144: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

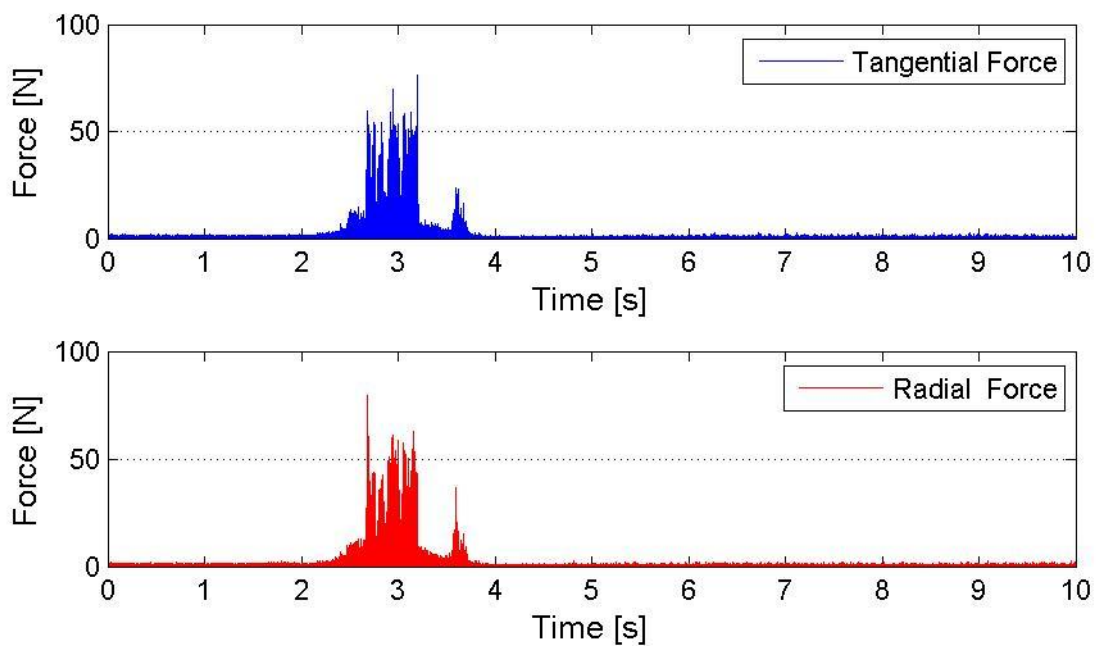


Figure F -145: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

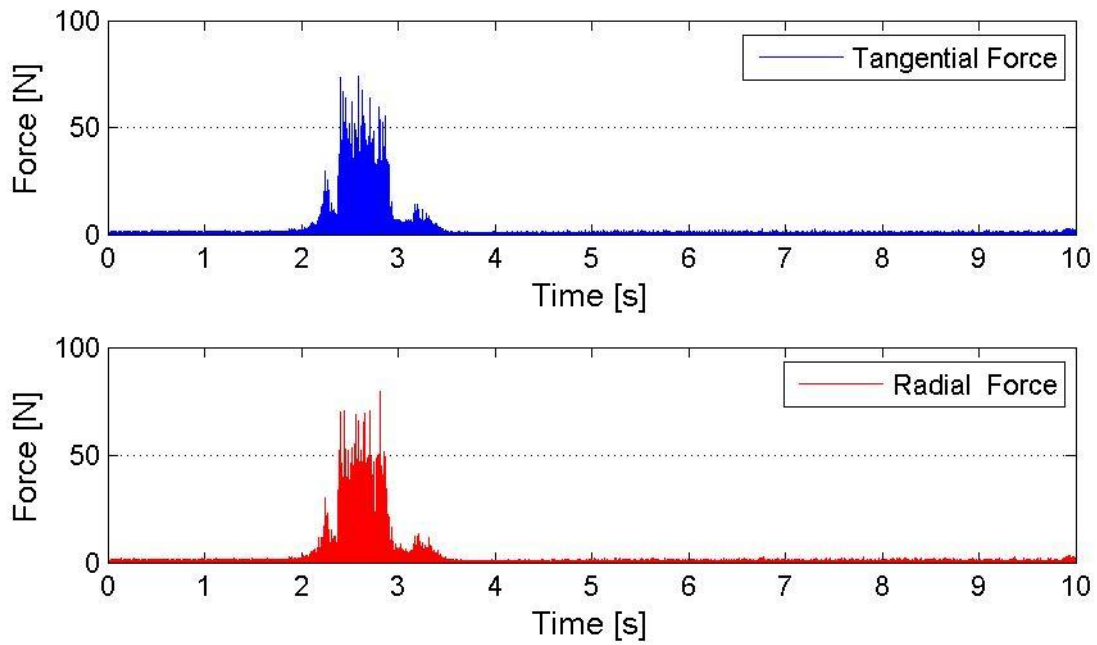


Figure F -146: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

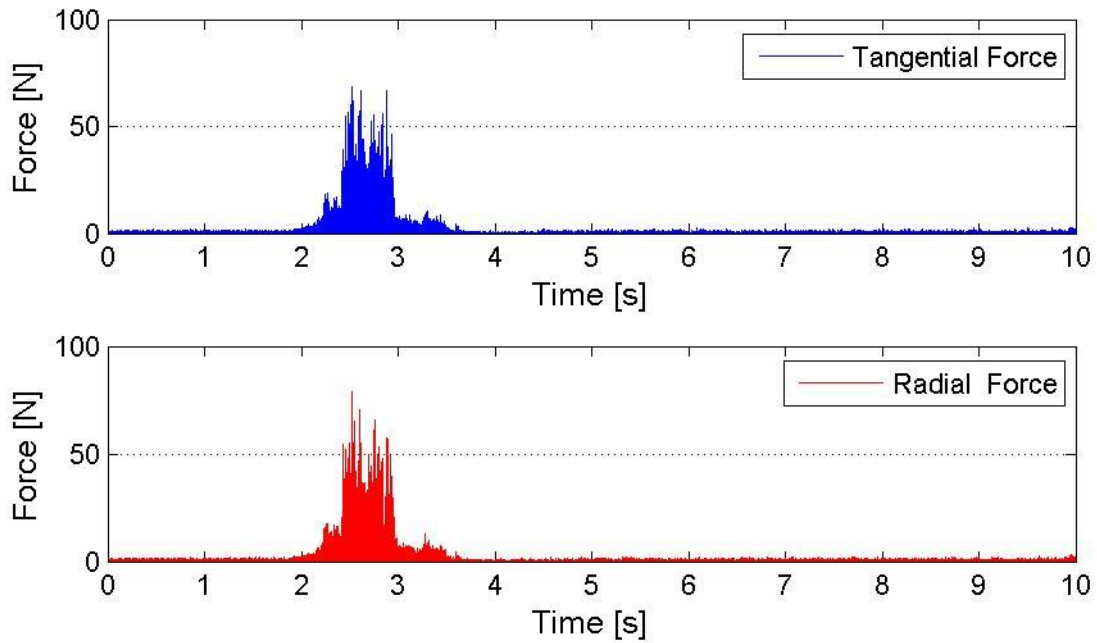


Figure F -147: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

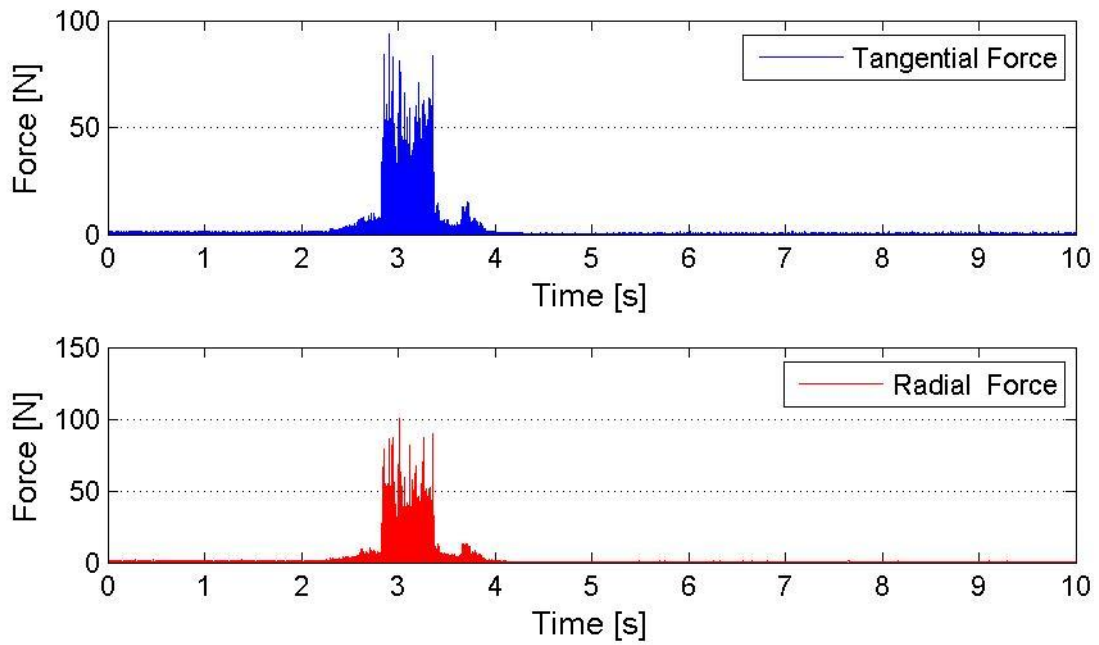


Figure F-148: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

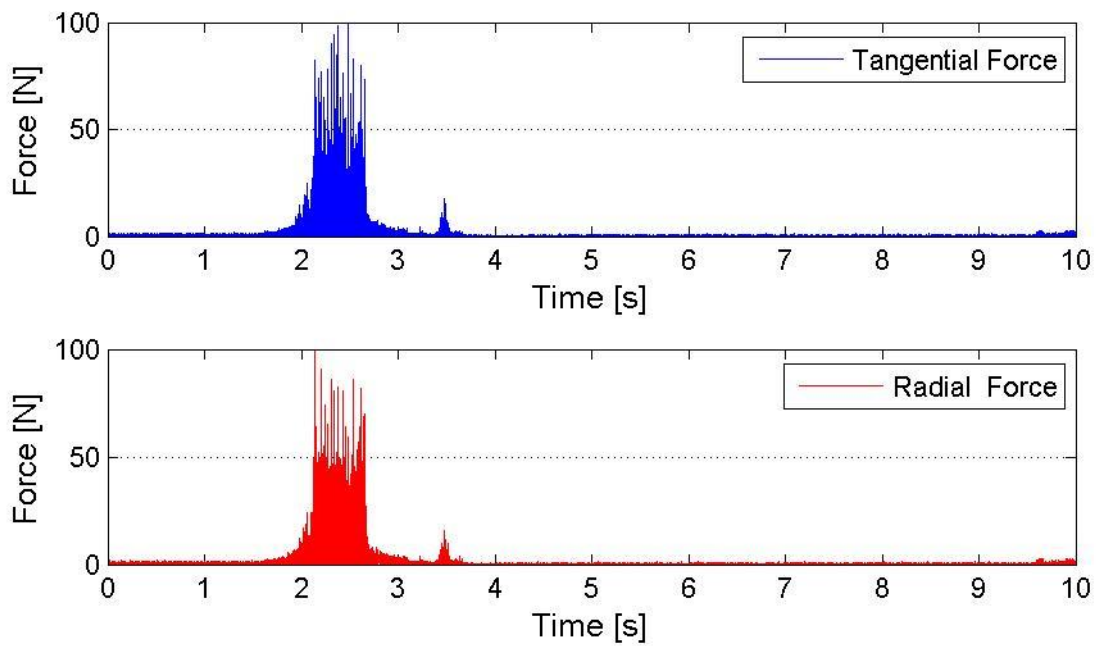


Figure F-149: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

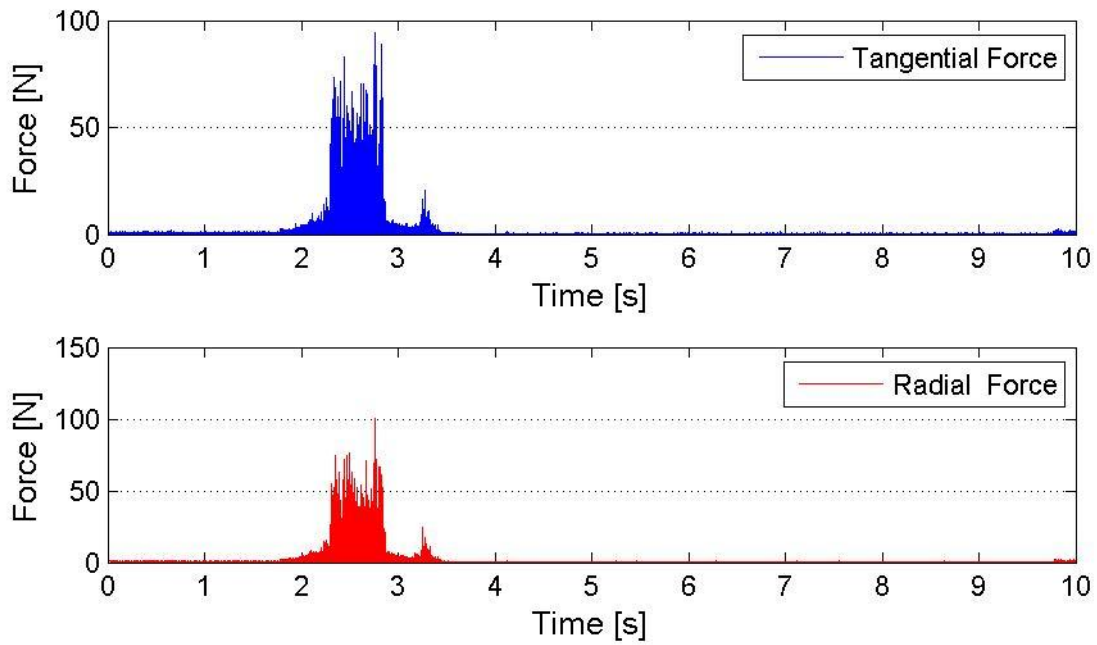


Figure F-150: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

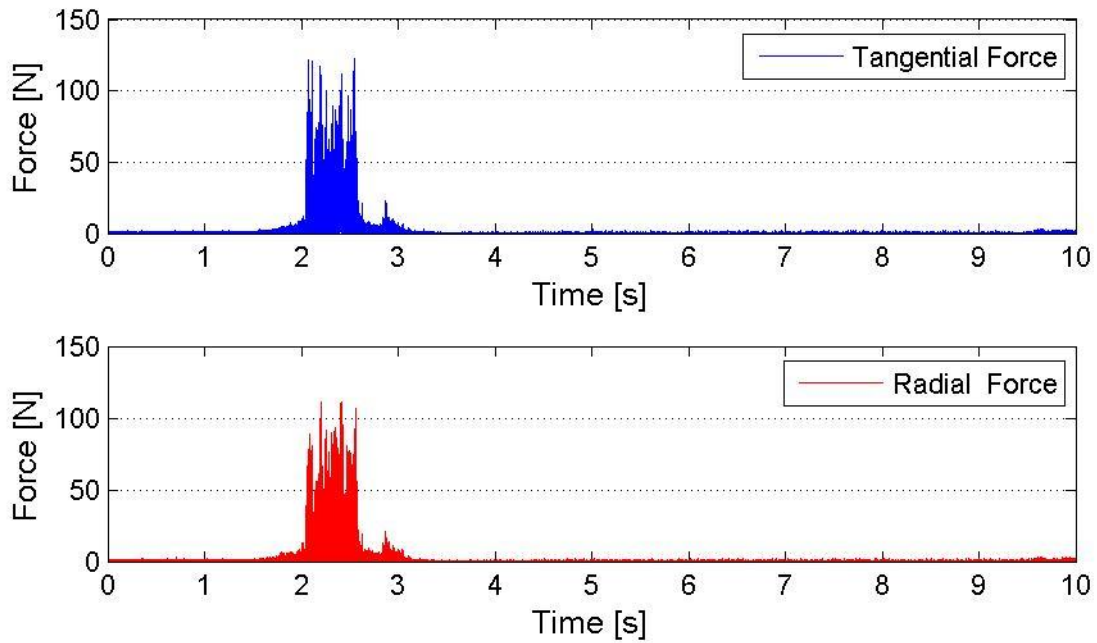


Figure F-151: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

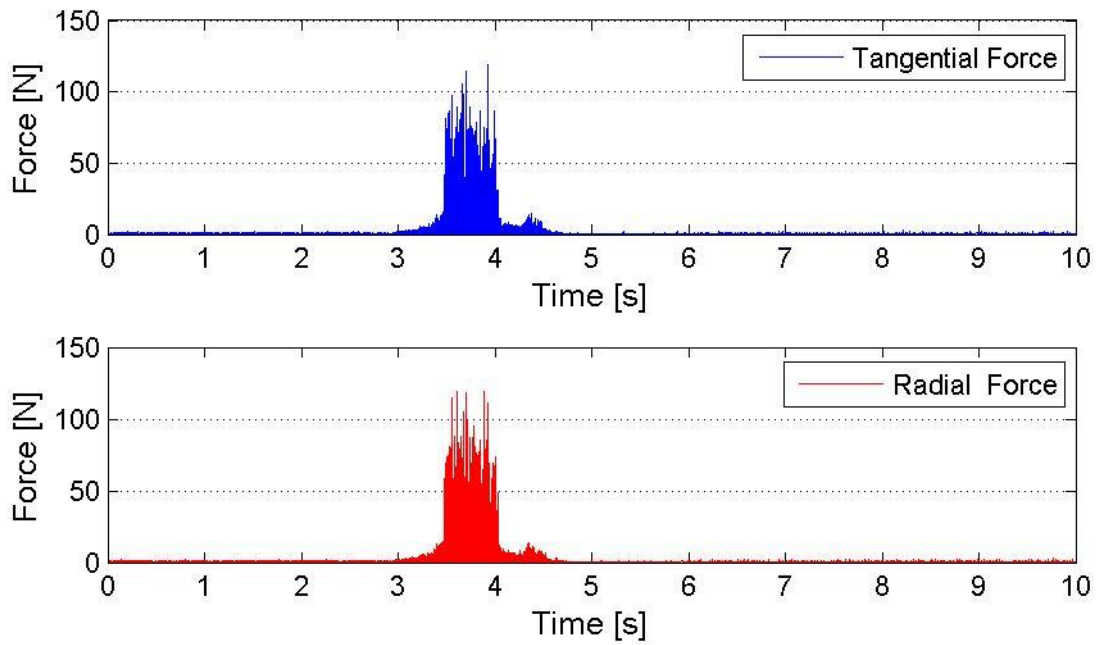


Figure F-152: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

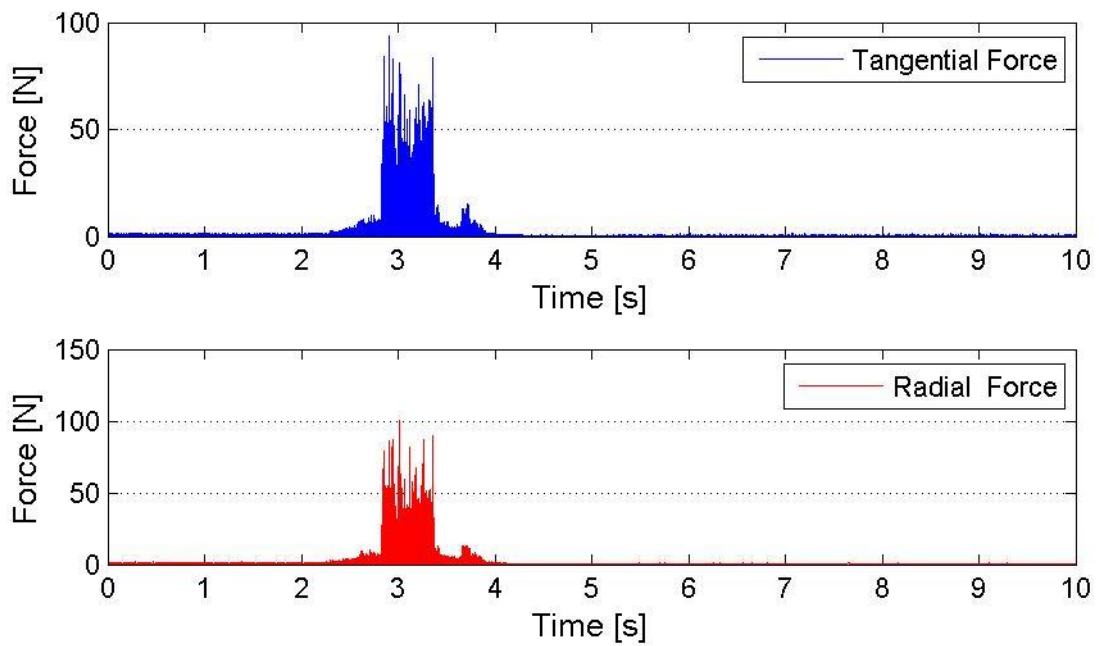


Figure F-153: Tangential and radial cutting force of AAC at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

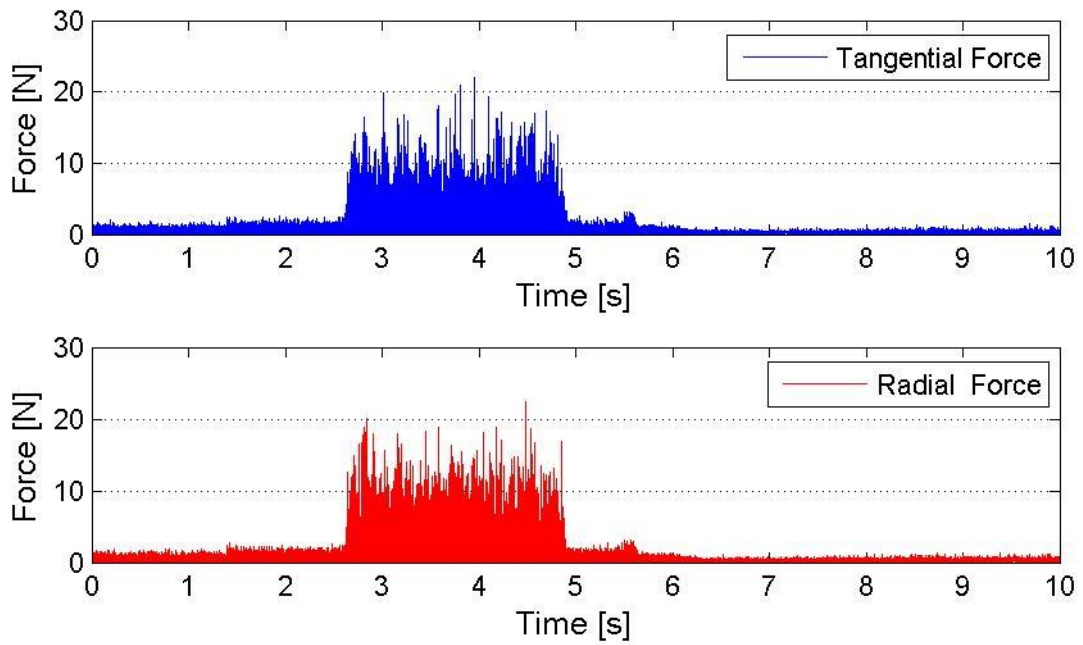


Figure F-154: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

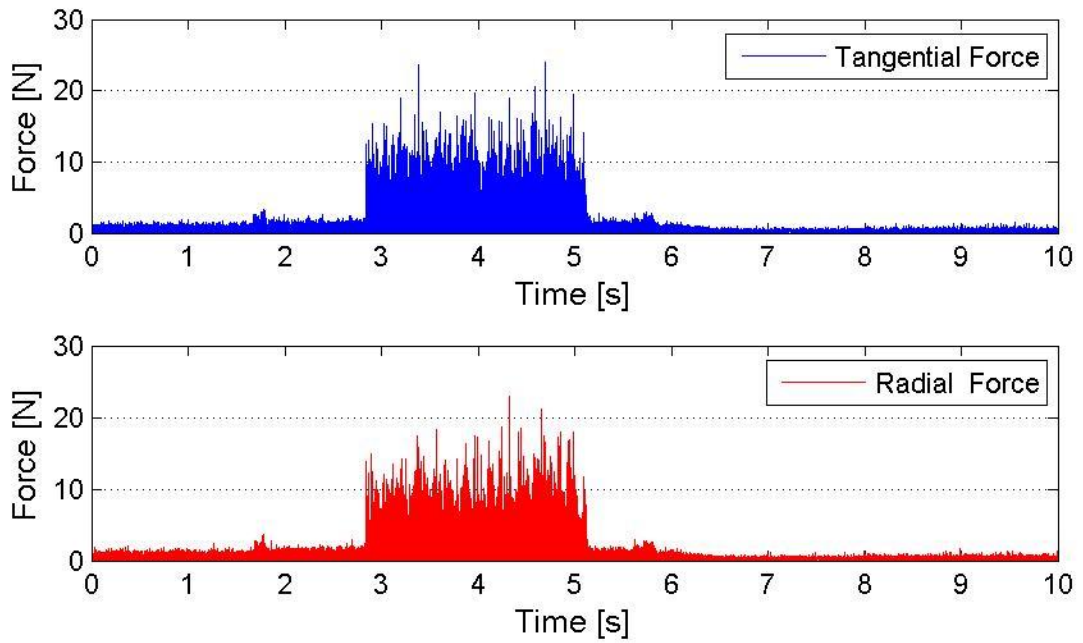


Figure F-155: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

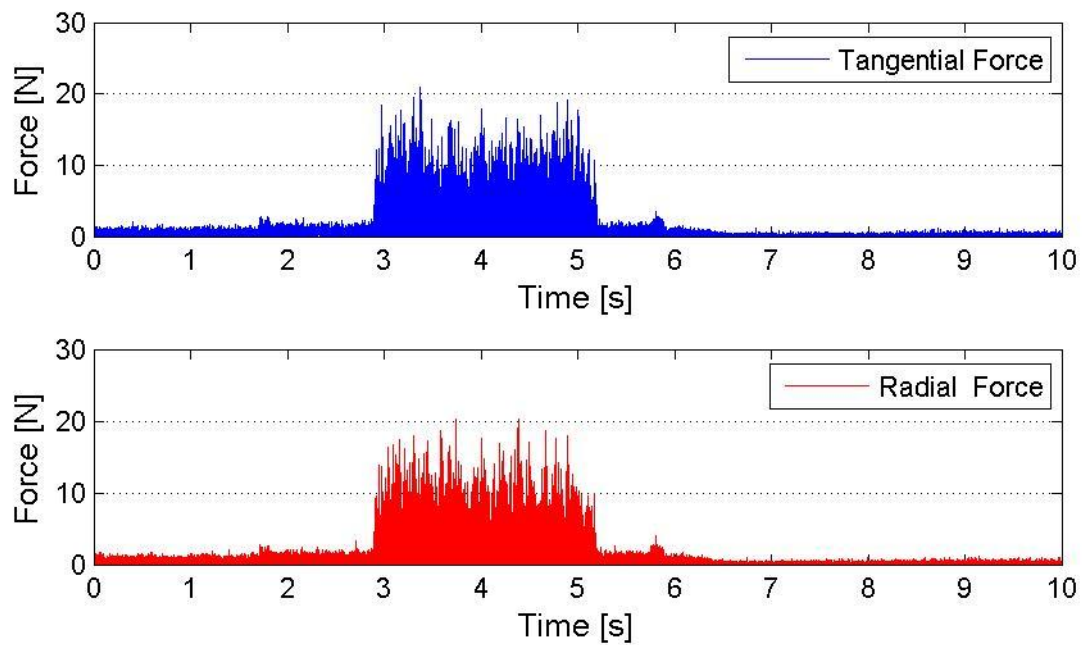


Figure F-156: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

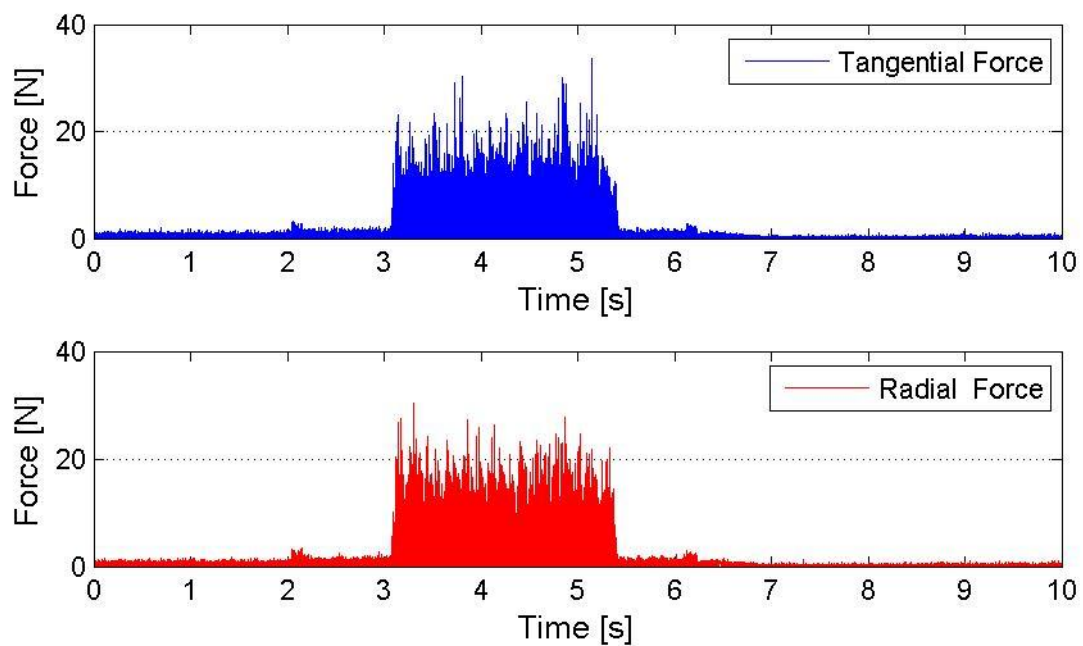


Figure F-157: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

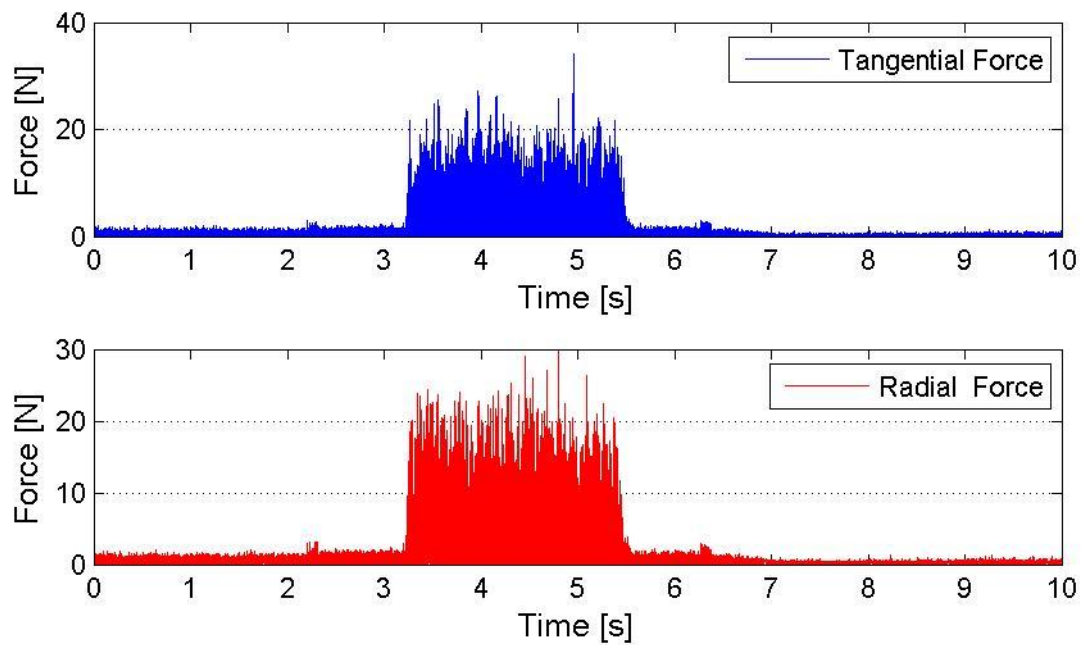


Figure F-158: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

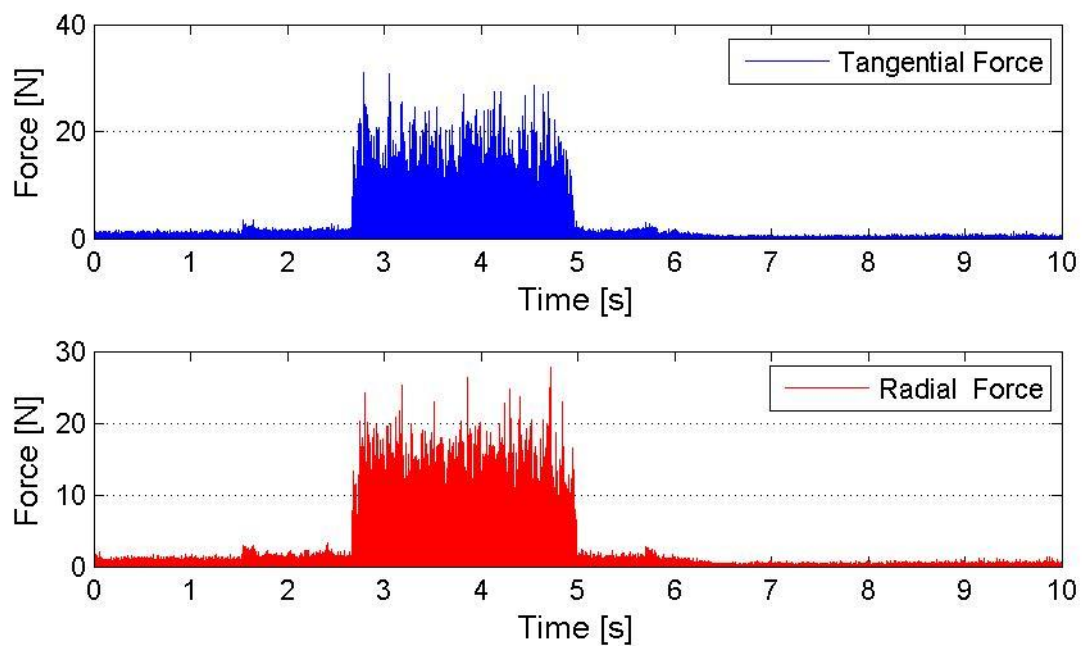


Figure F-159: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

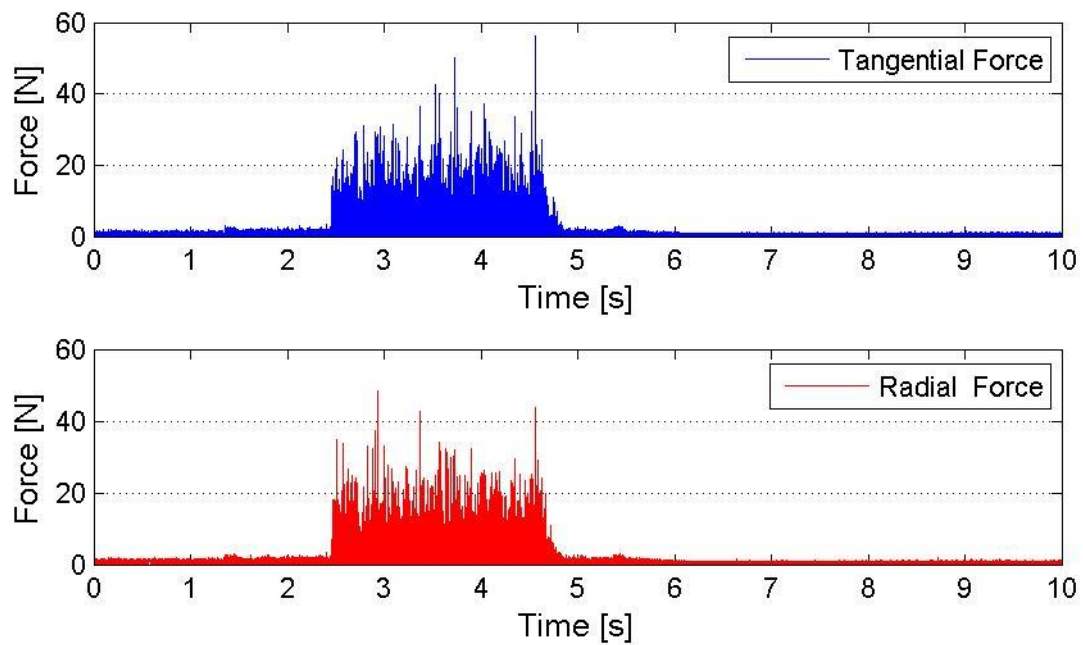


Figure F-160: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

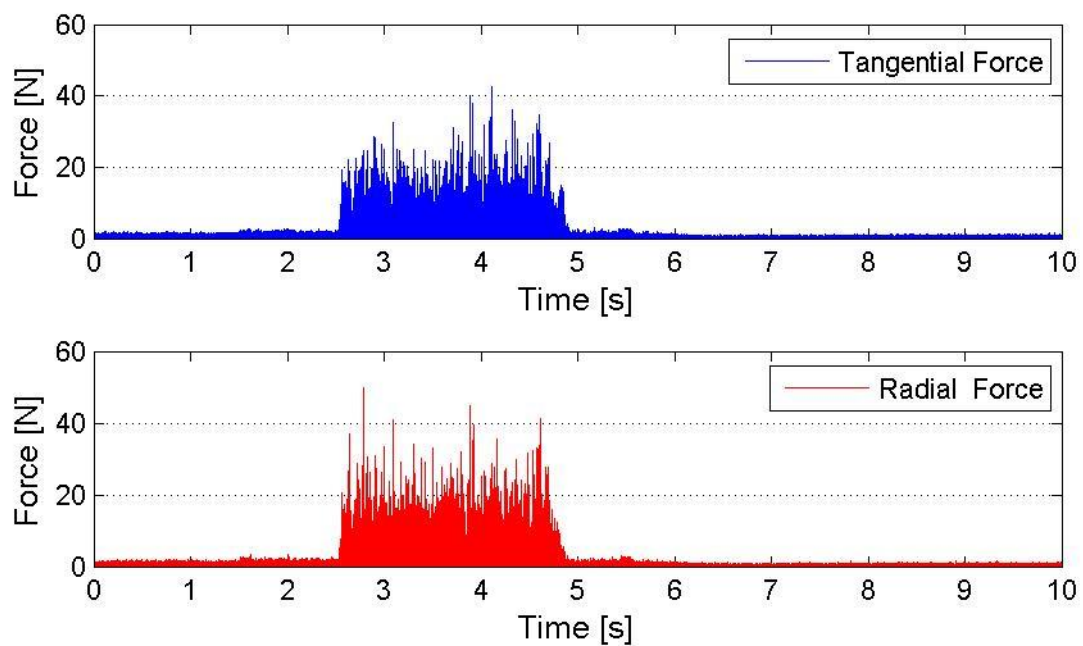


Figure F-161: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

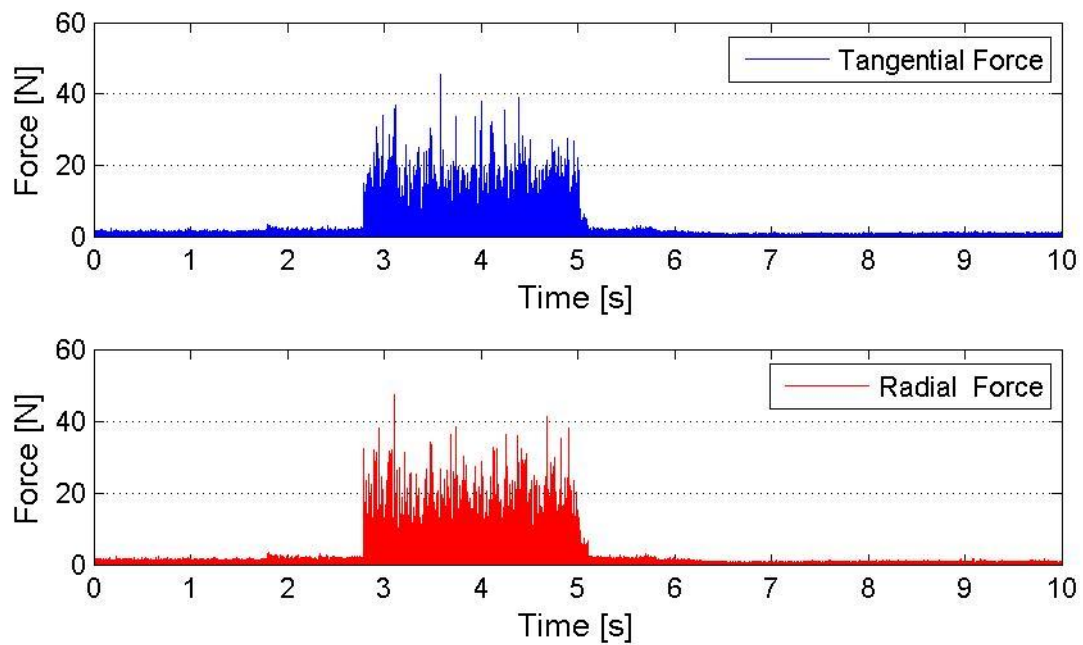


Figure F-162: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

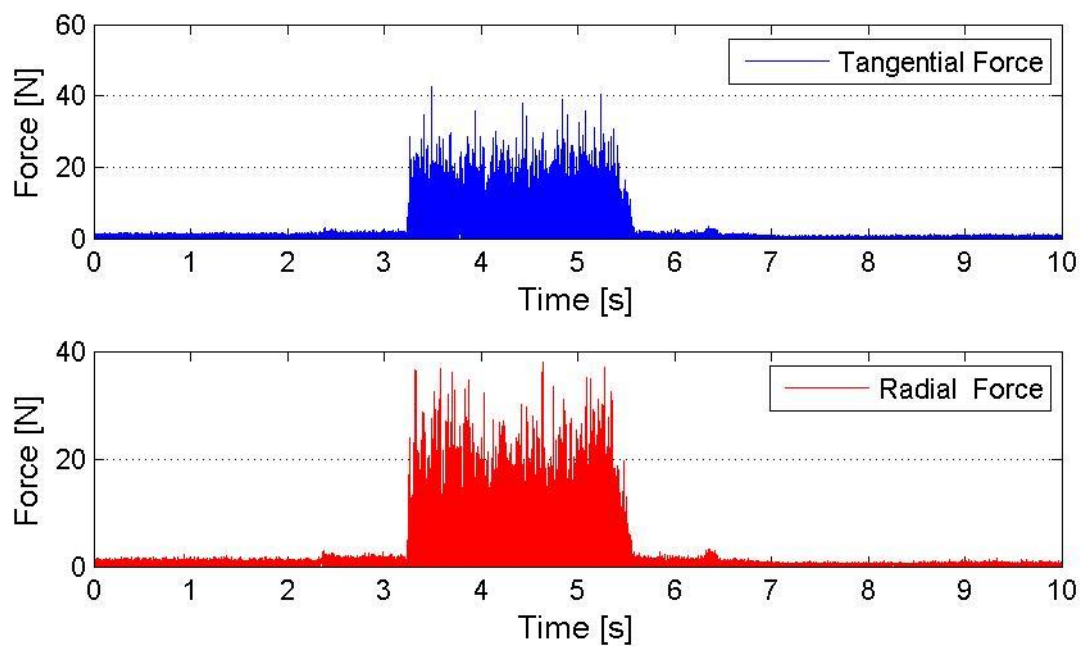


Figure F-163: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

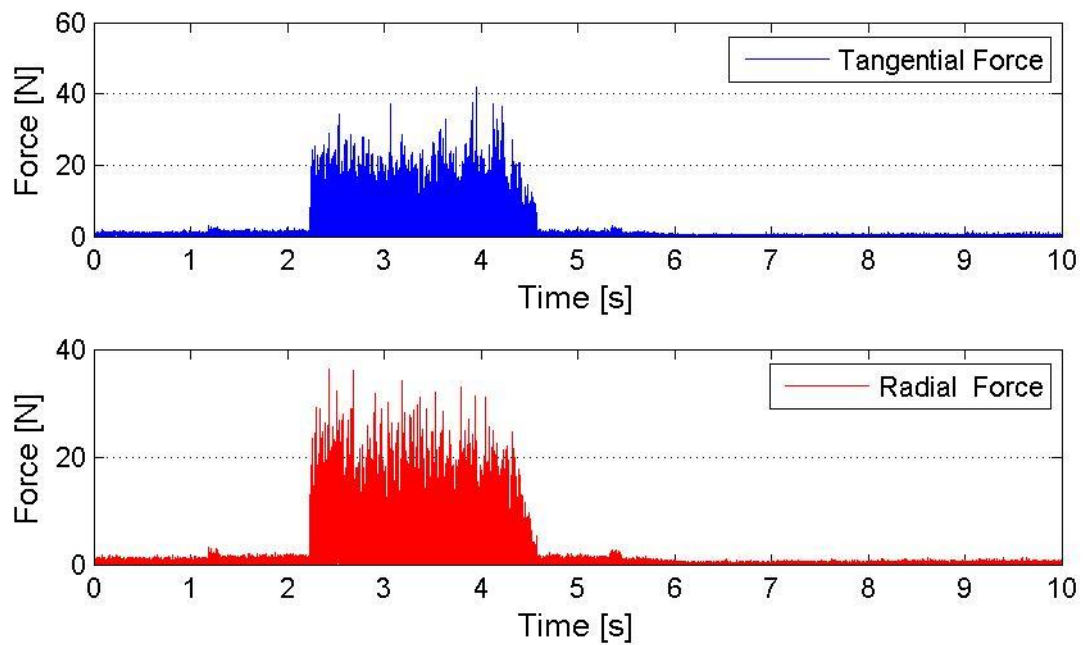


Figure F-164: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

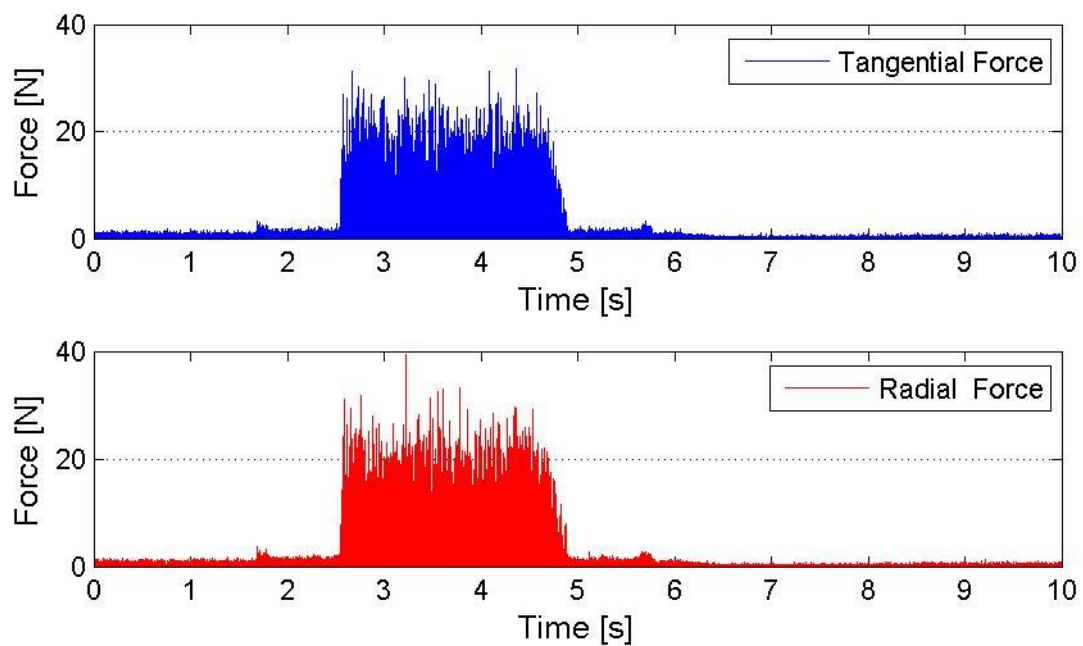


Figure F-165: Tangential and radial cutting force of AAC at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

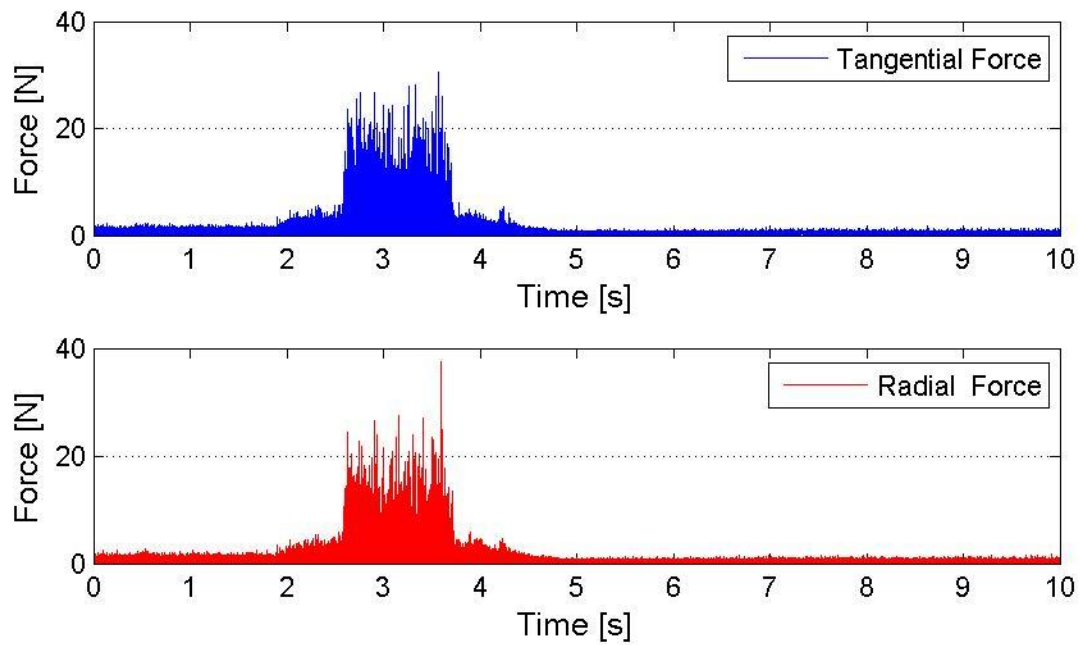


Figure F-166: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

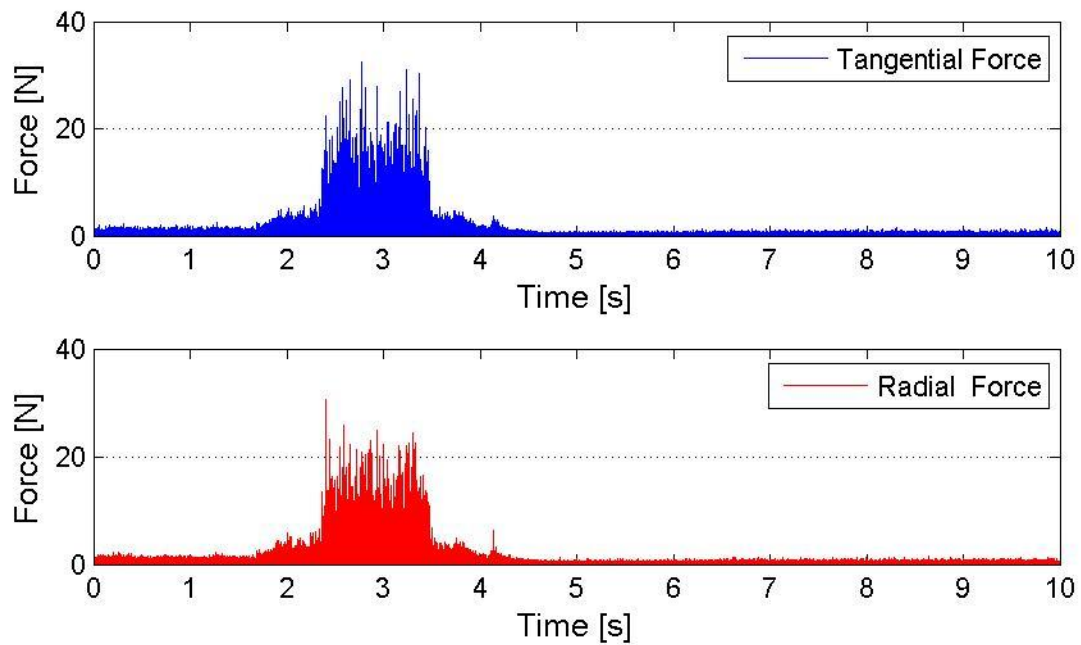


Figure F-167: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

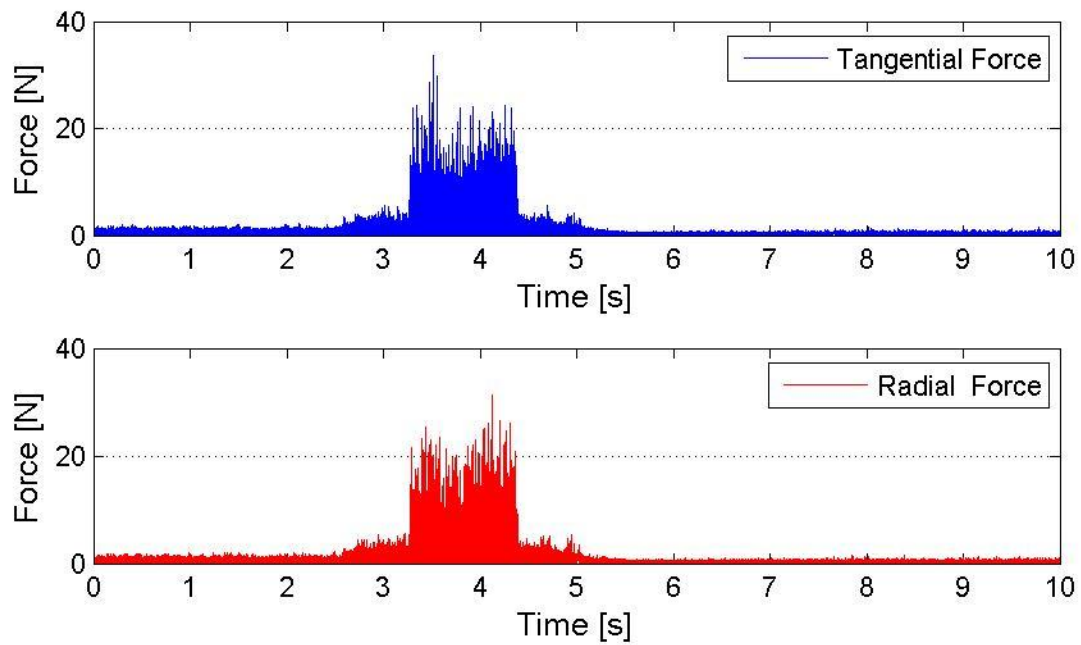


Figure F-168: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

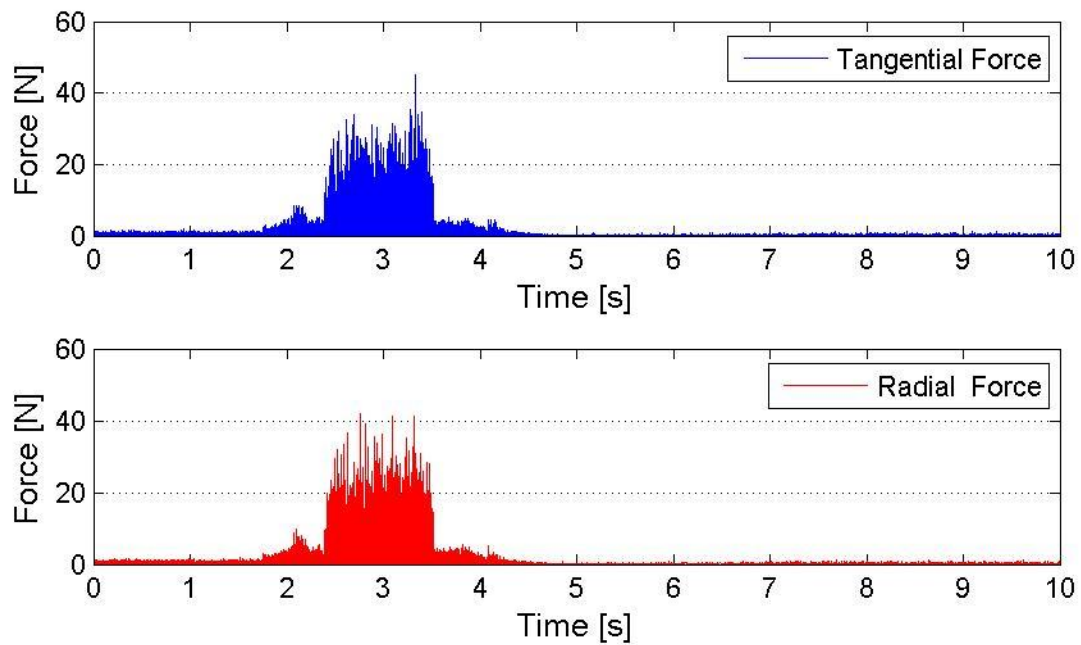


Figure F-169: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

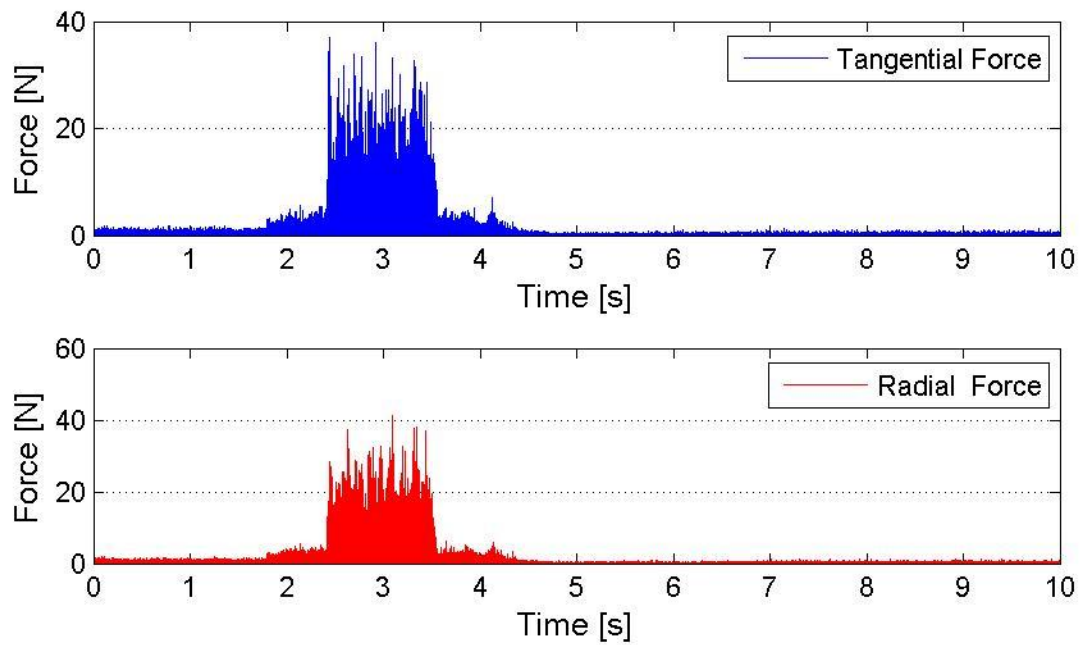


Figure F-170: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

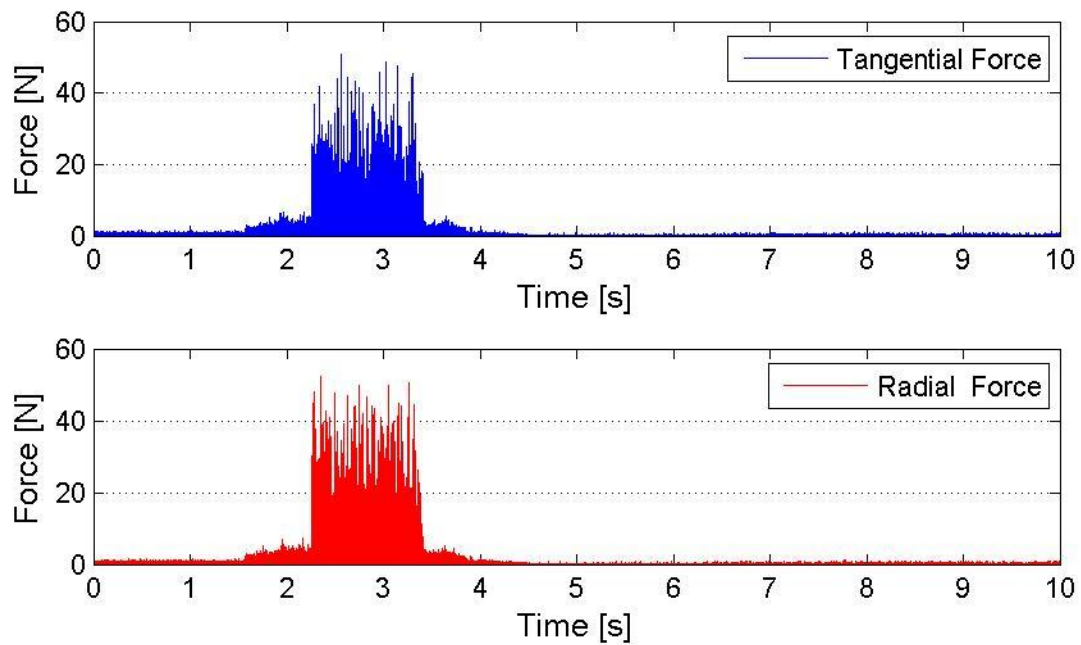


Figure F-171: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

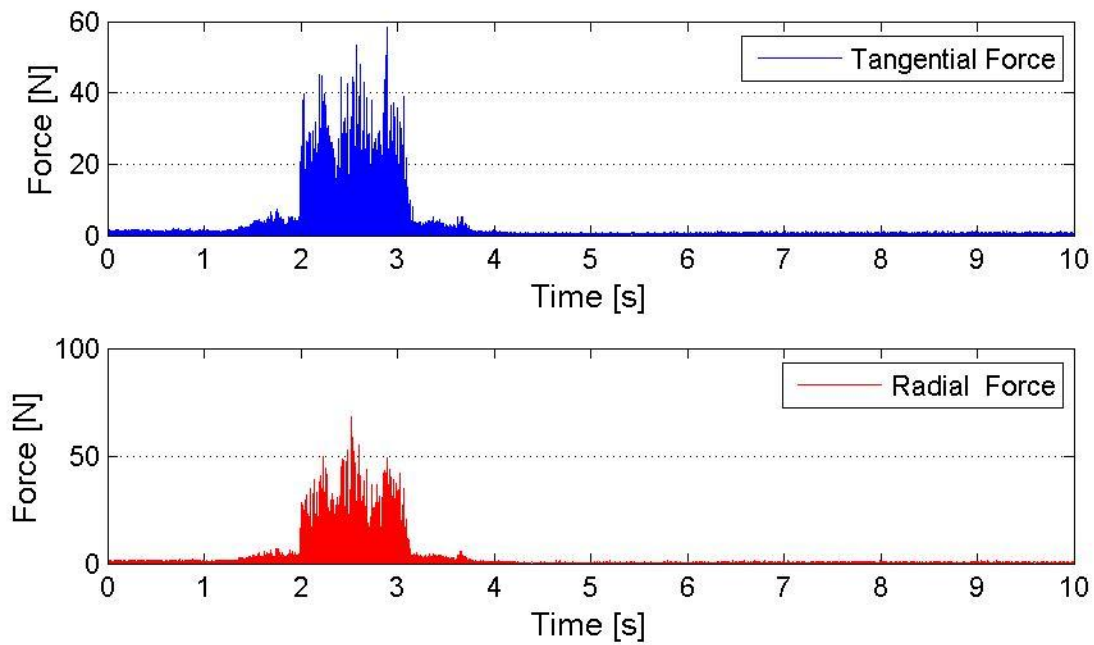


Figure F-172: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

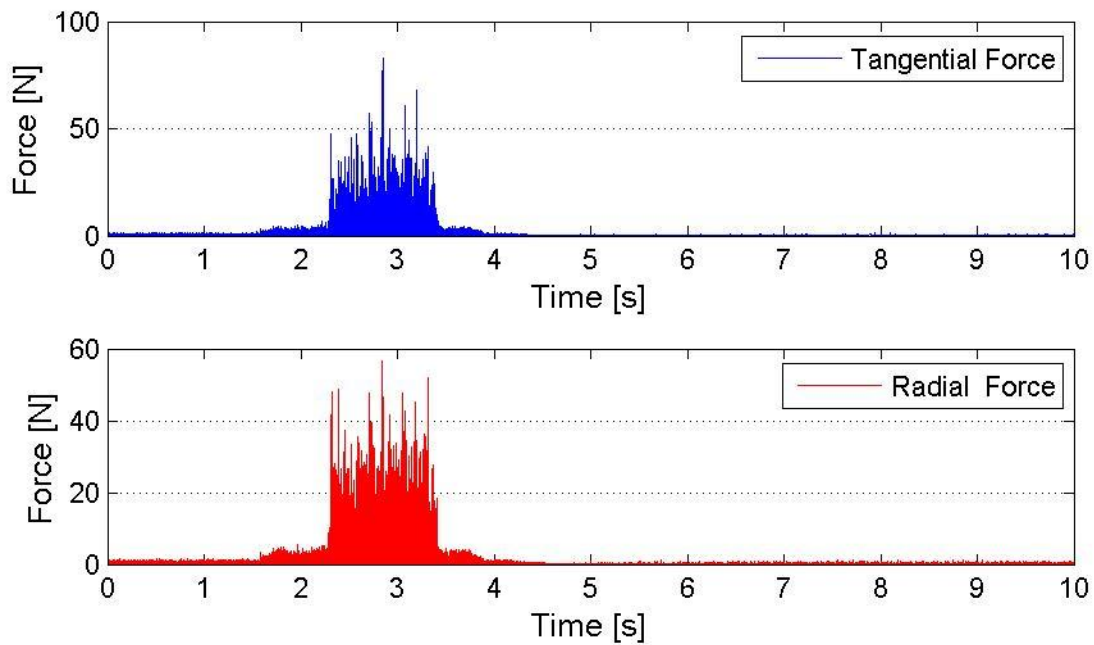


Figure F-173: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

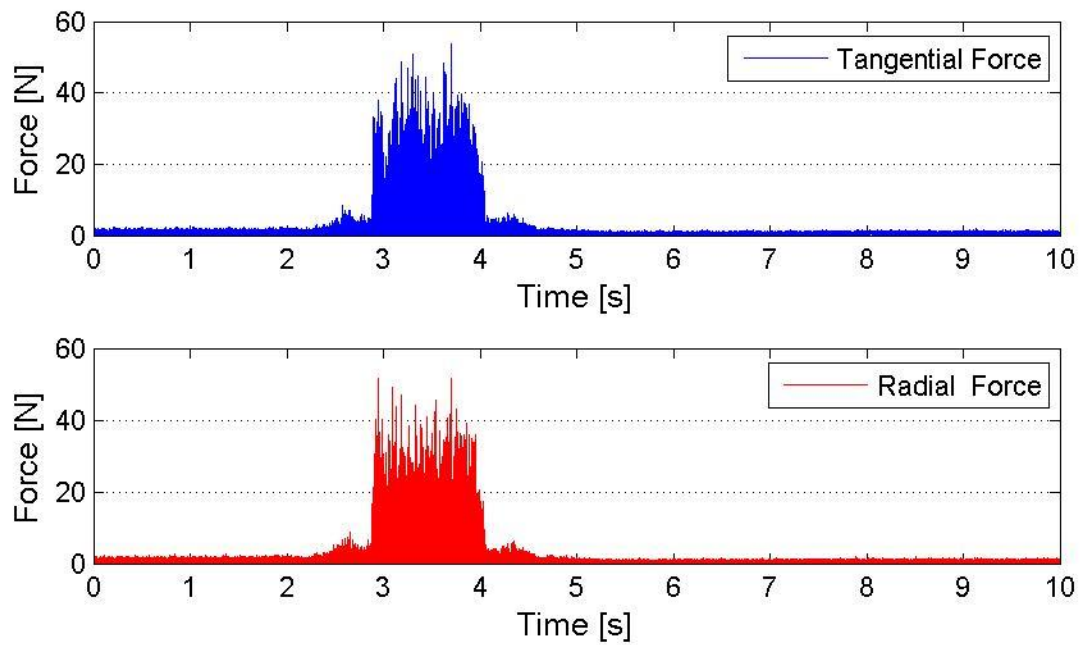


Figure F-174: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

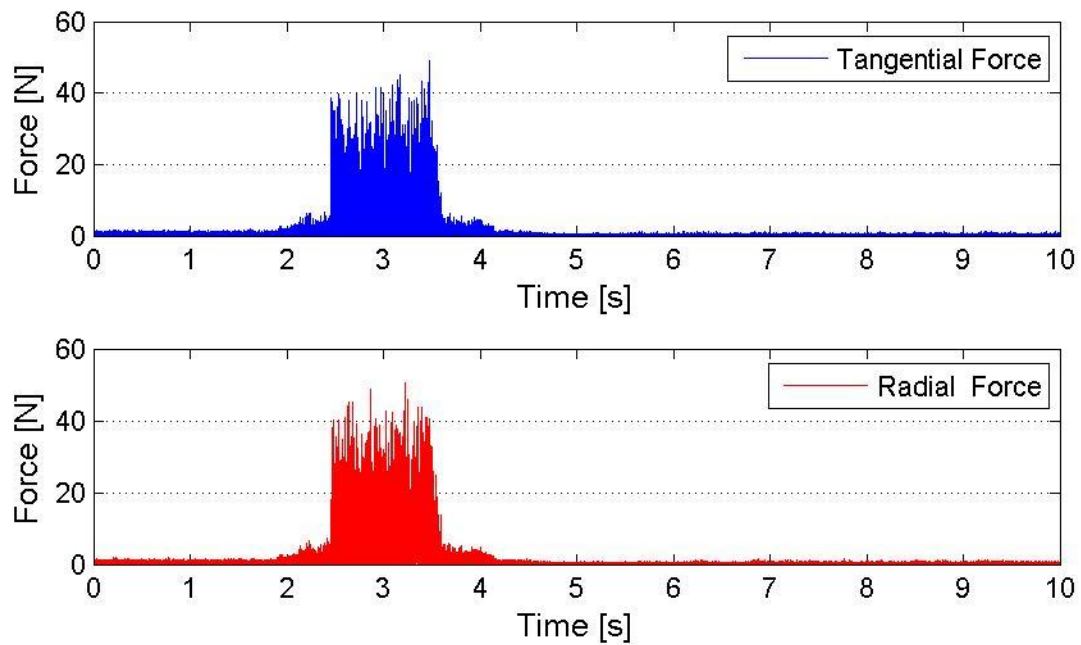


Figure F-175: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

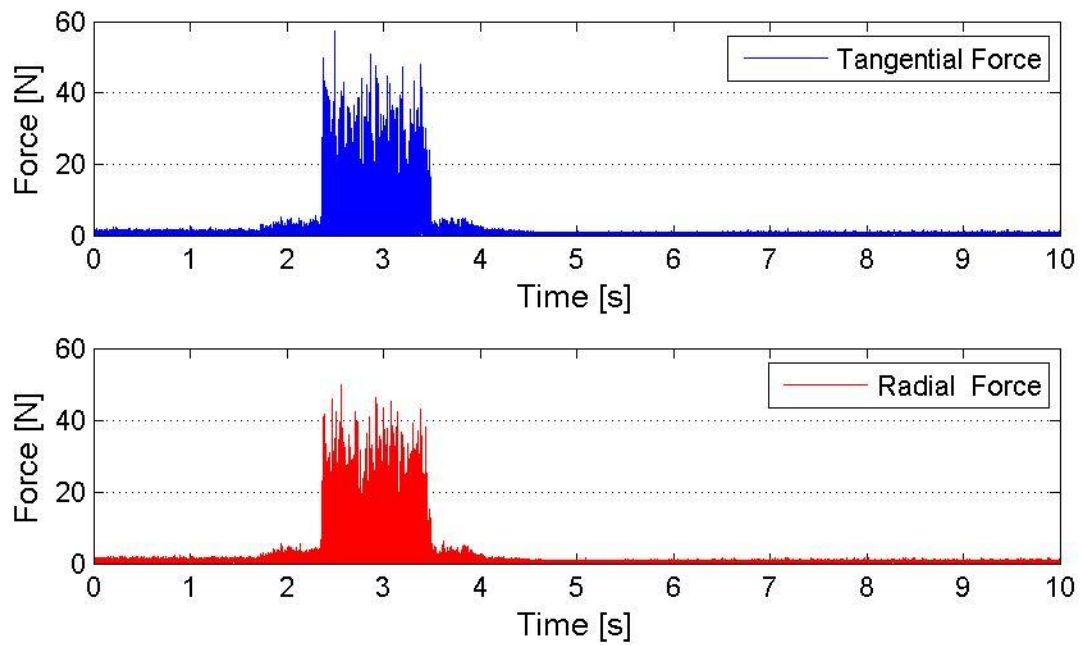


Figure F-176: Tangential and radial cutting force of AAC at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

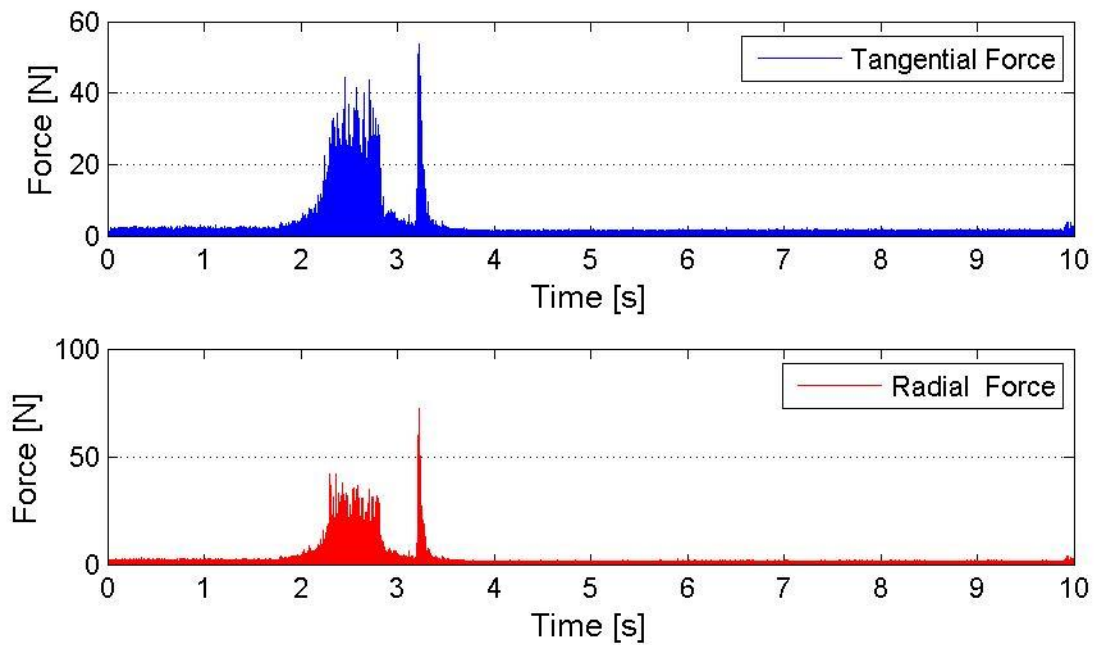


Figure F-177: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

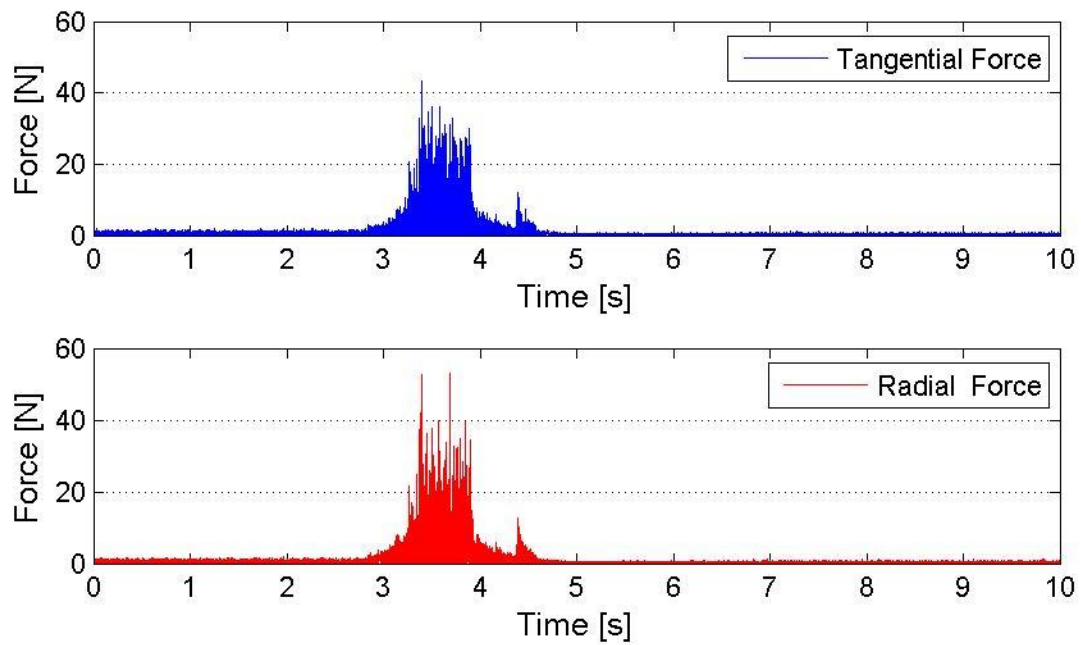


Figure F-178: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

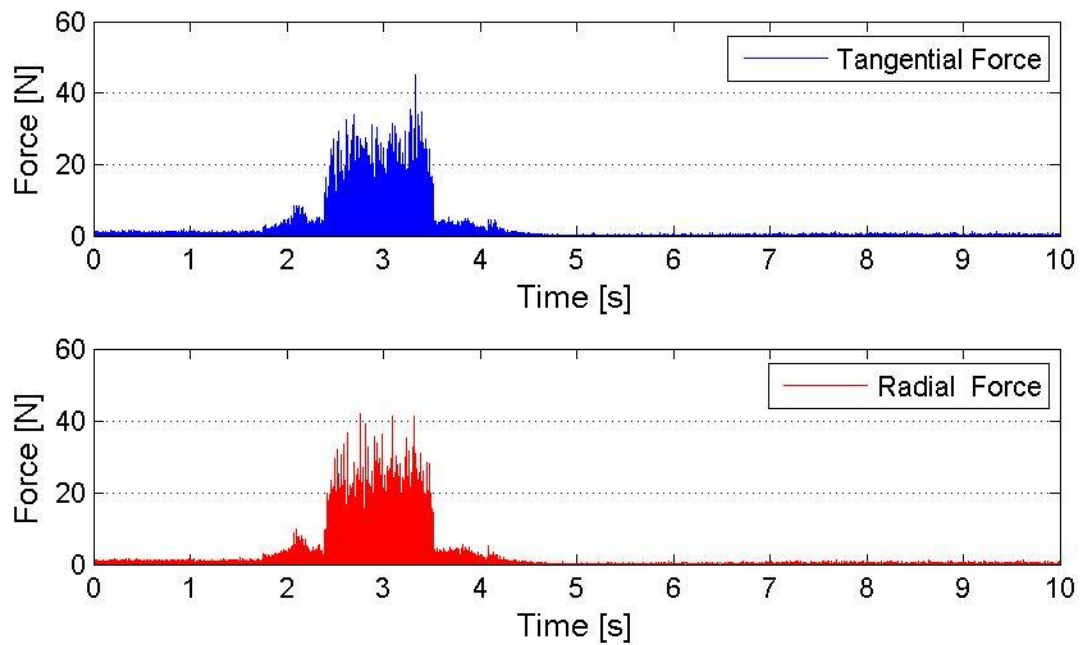


Figure F-179: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

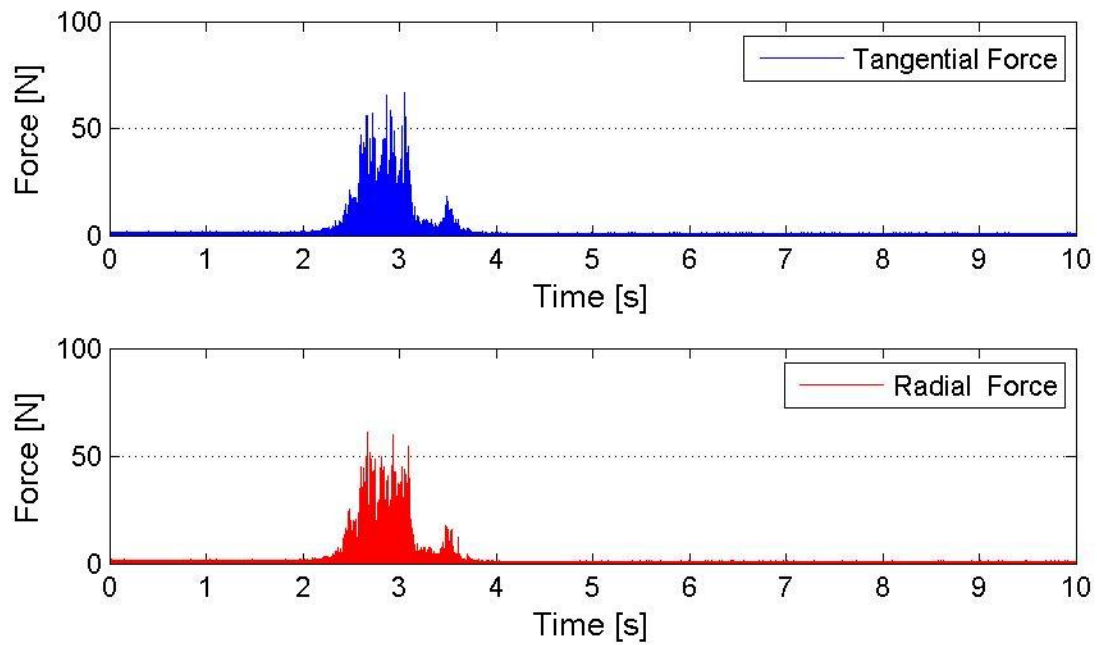


Figure F-180: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

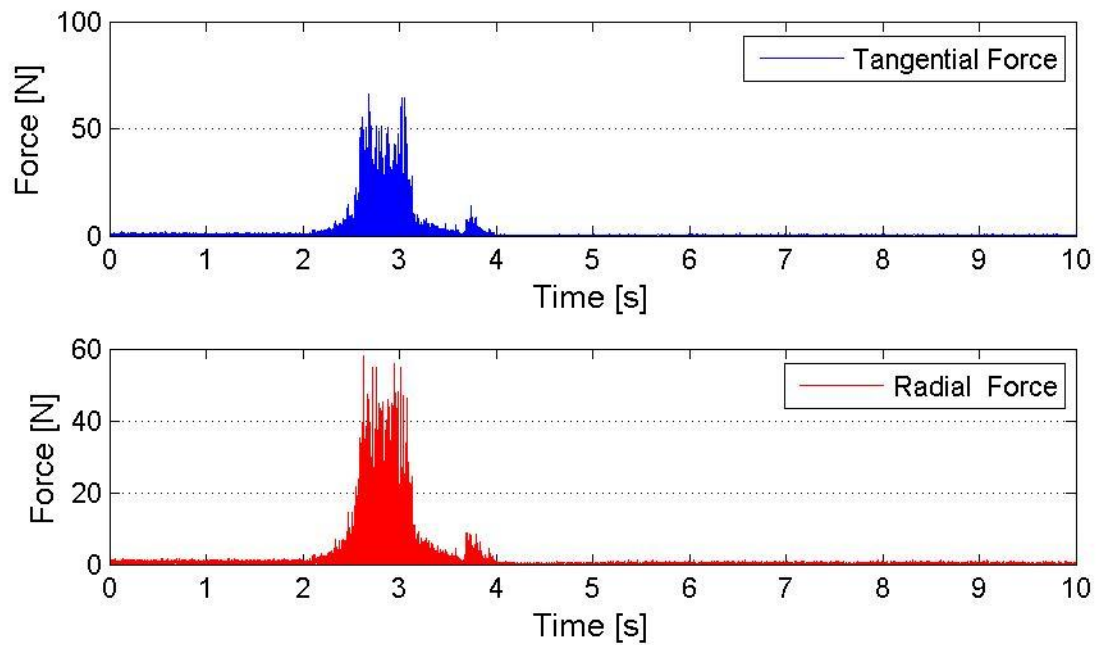


Figure F-181: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

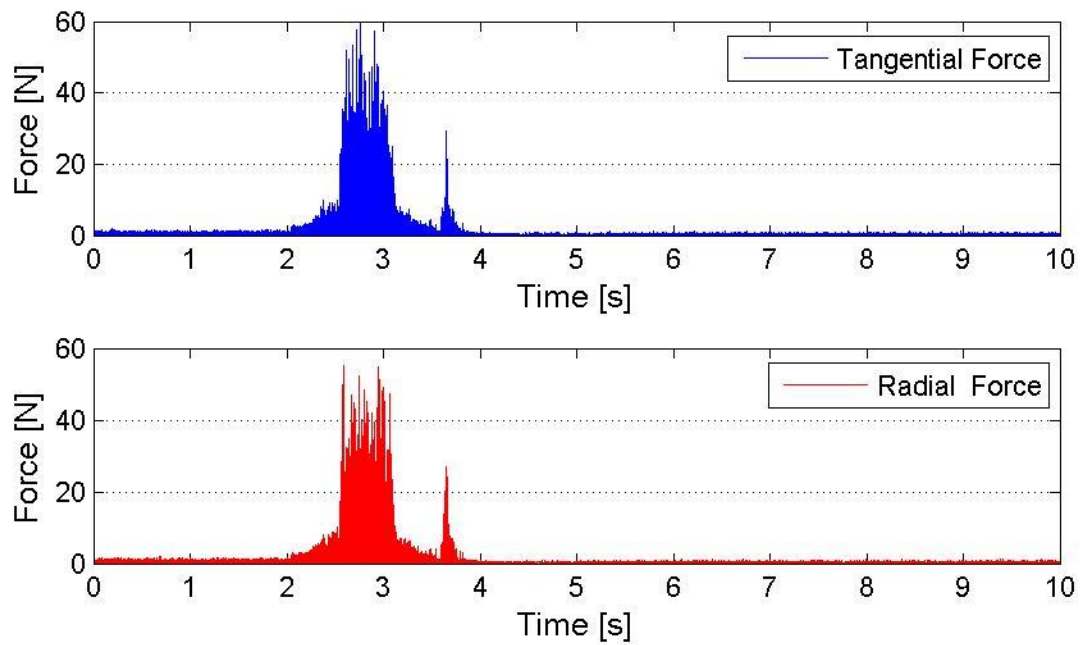


Figure F-182: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

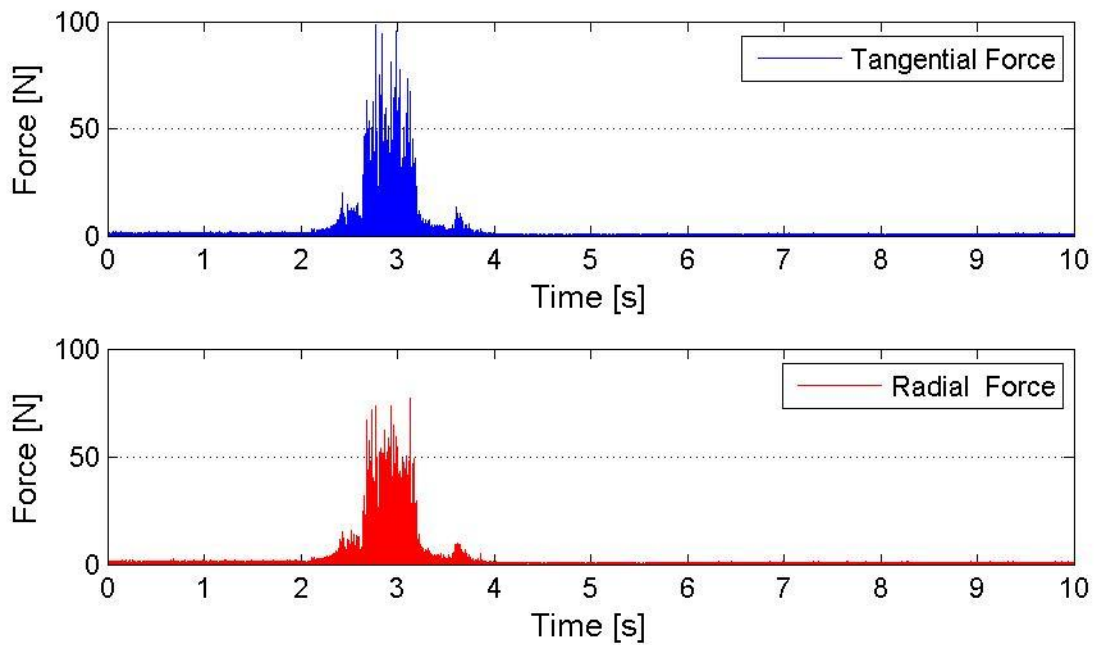


Figure F-183: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

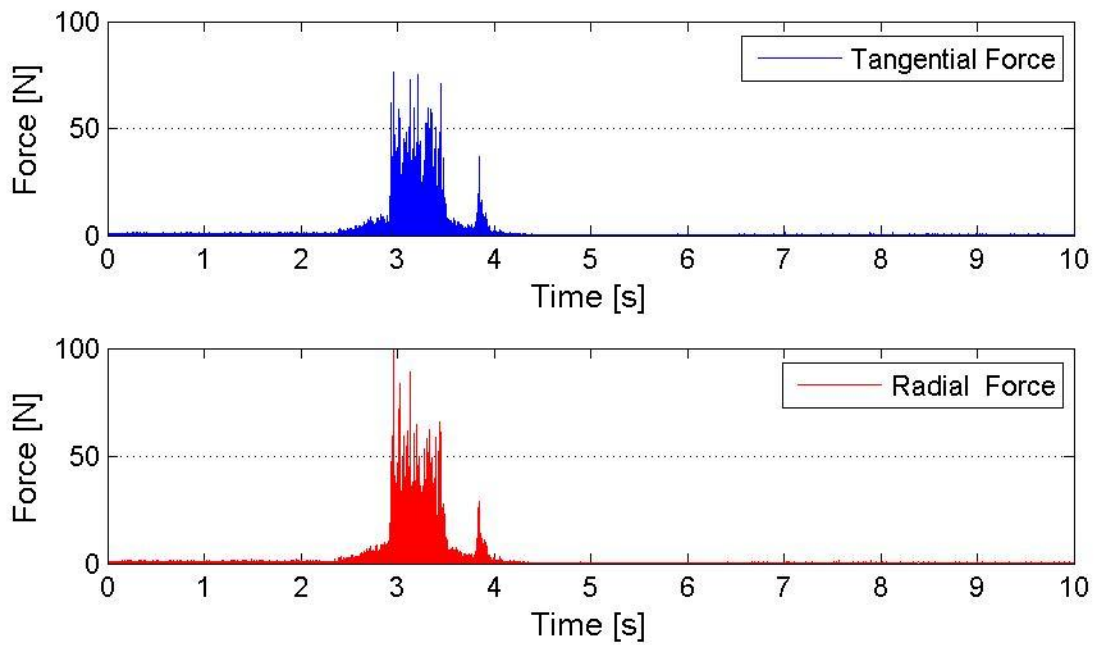


Figure F-184: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

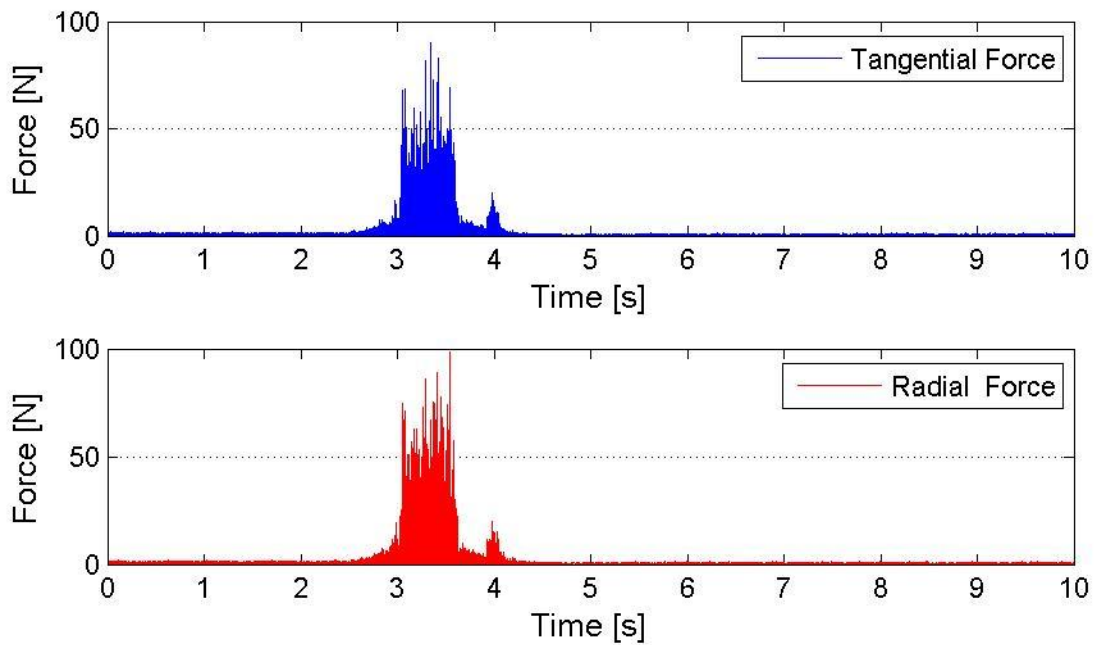


Figure F-185: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

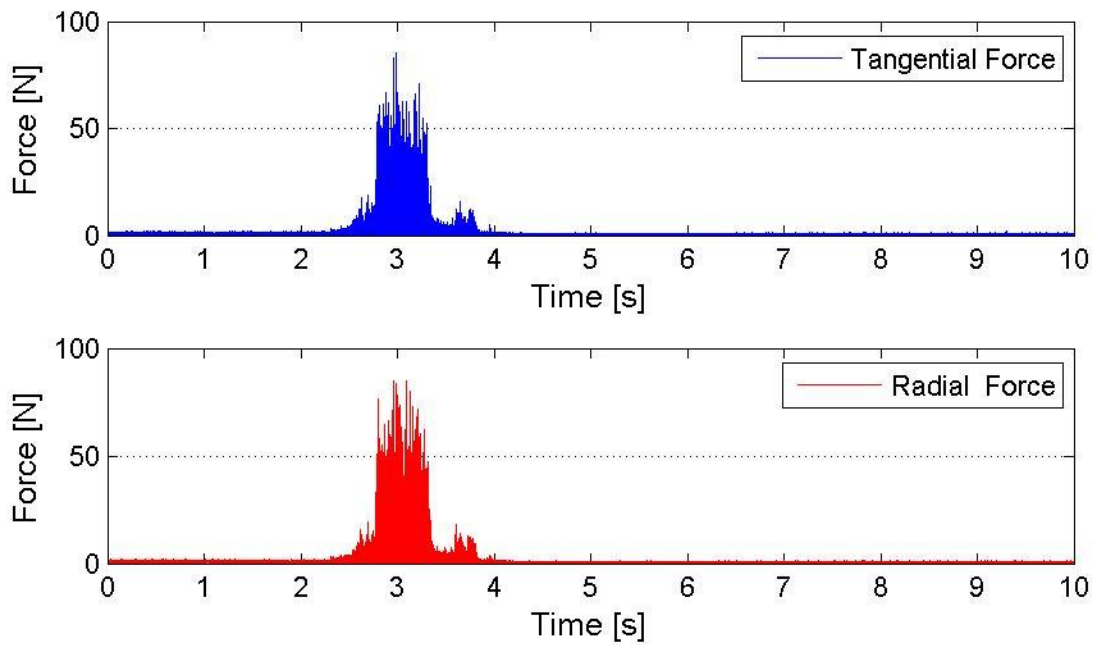


Figure F-186: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

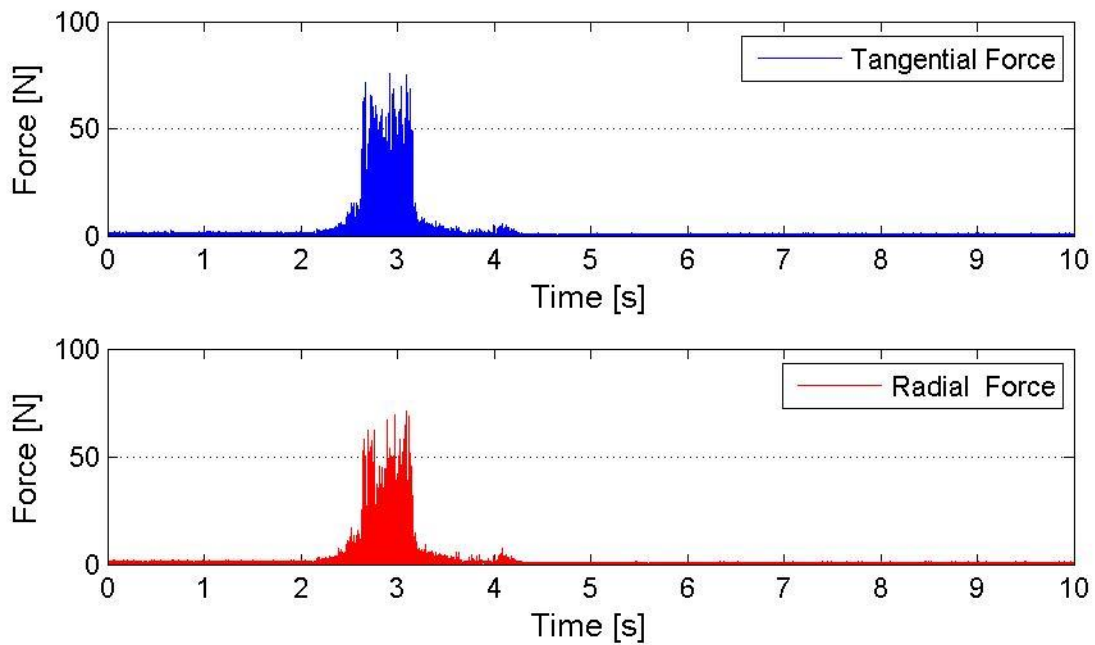


Figure F-187: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

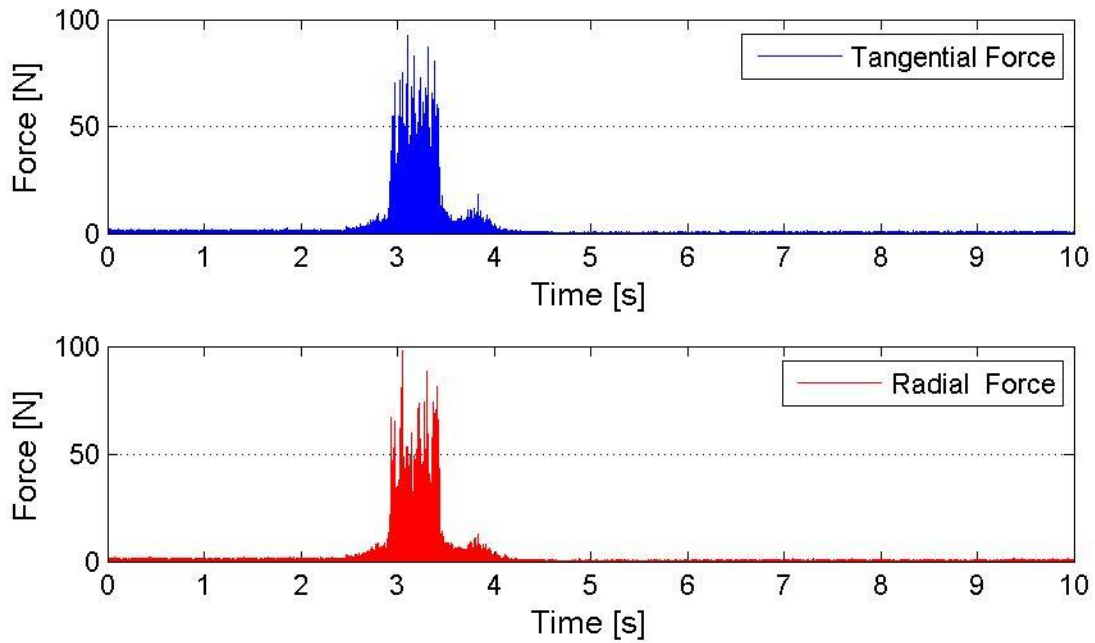


Figure F-188: Tangential and radial cutting force of AAC at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

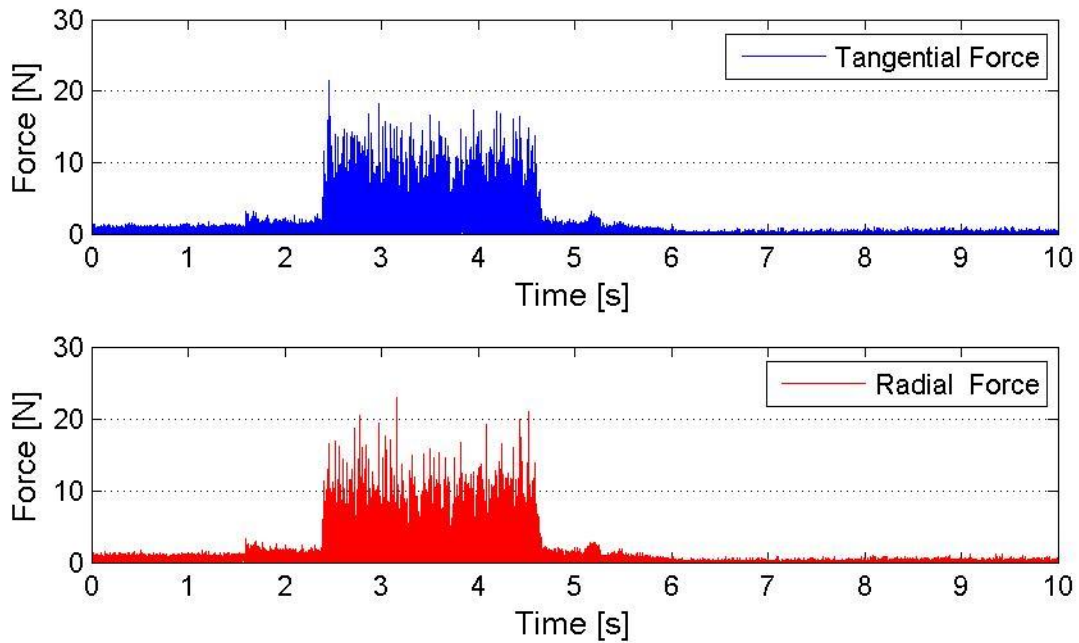


Figure F-189: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

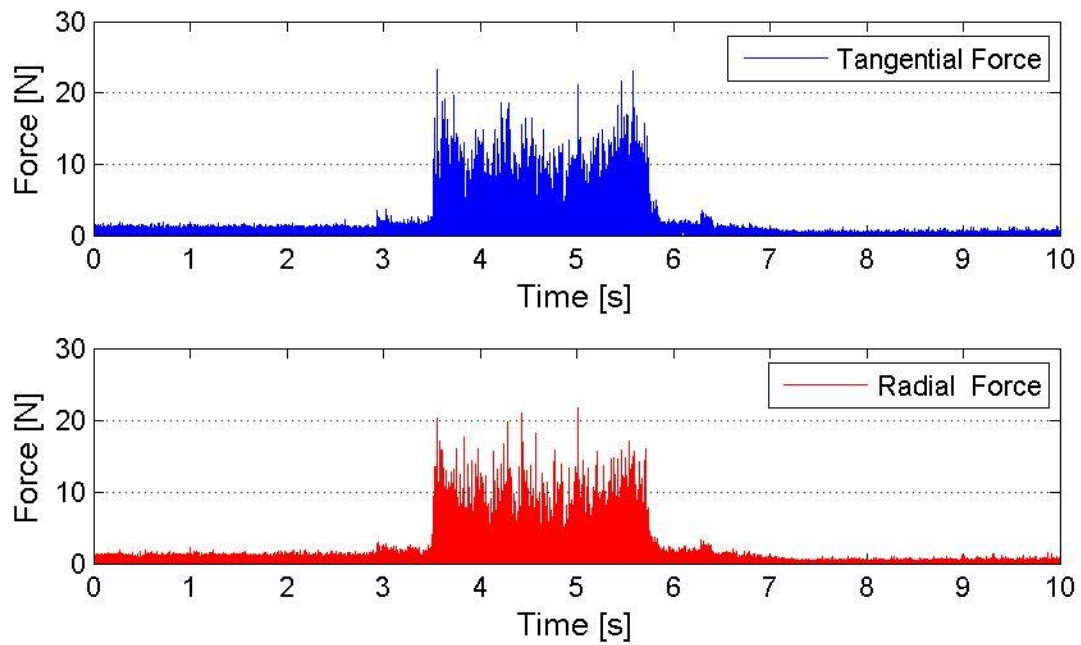


Figure F-190: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

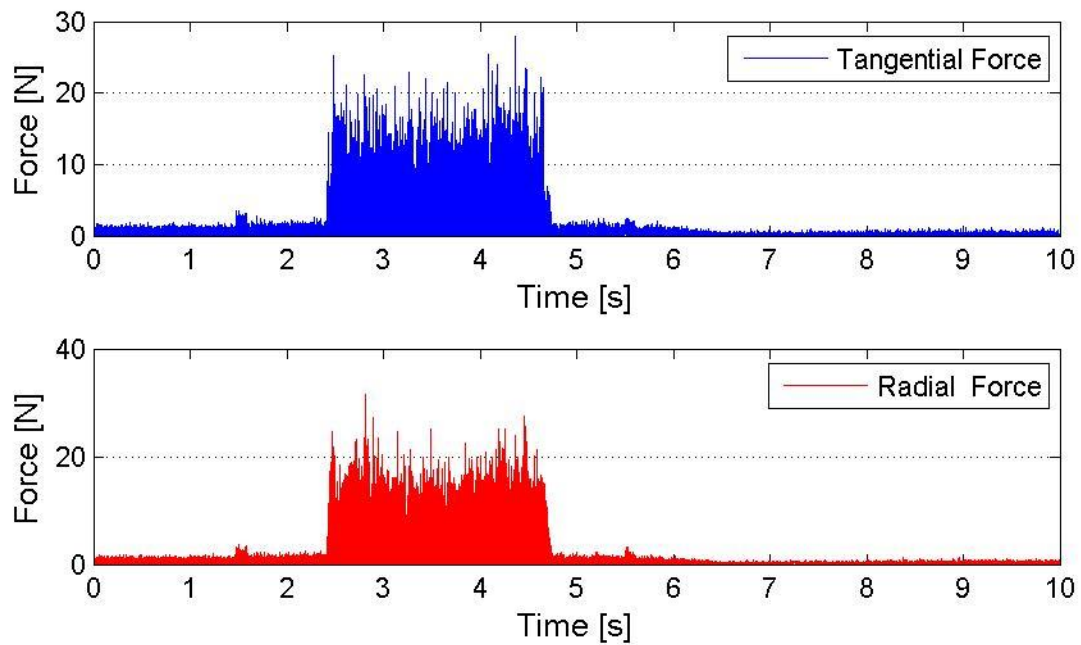


Figure F-191: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

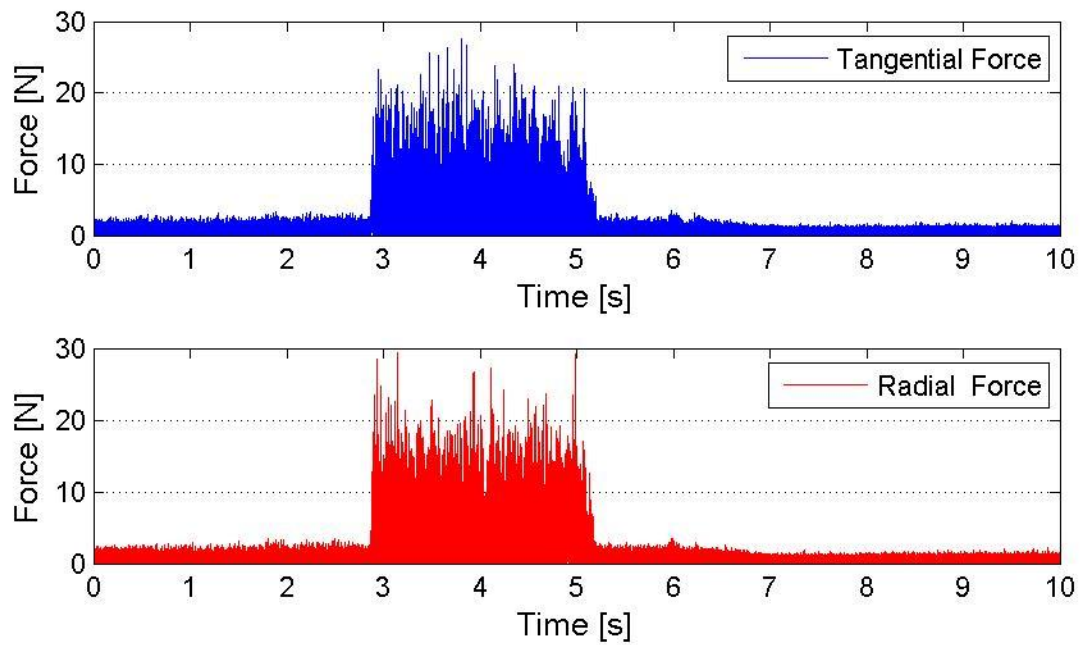


Figure F-192: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

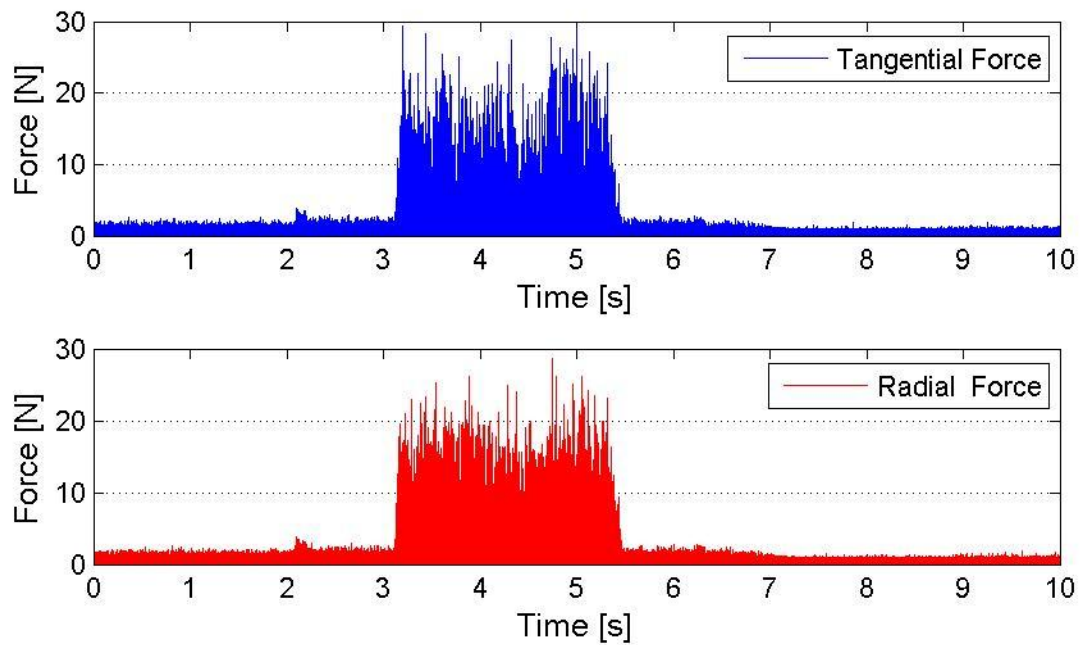


Figure F-193: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

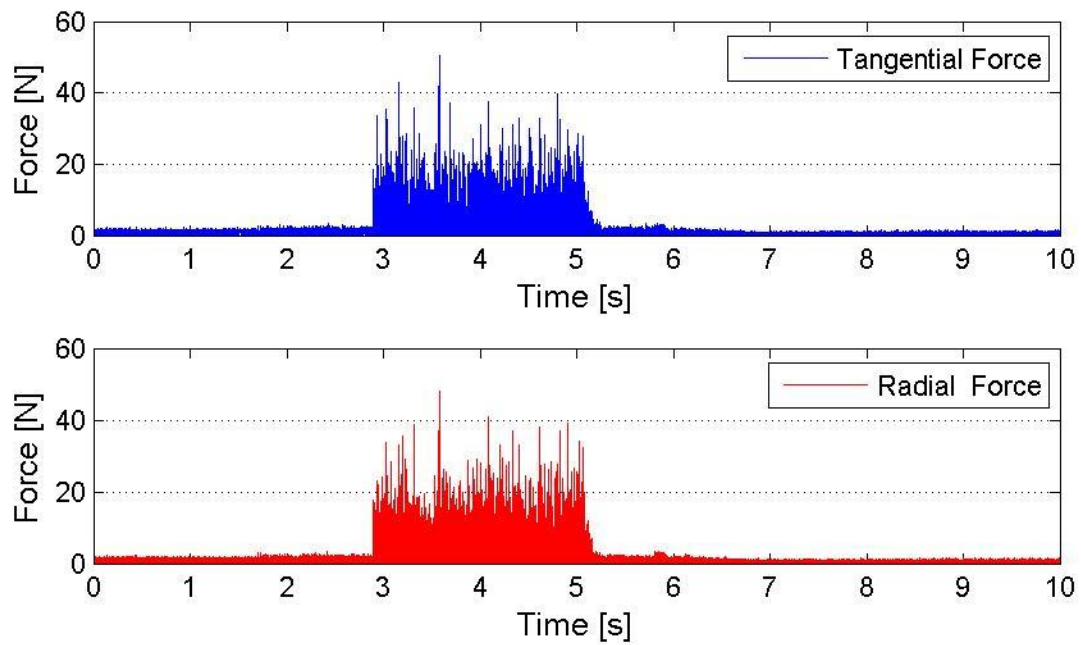


Figure F-194: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

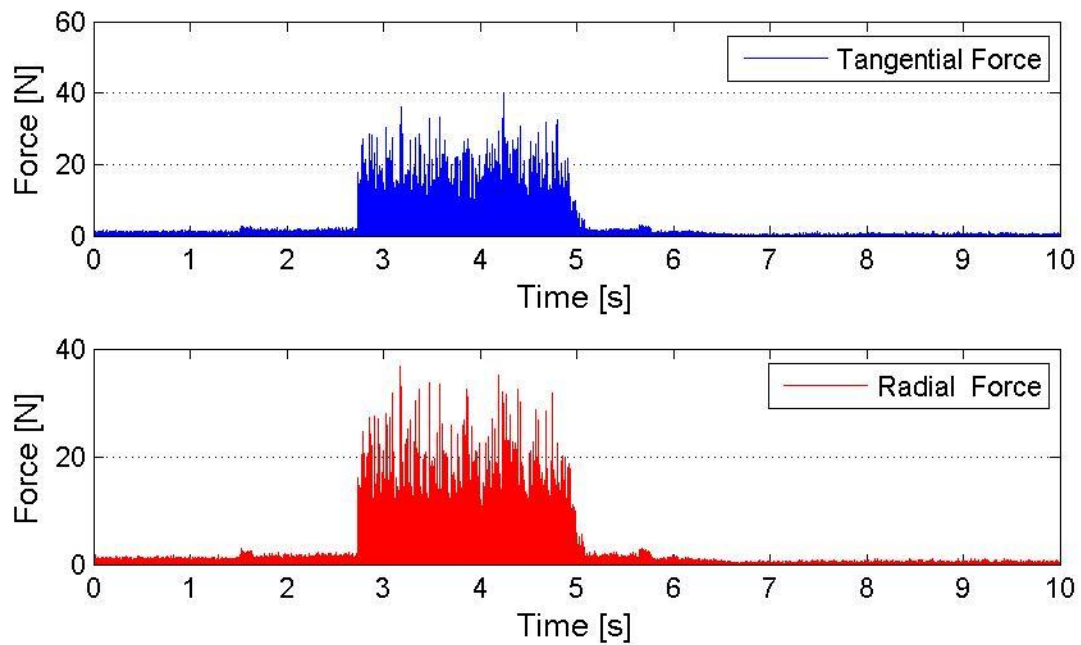


Figure F-195: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

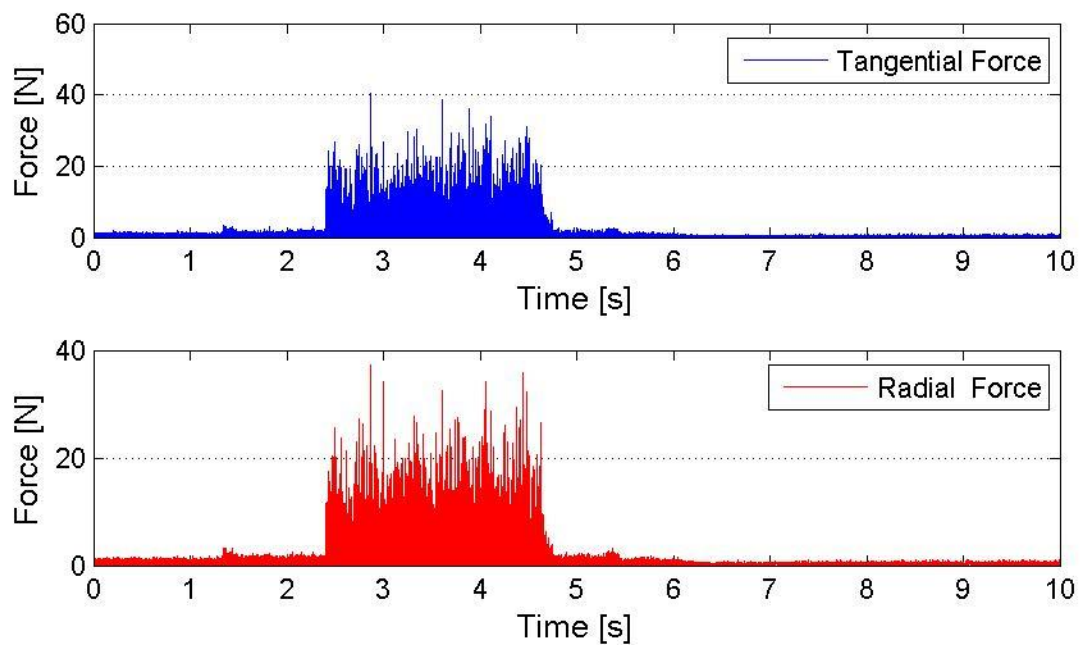


Figure F-196: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

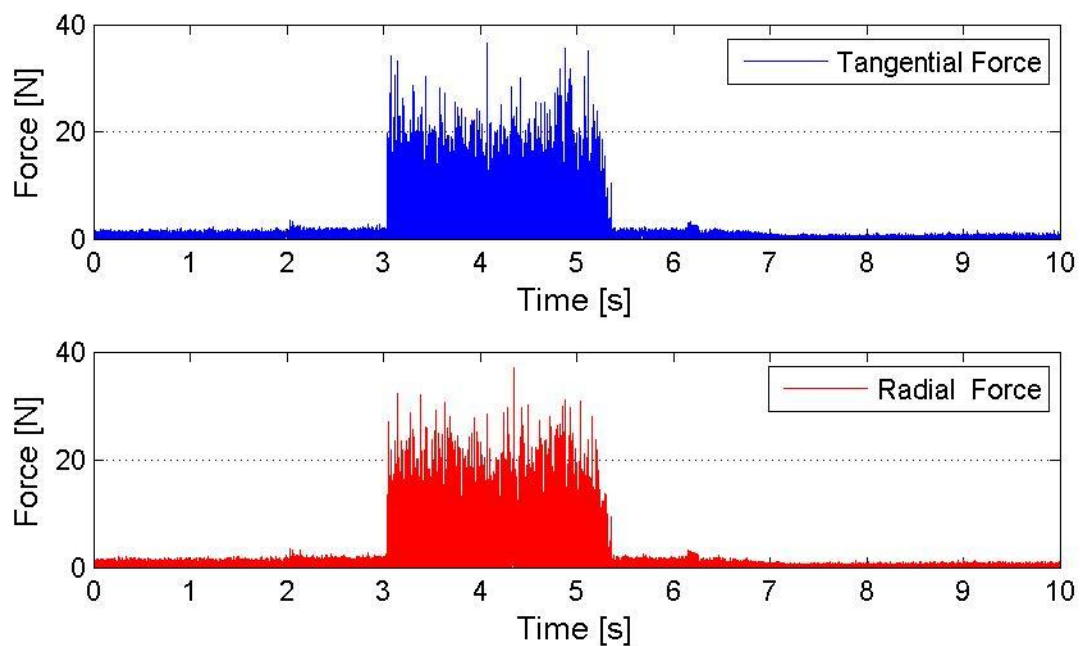


Figure F-197: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

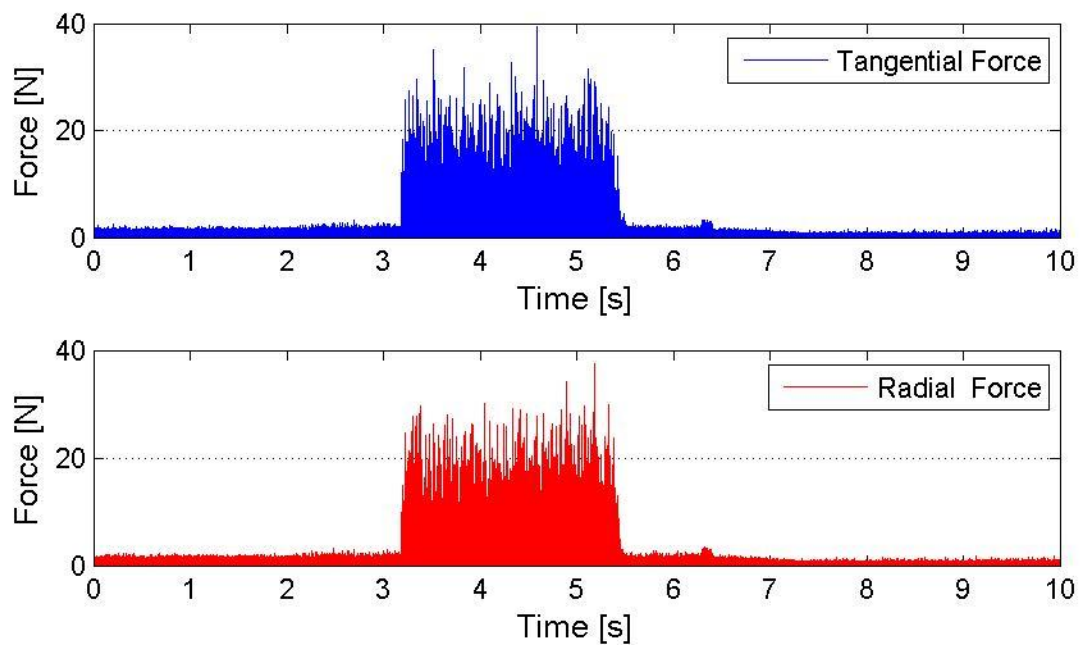


Figure F-198: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

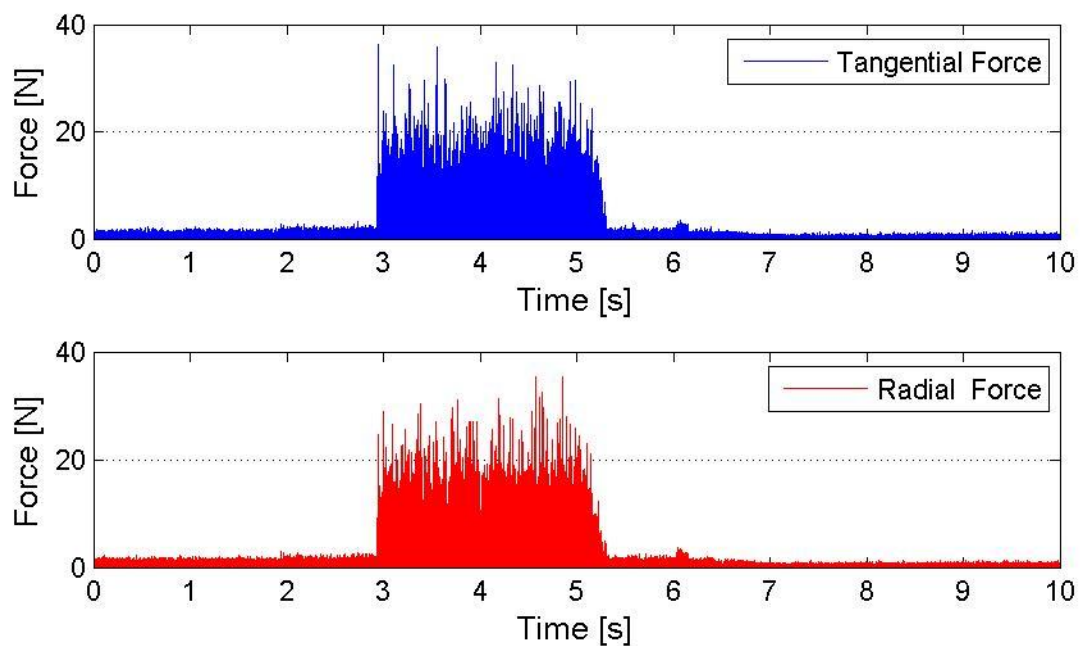


Figure F-199: Tangential and radial cutting force of AAC at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

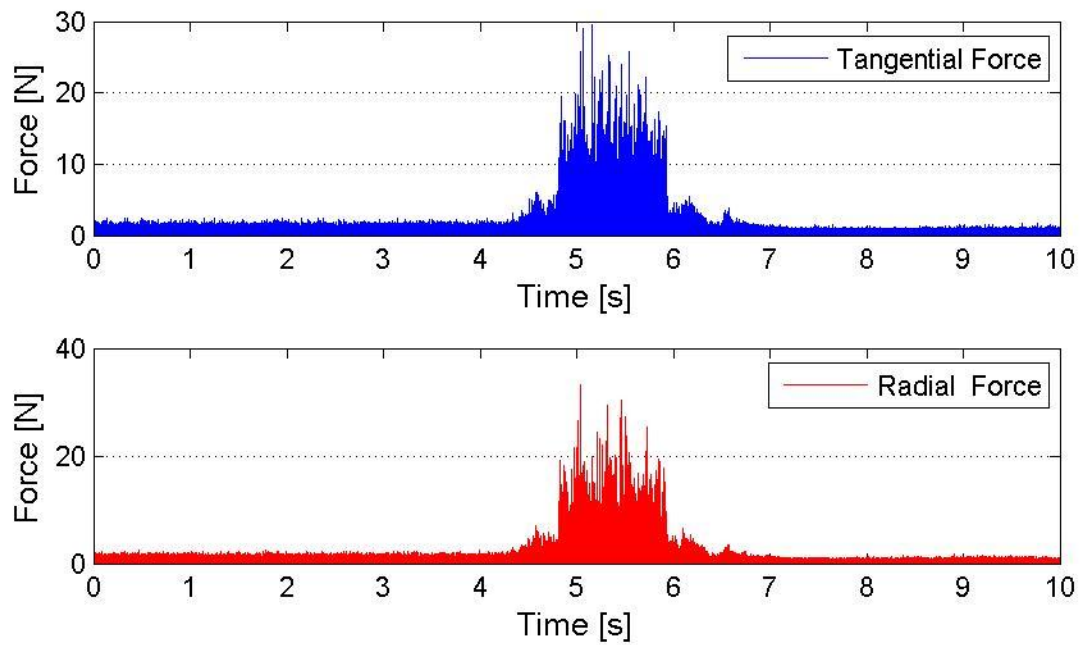


Figure F-200: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

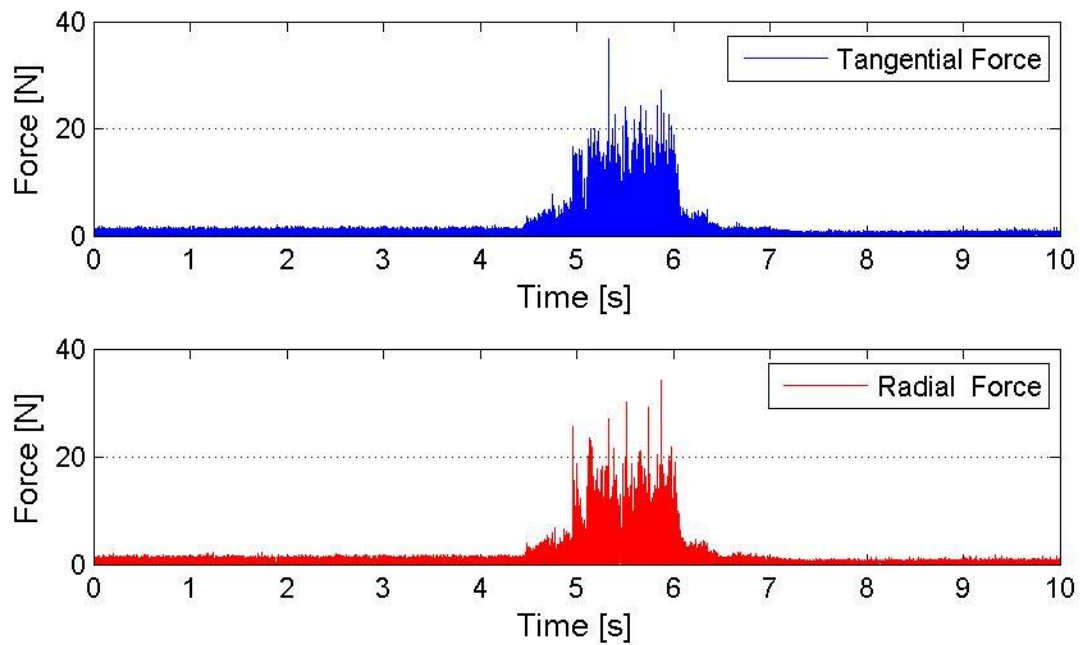


Figure F-201: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

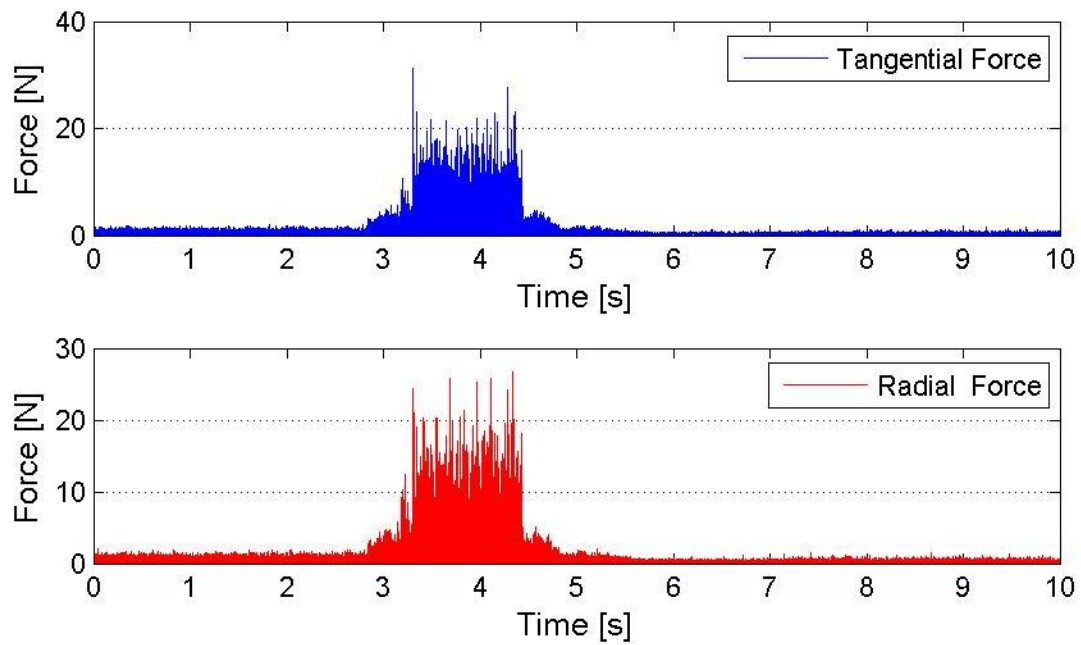


Figure F-202: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

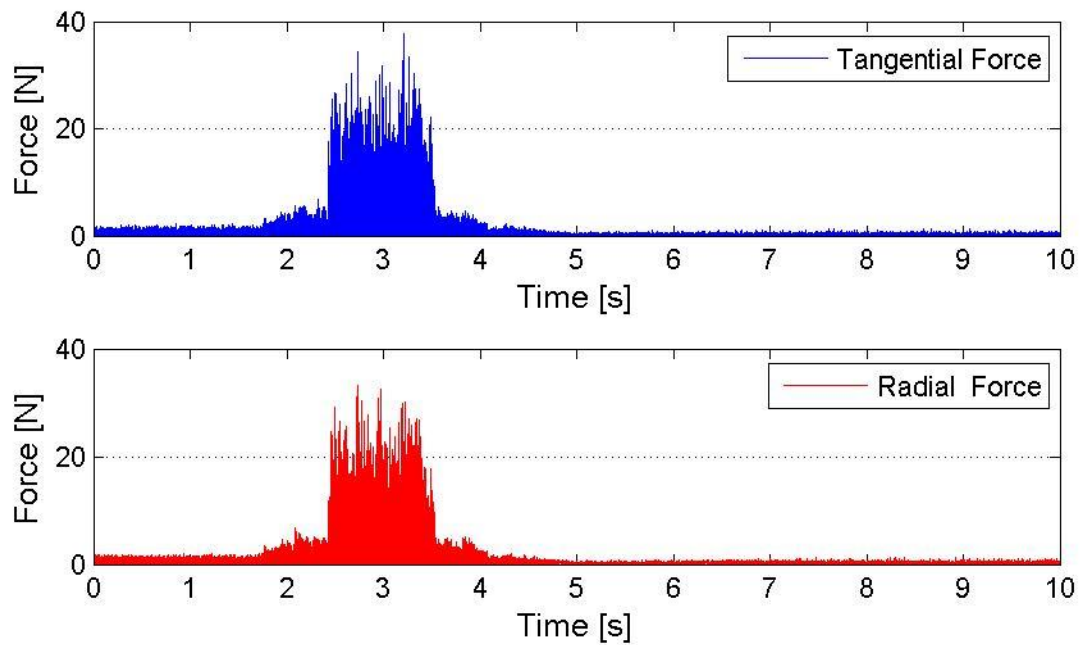


Figure F-203: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

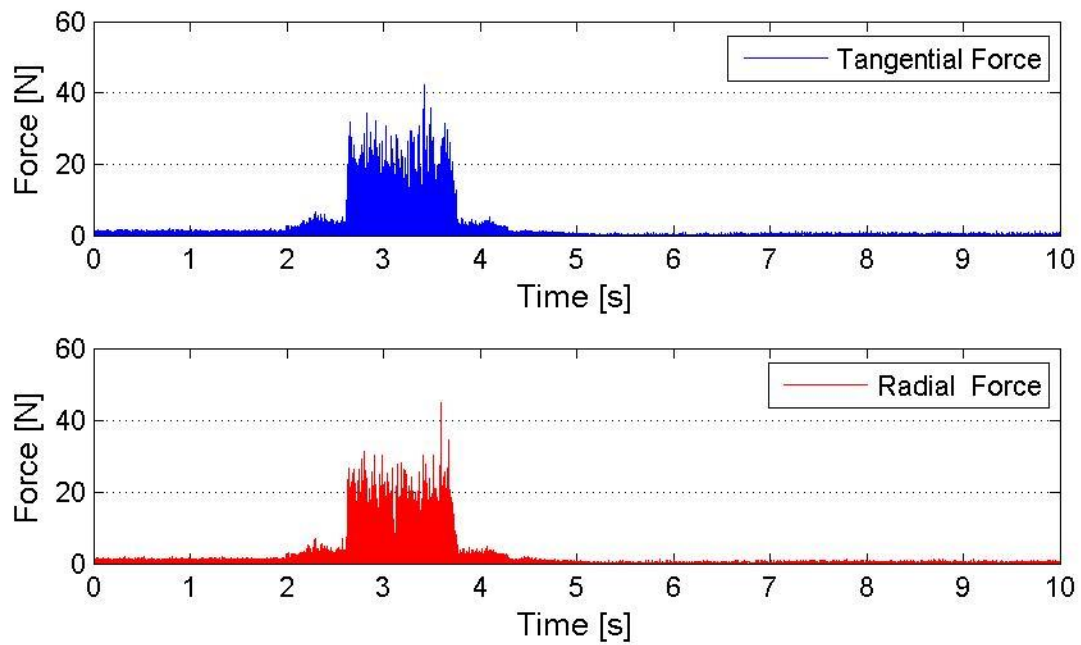


Figure F-204: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

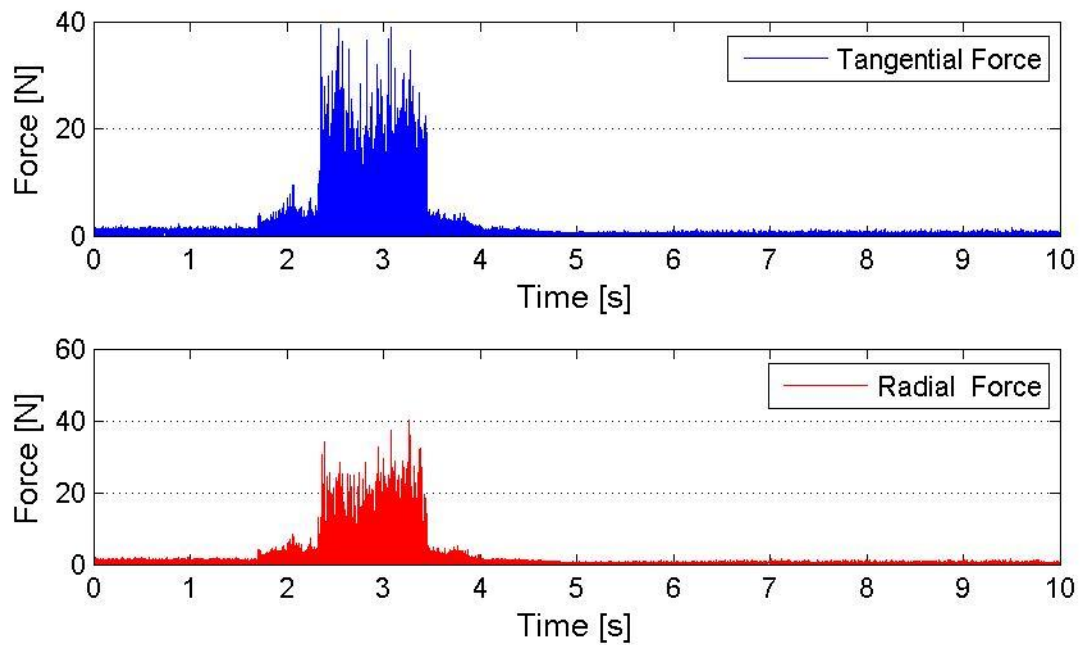


Figure F-205: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

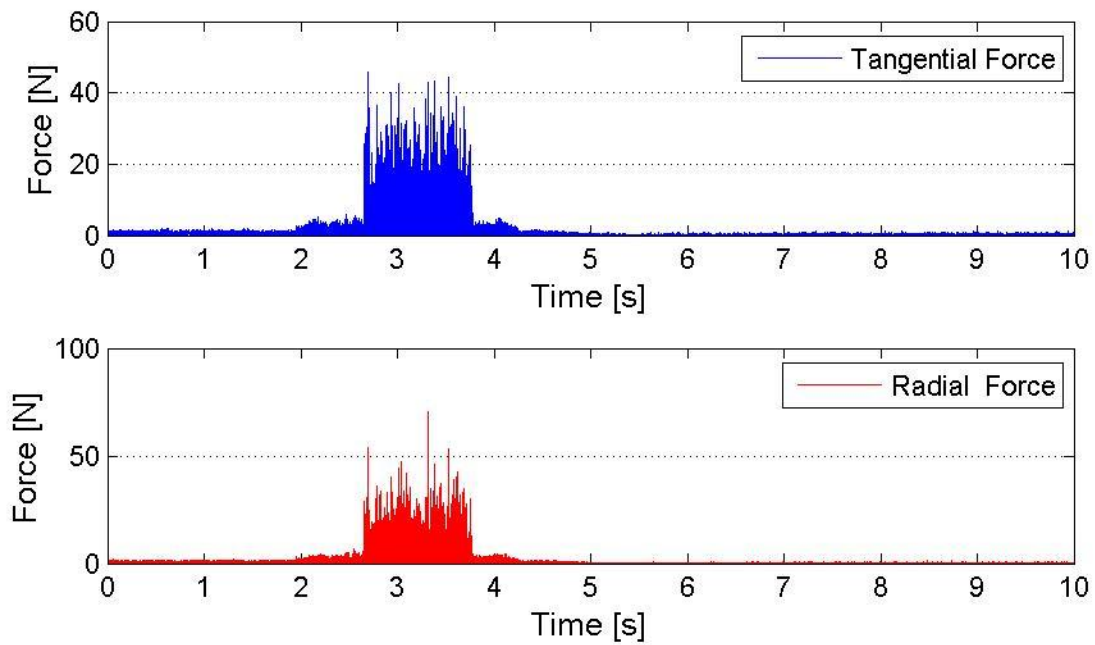


Figure F-206: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

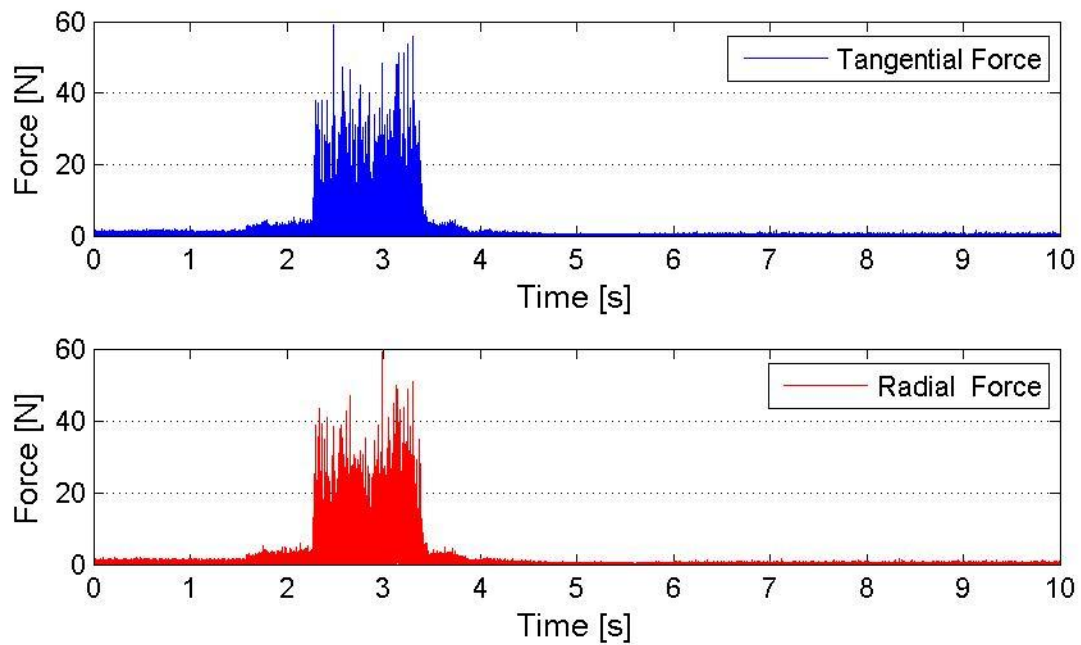


Figure F-207: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

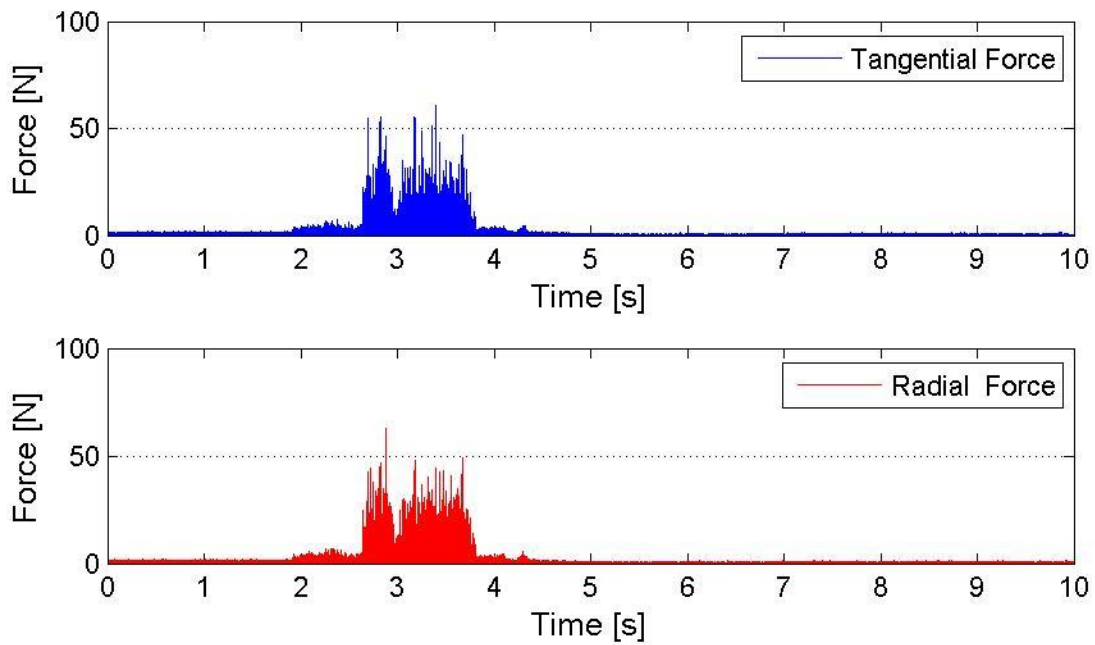


Figure F-208: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

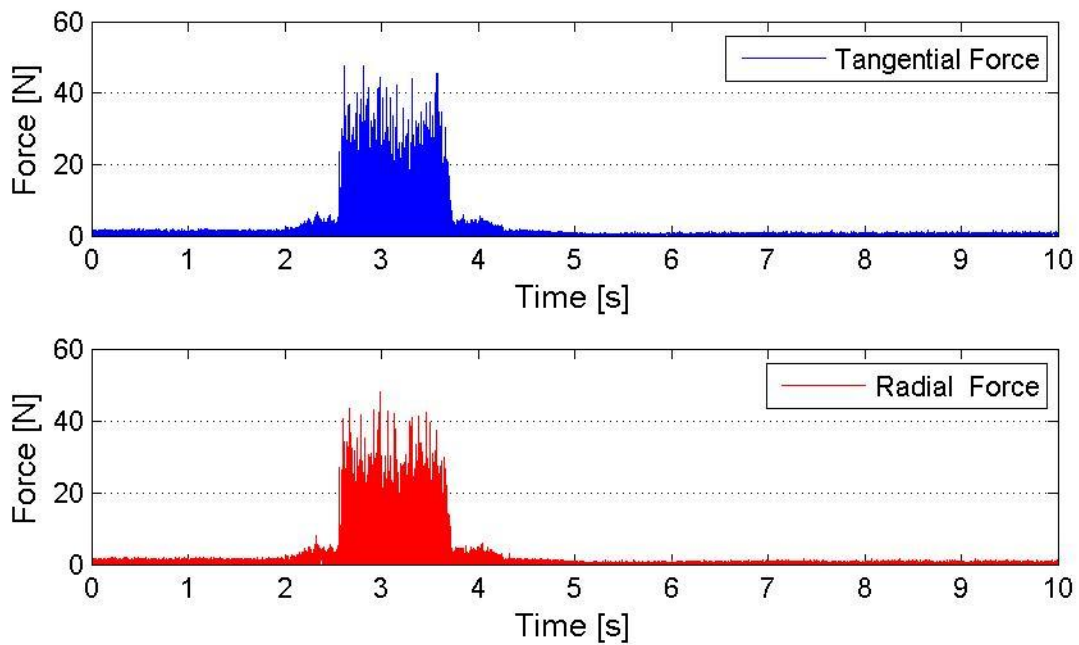


Figure F-209: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

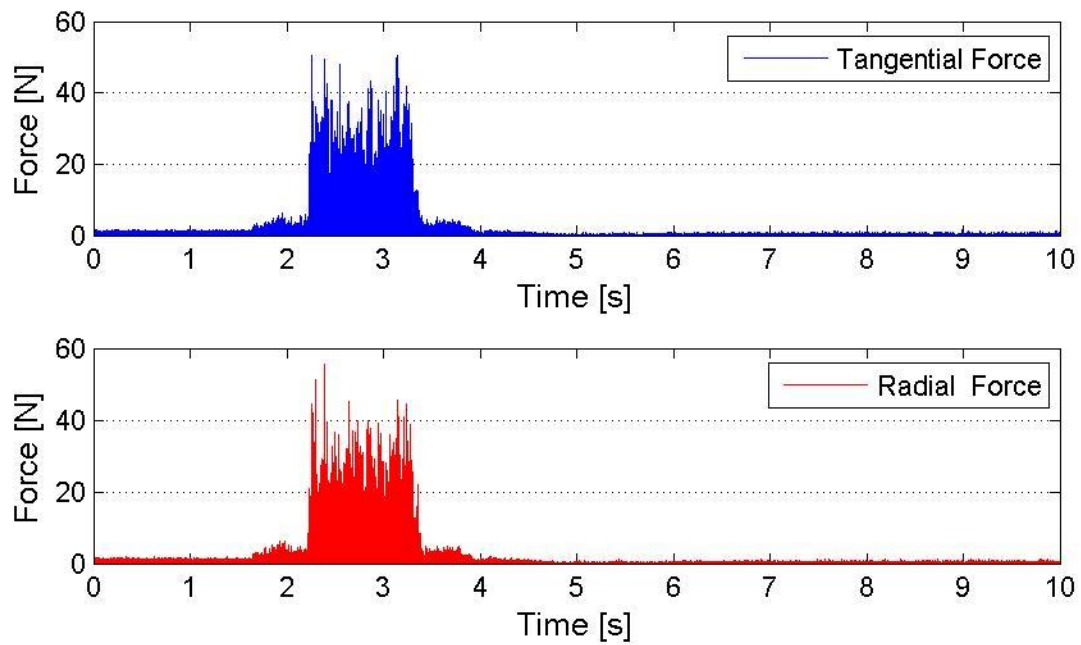


Figure F-210: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

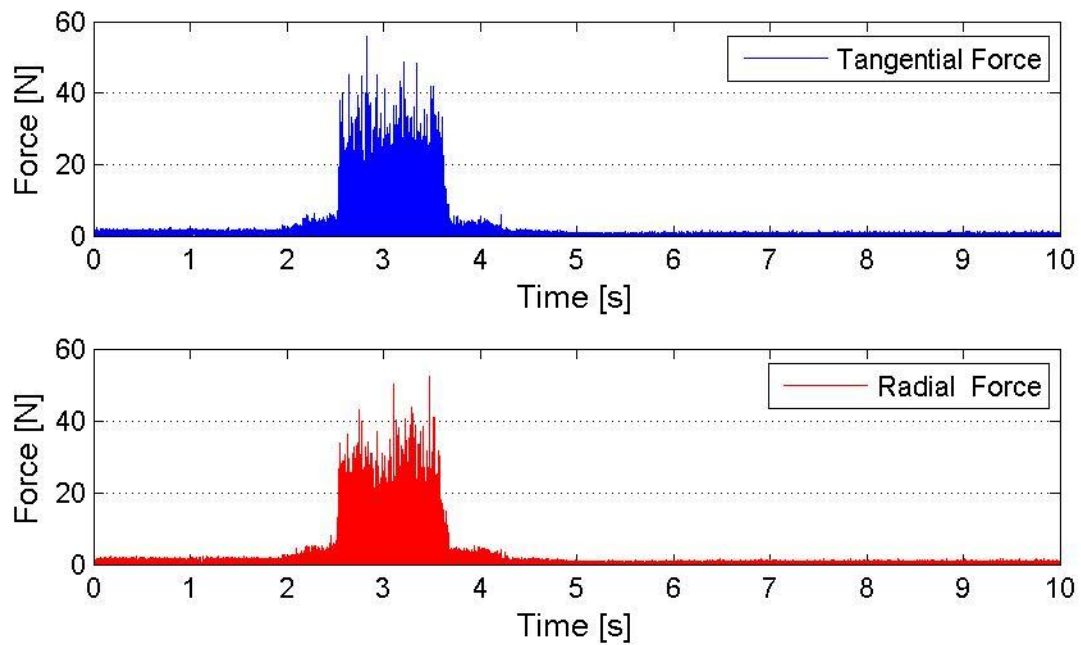


Figure F-211: Tangential and radial cutting force of AAC at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

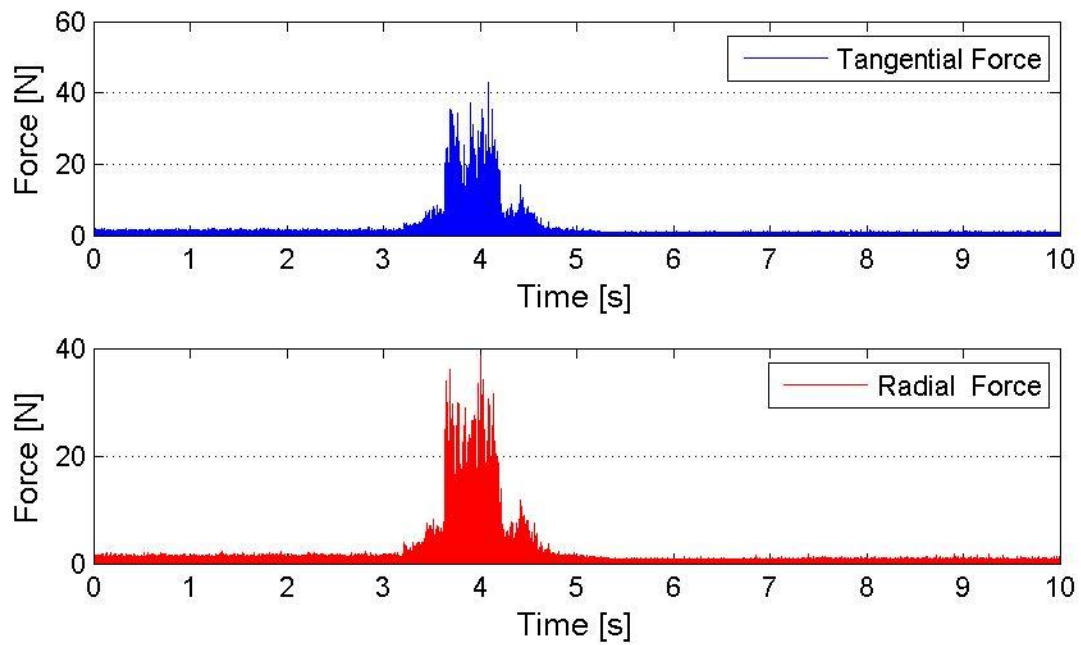


Figure F-212: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

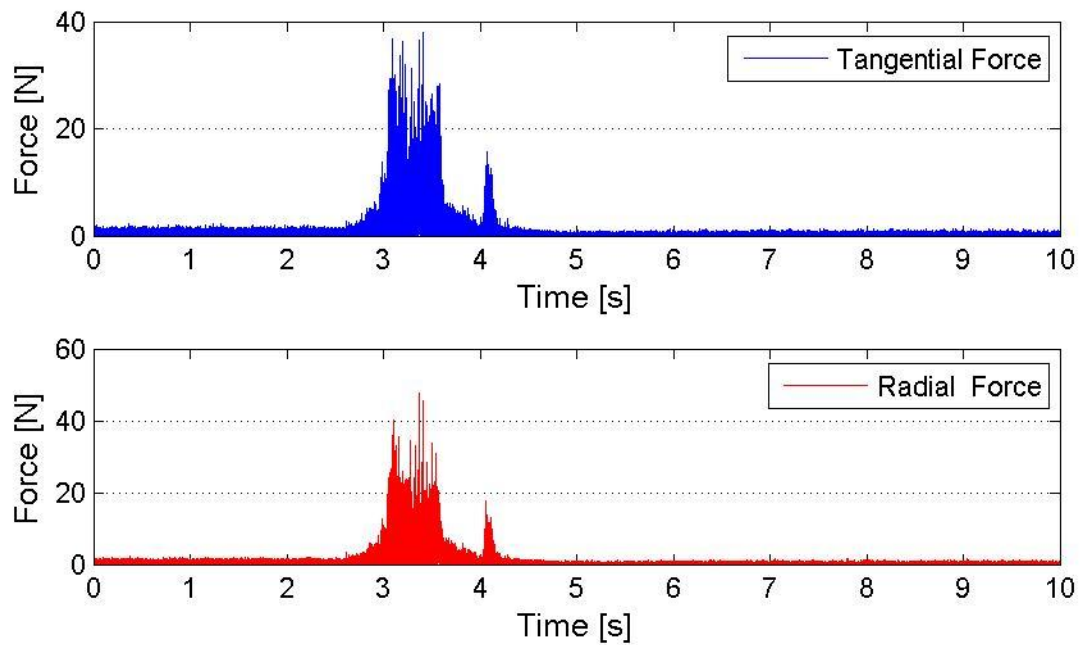


Figure F-213: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

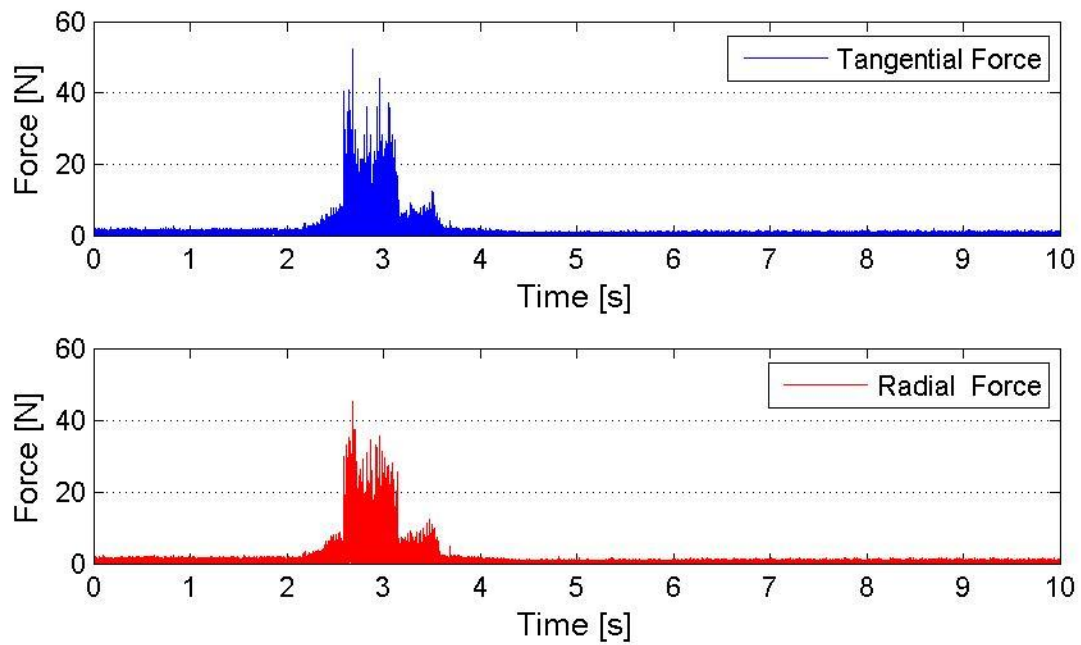


Figure F-214: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

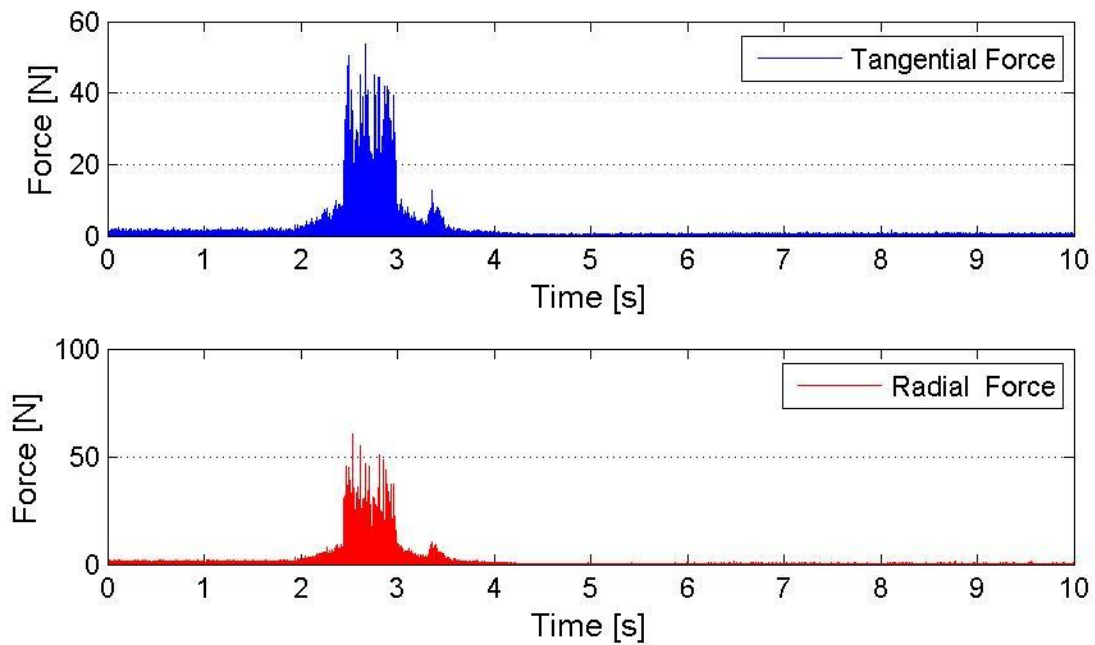


Figure F-215: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

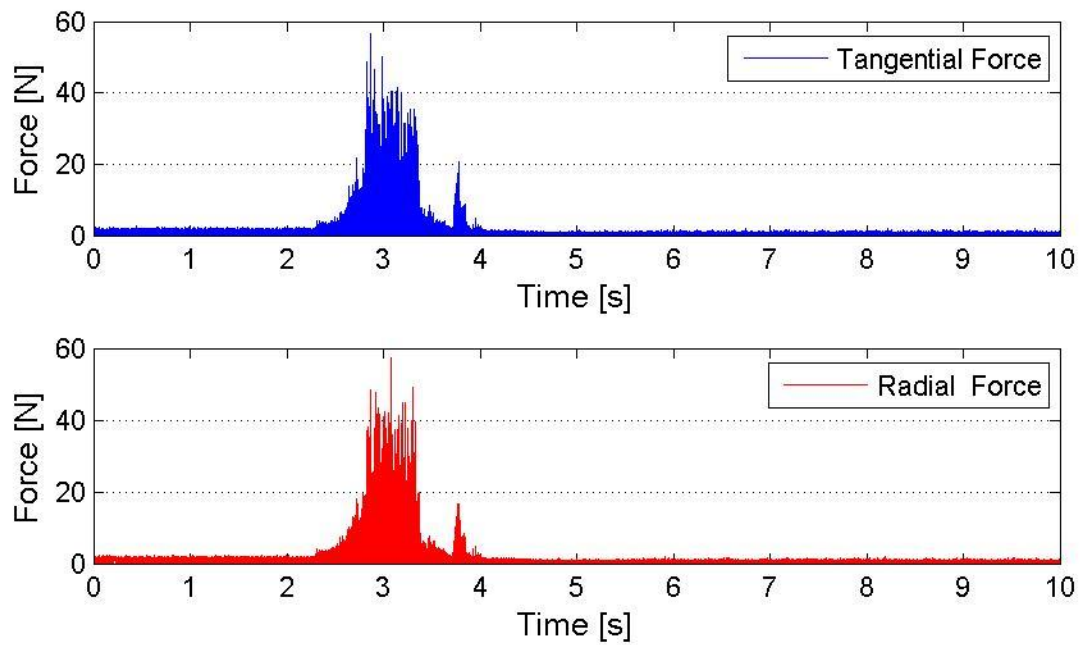


Figure F-216: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

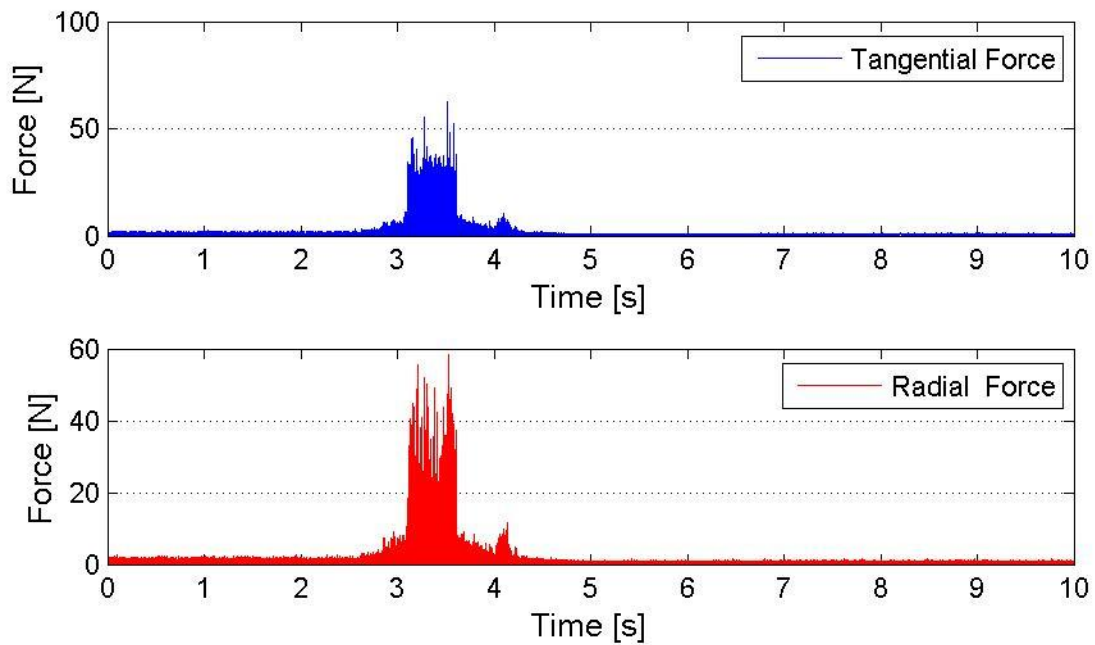


Figure F-217: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

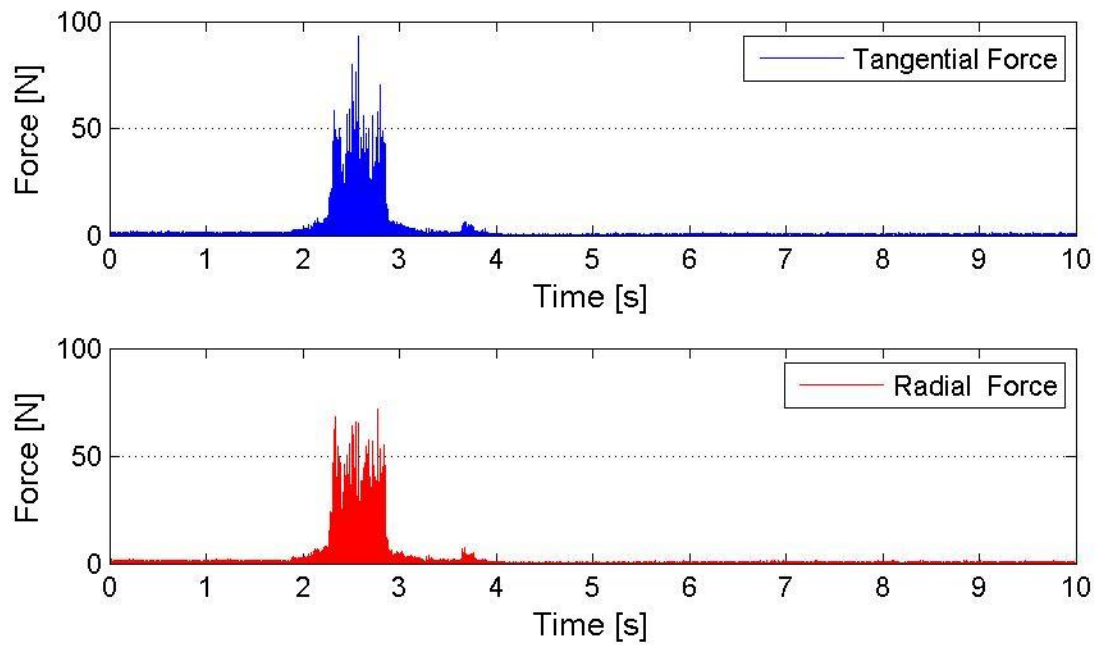


Figure F-218: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

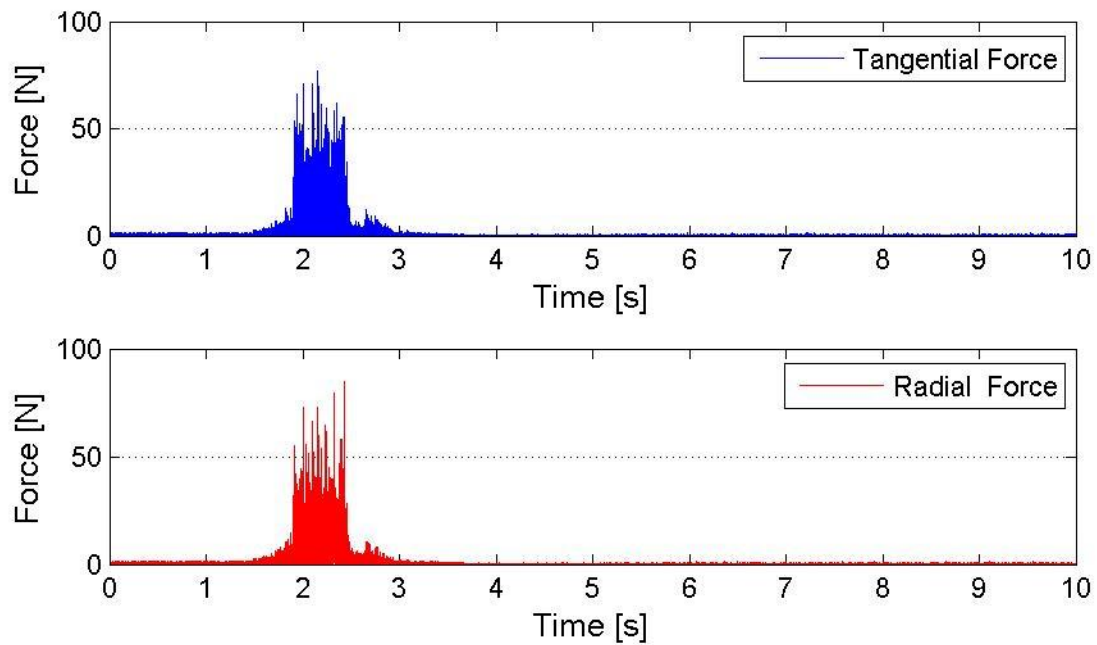


Figure F-219: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

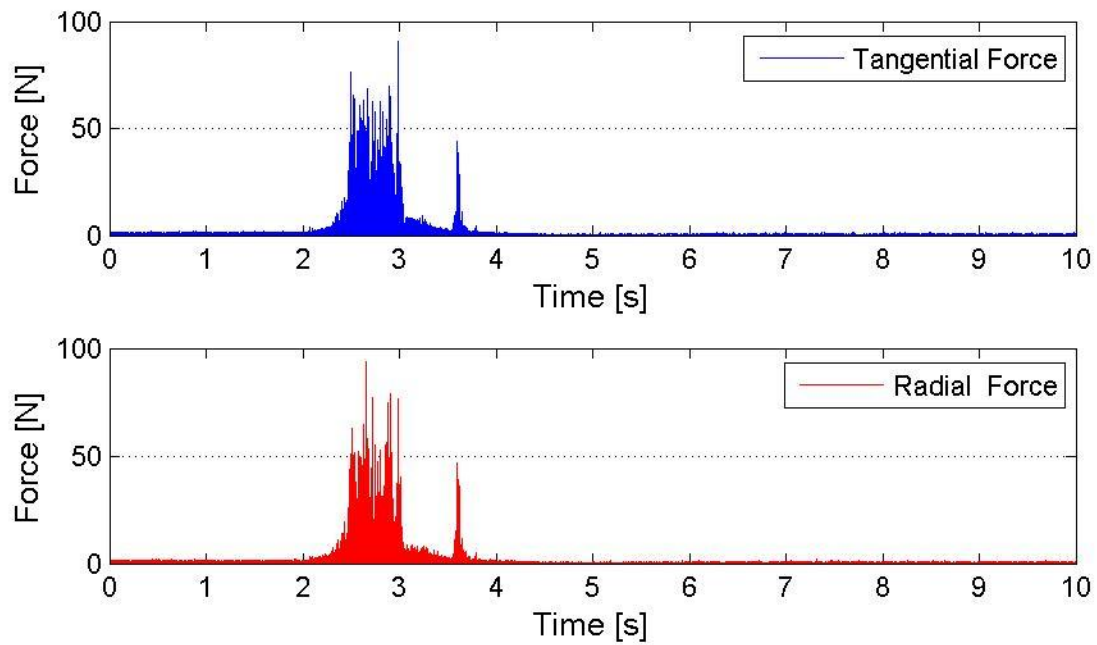


Figure F-220: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

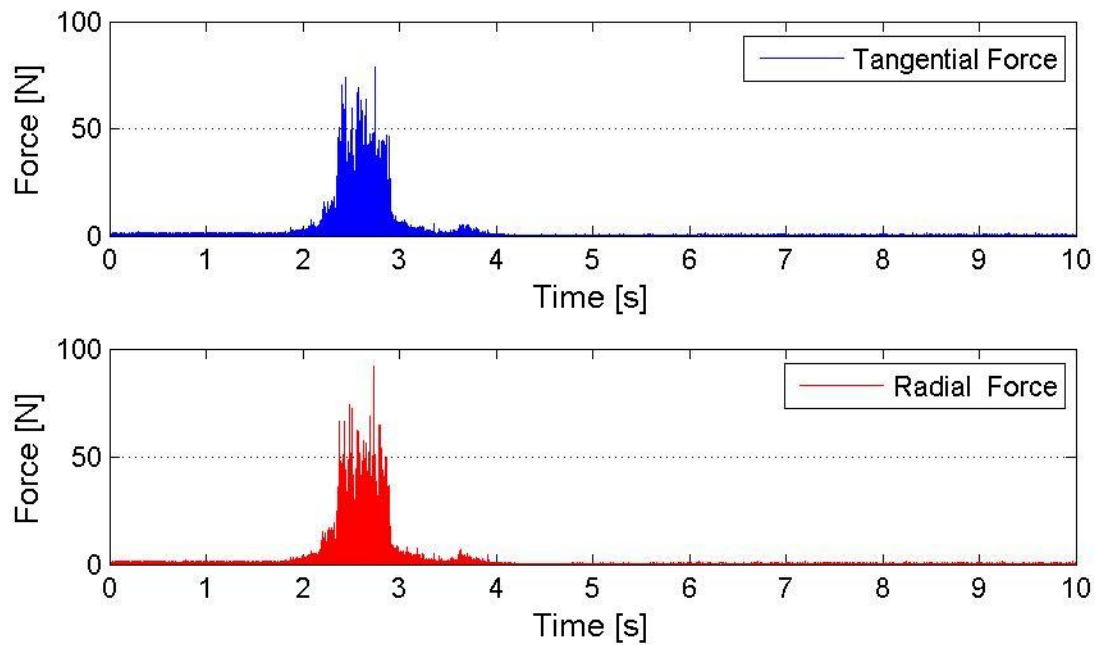


Figure F-221: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

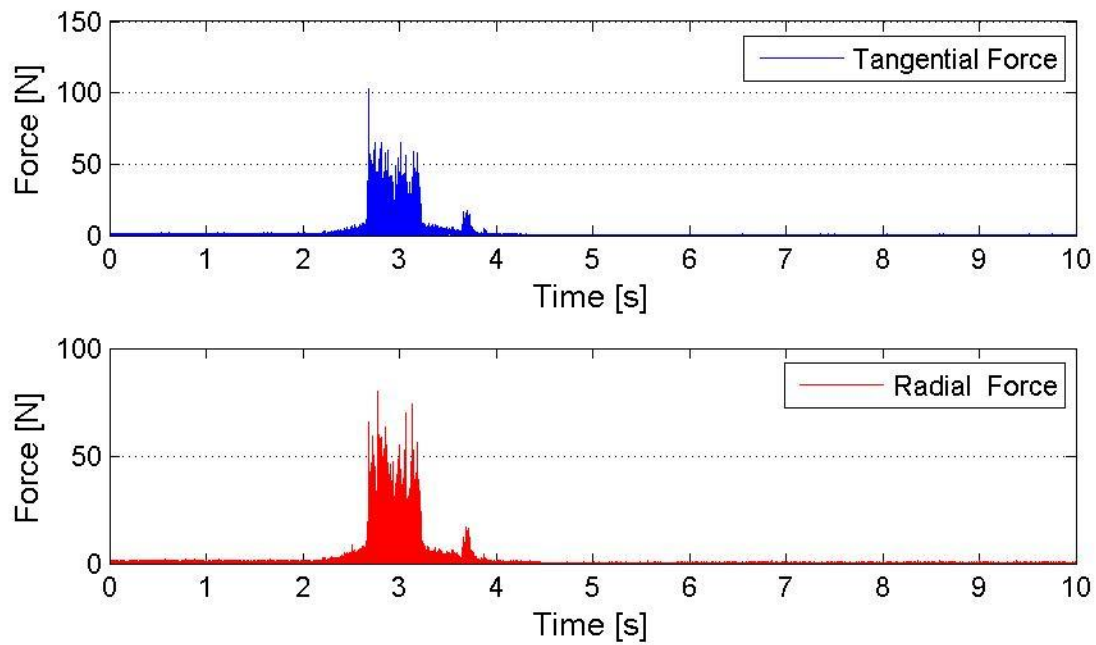


Figure F-222: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

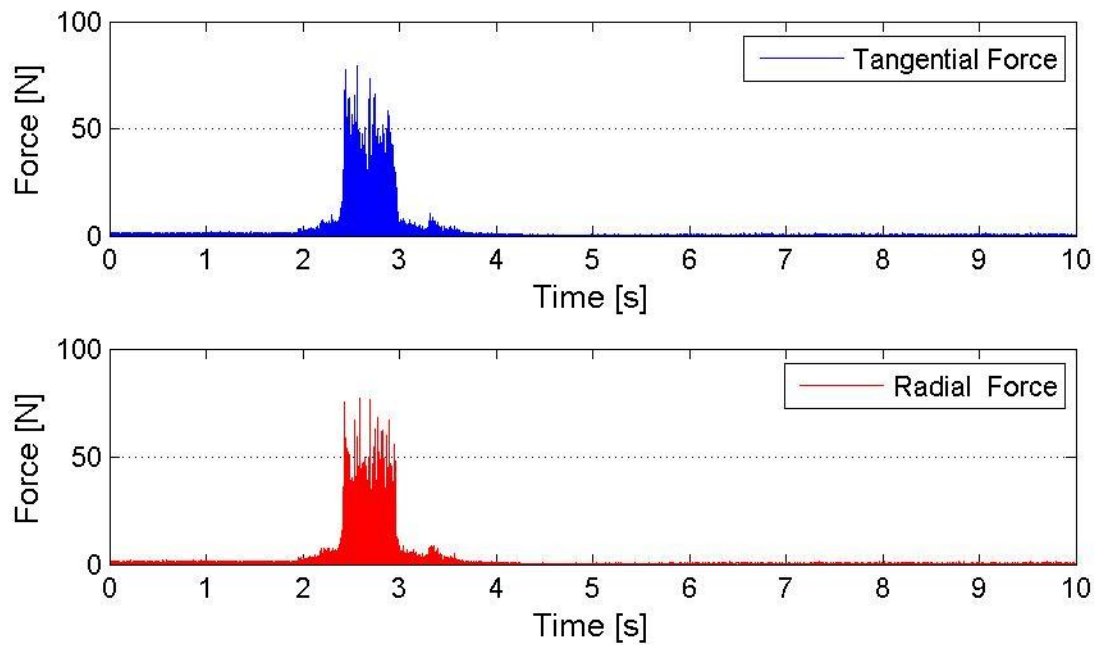


Figure F-223: Tangential and radial cutting force of AAC at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

Appendix: G. Cfoam cutting force DOE results

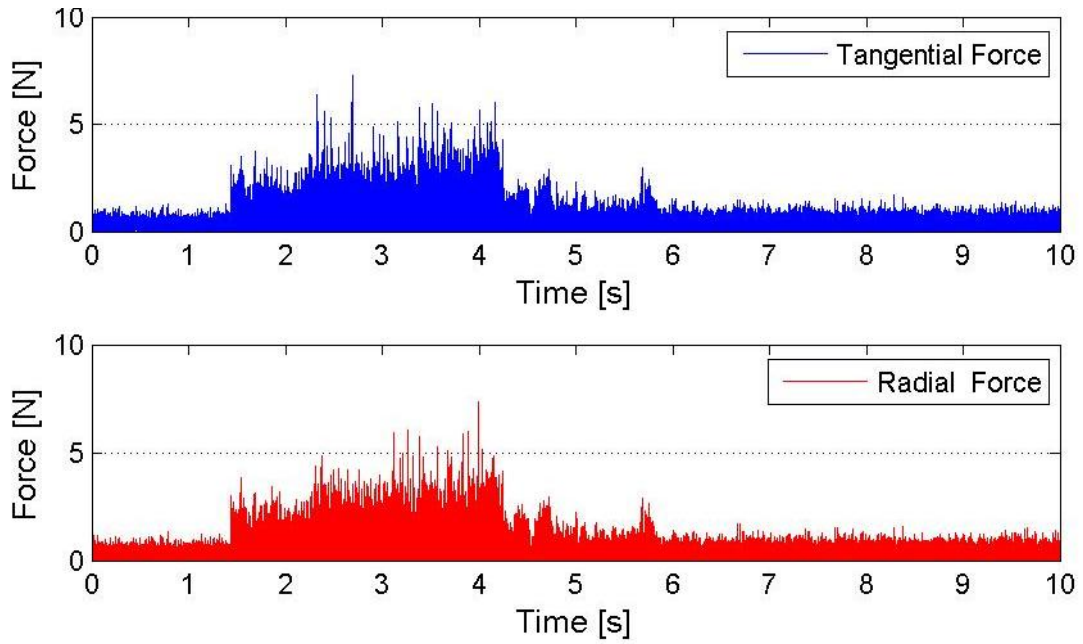


Figure G-224: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

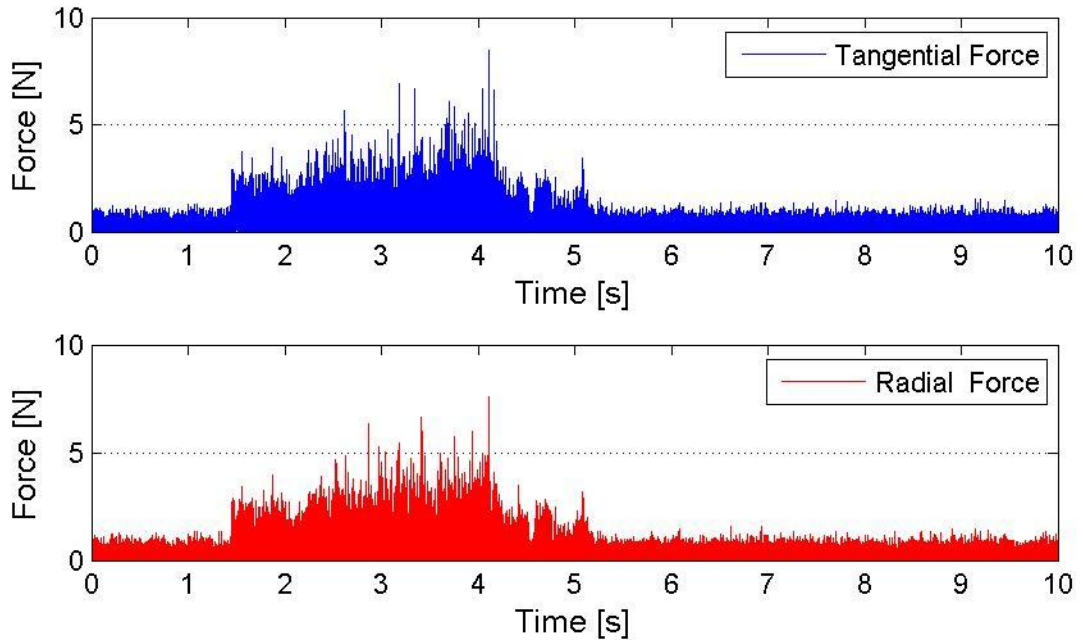


Figure G-225: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

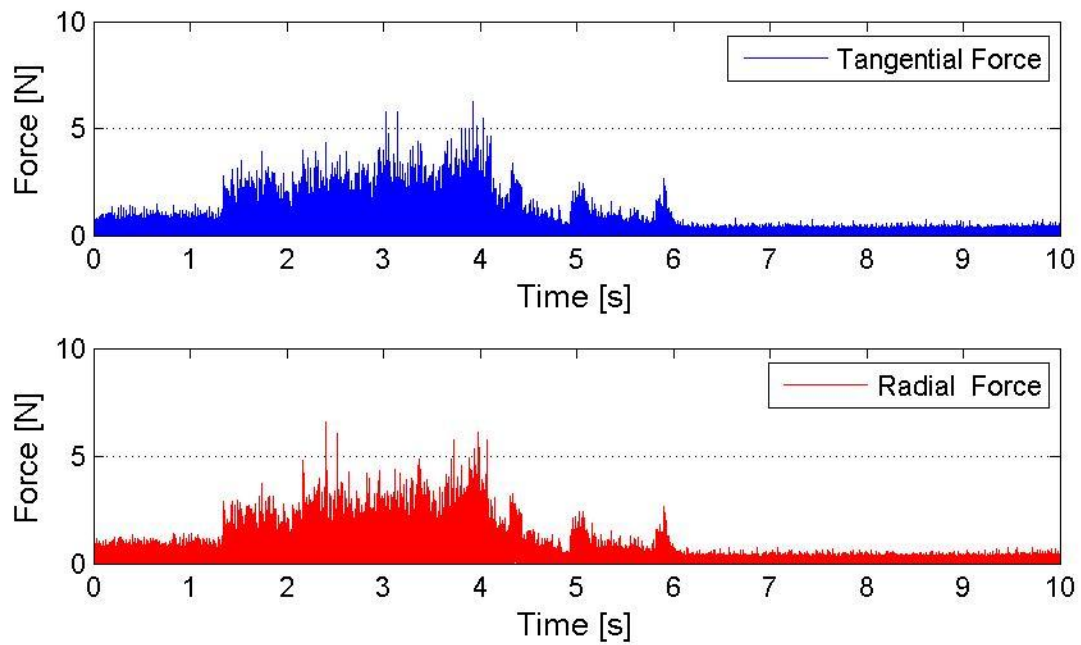


Figure G-226: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

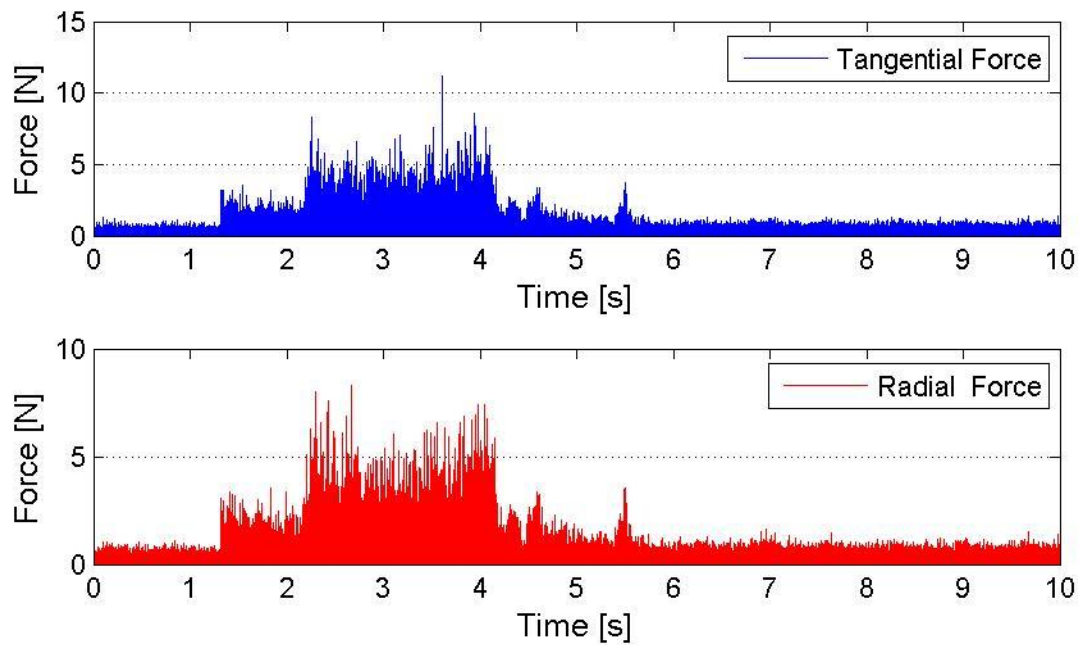


Figure G-227: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

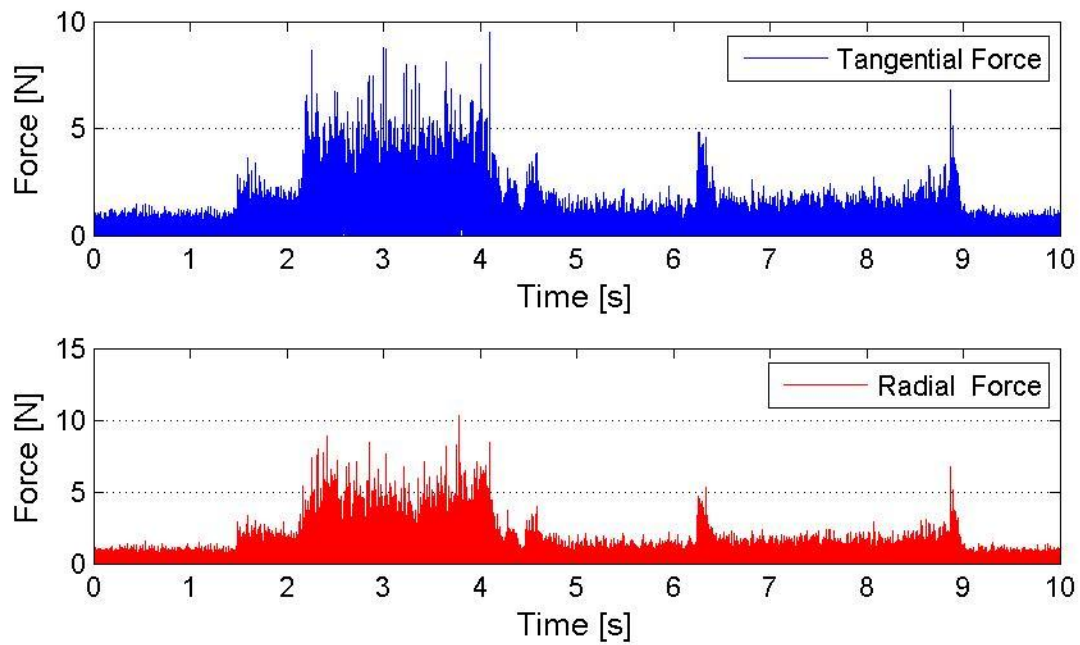


Figure G-228: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

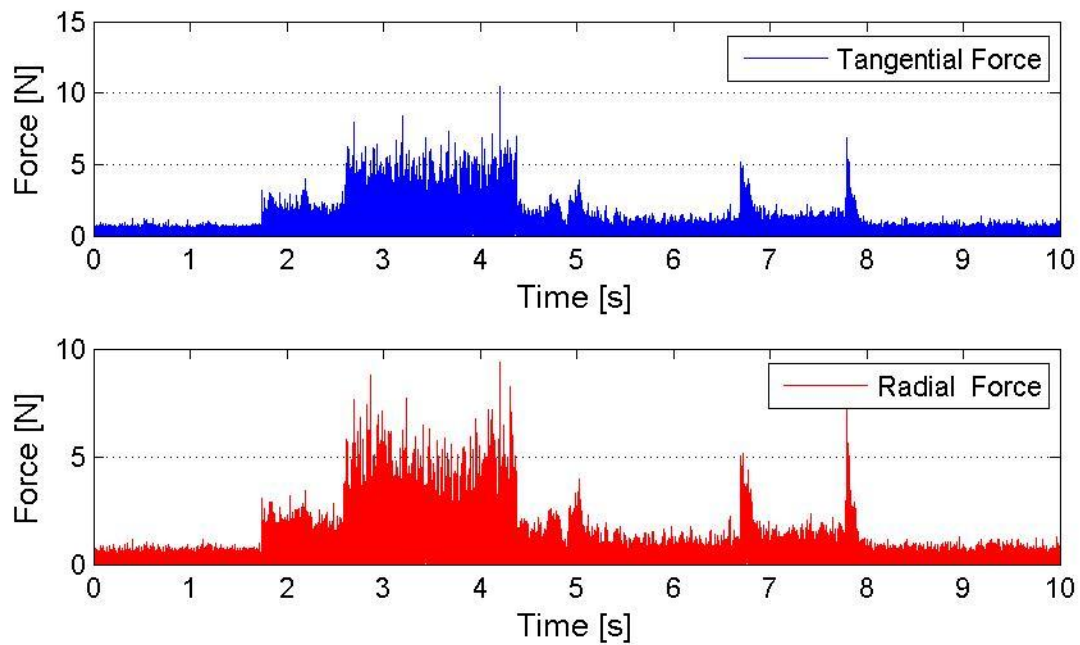


Figure G-229: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

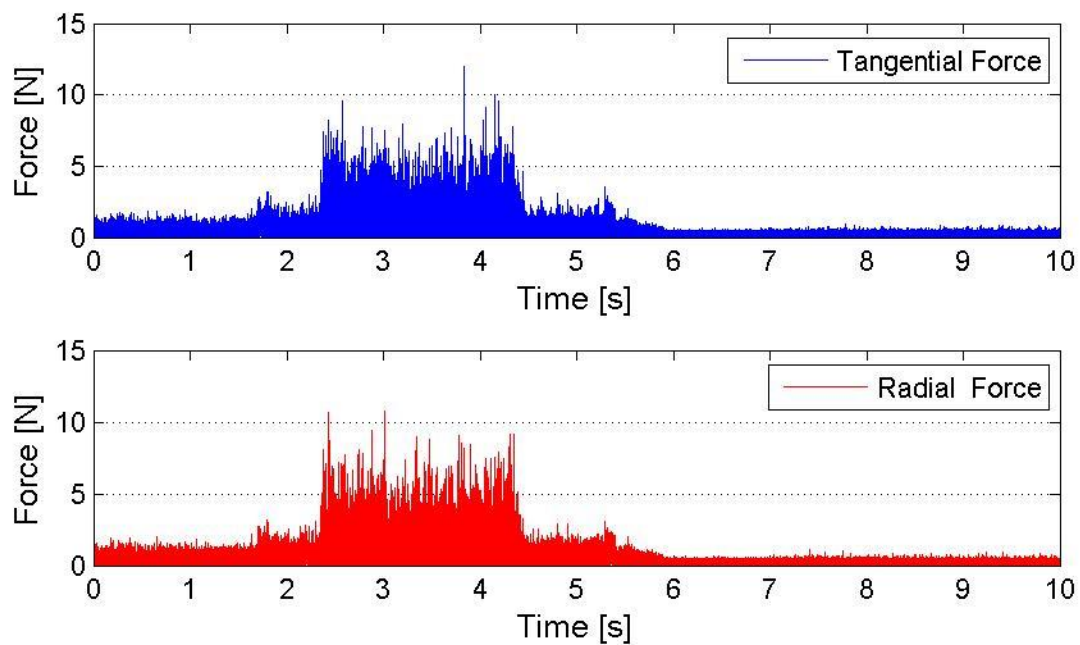


Figure G-230: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

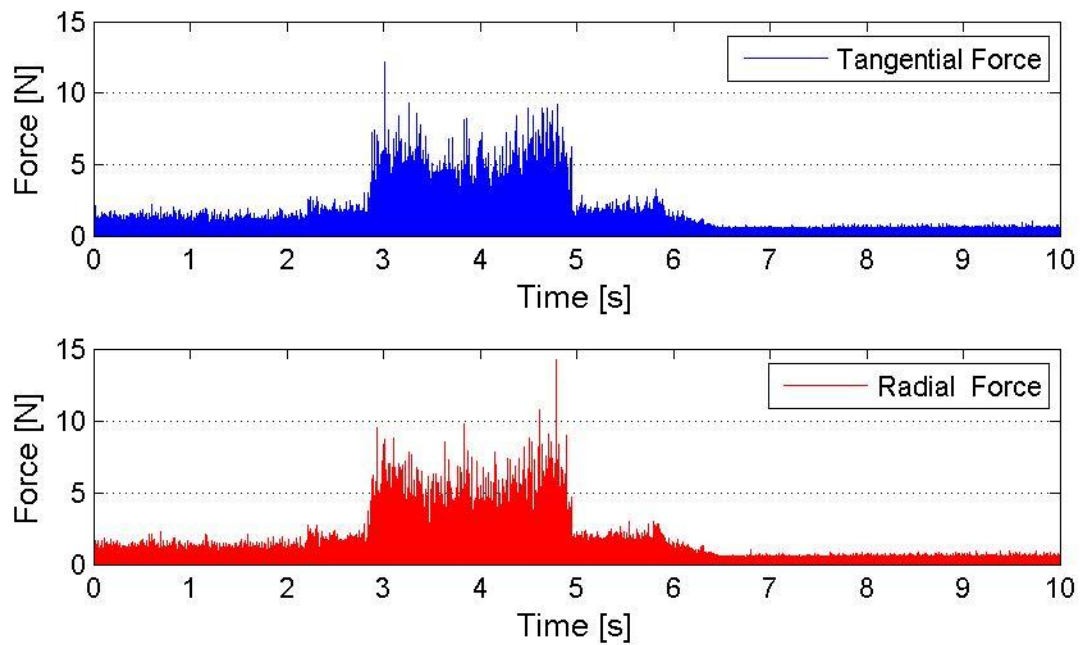


Figure G-231: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

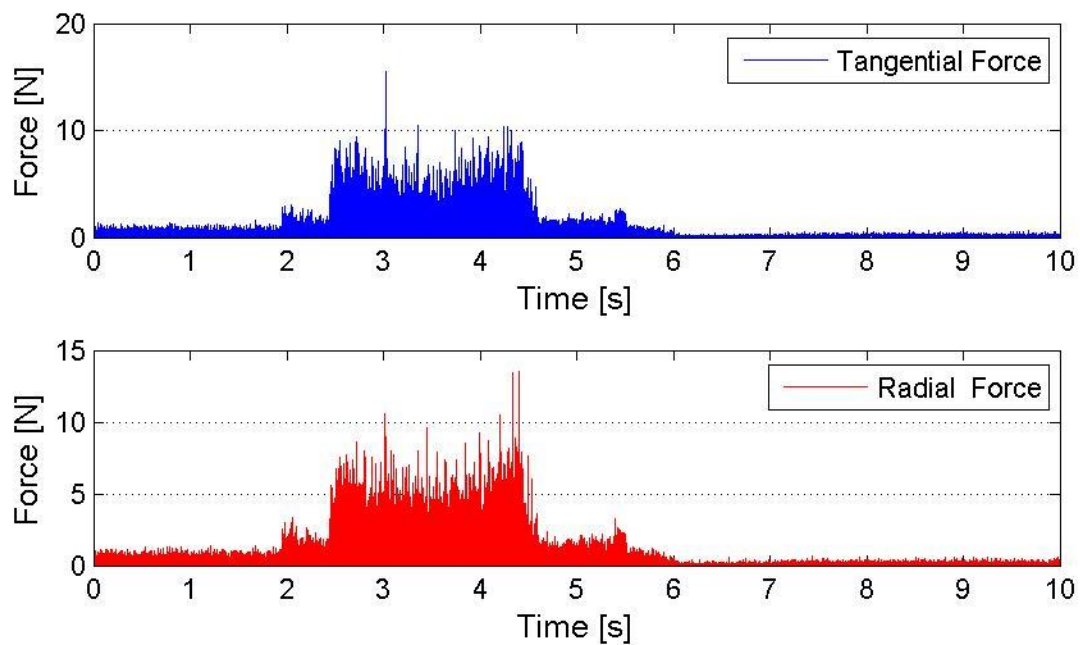


Figure G-232: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

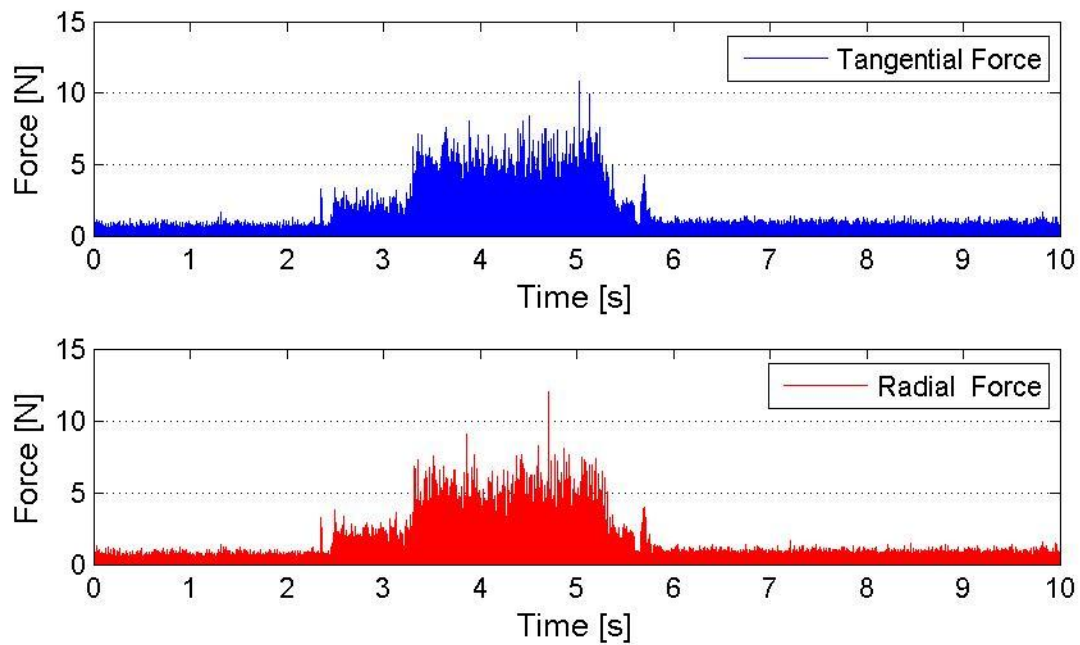


Figure G-233: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

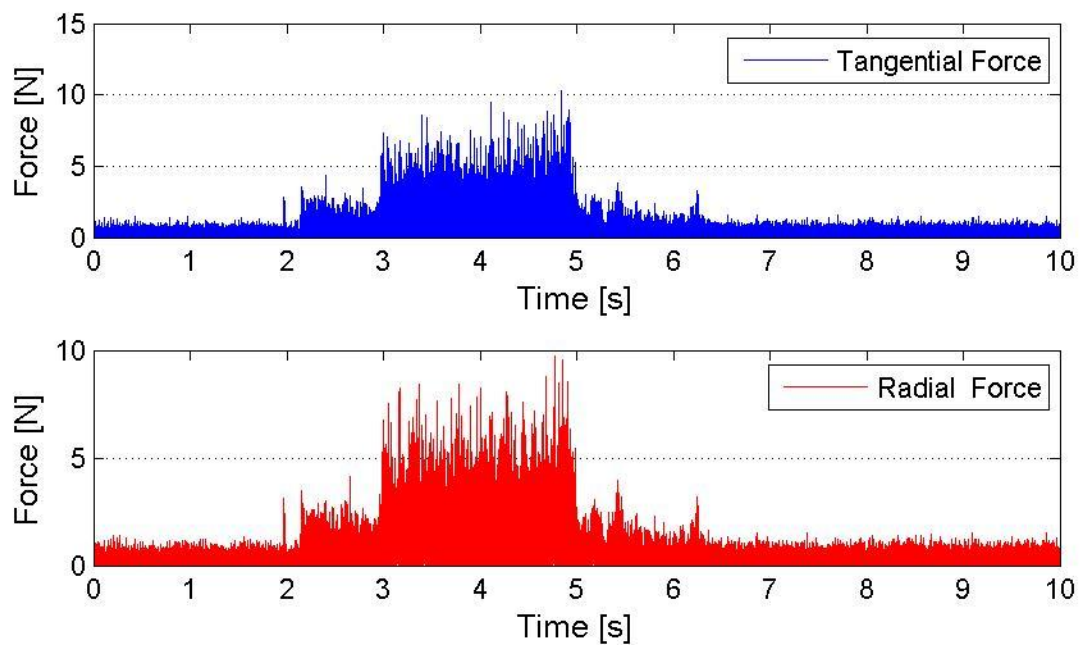


Figure G-234: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

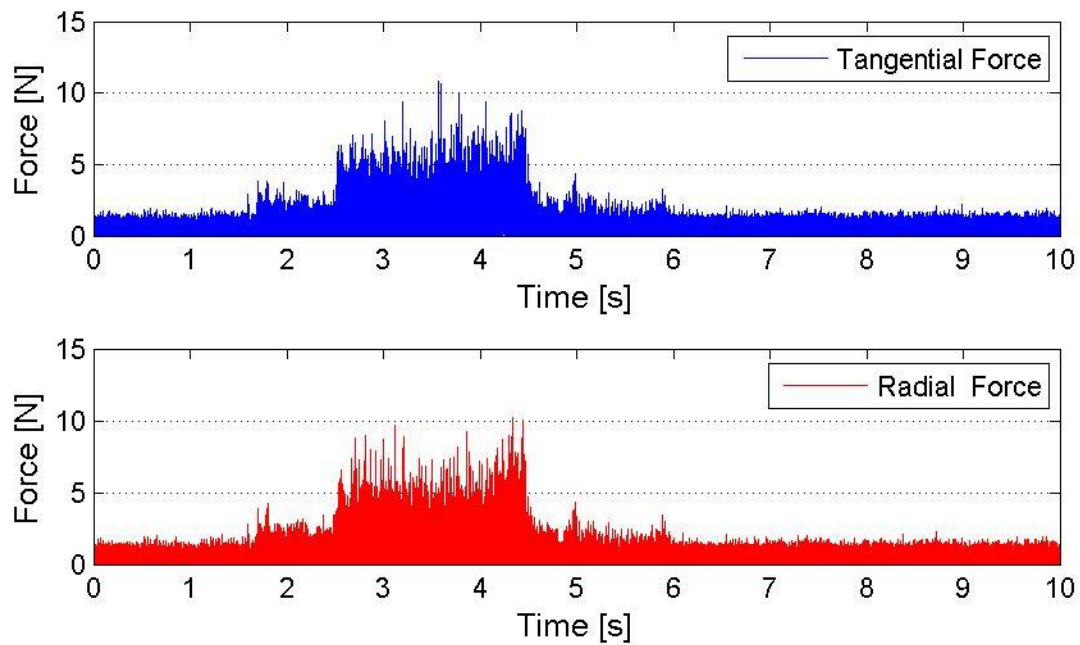


Figure G-235: Tangential and radial cutting force of Cfoam at 4000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

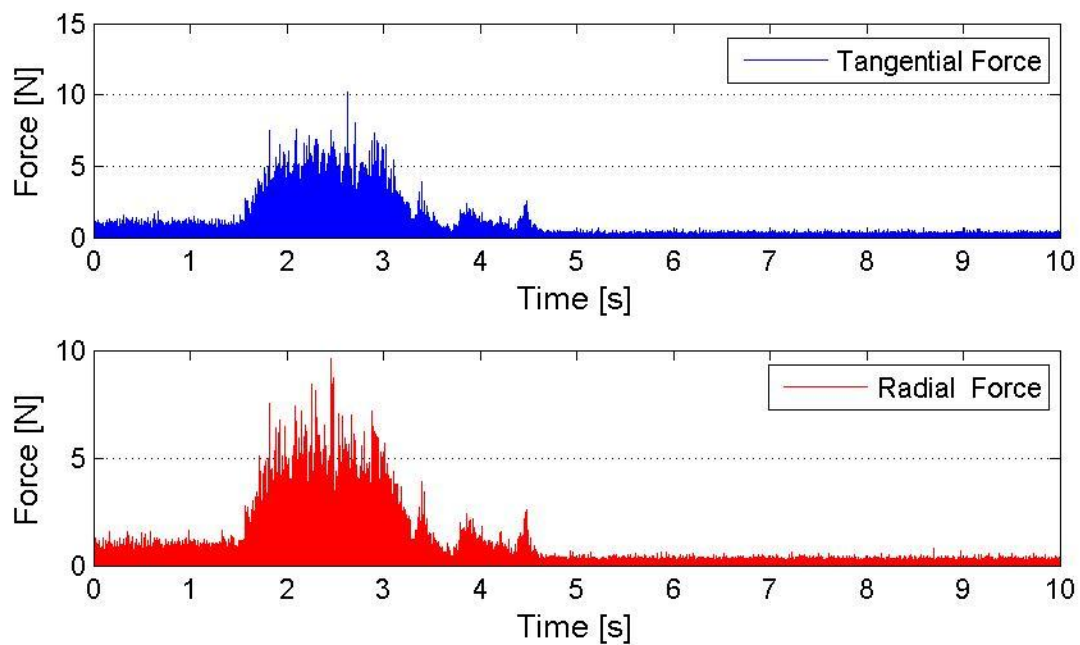


Figure G-236: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

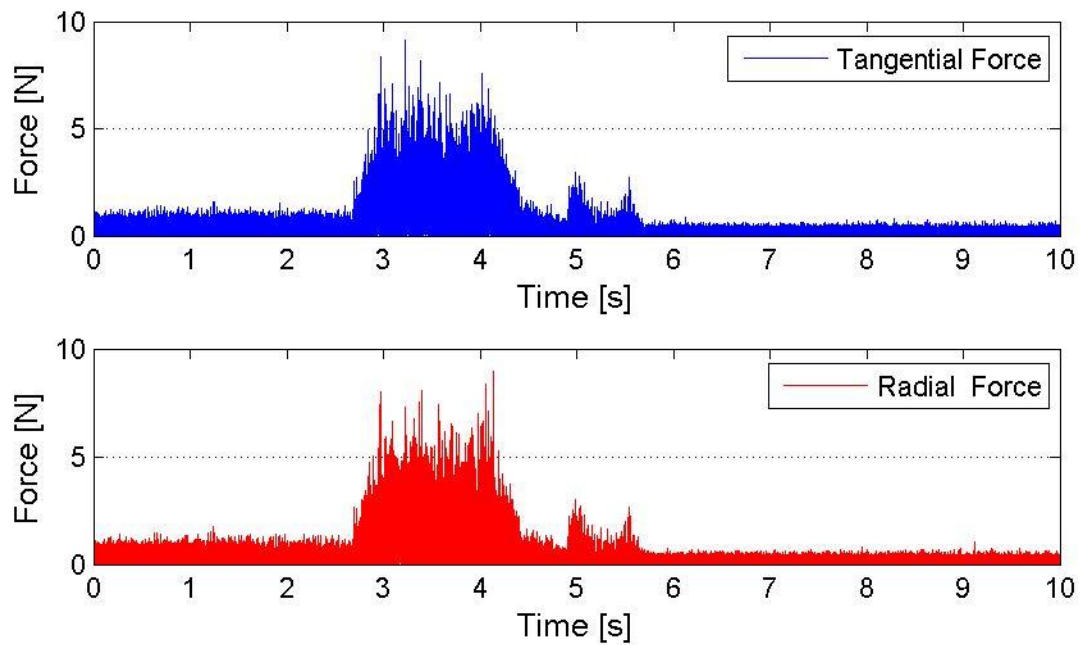


Figure G-237: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

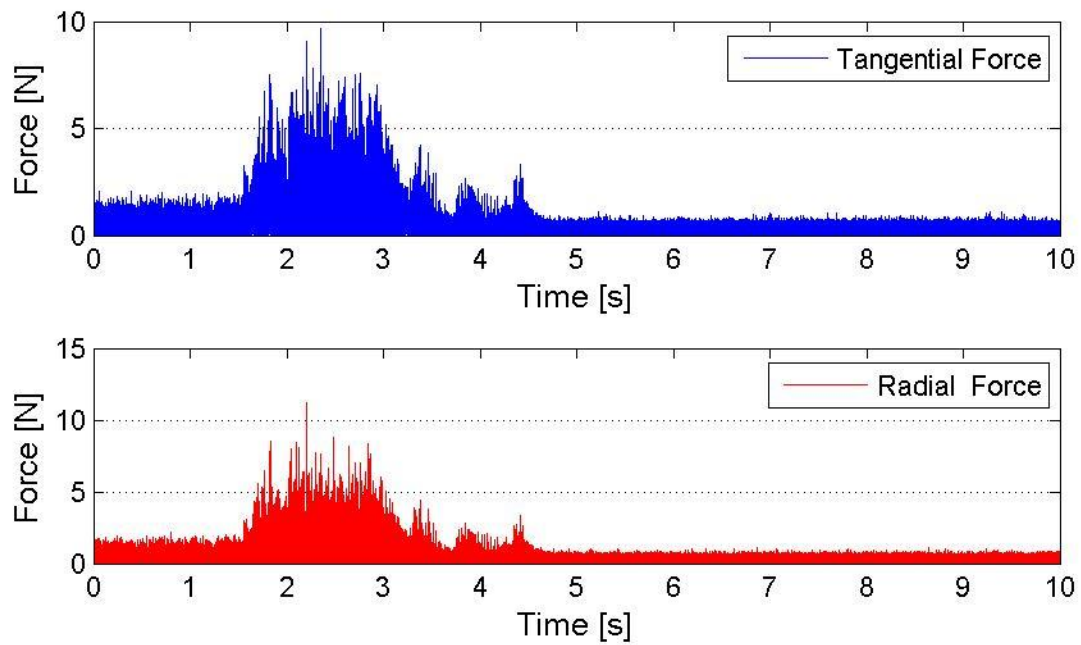


Figure G-238: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

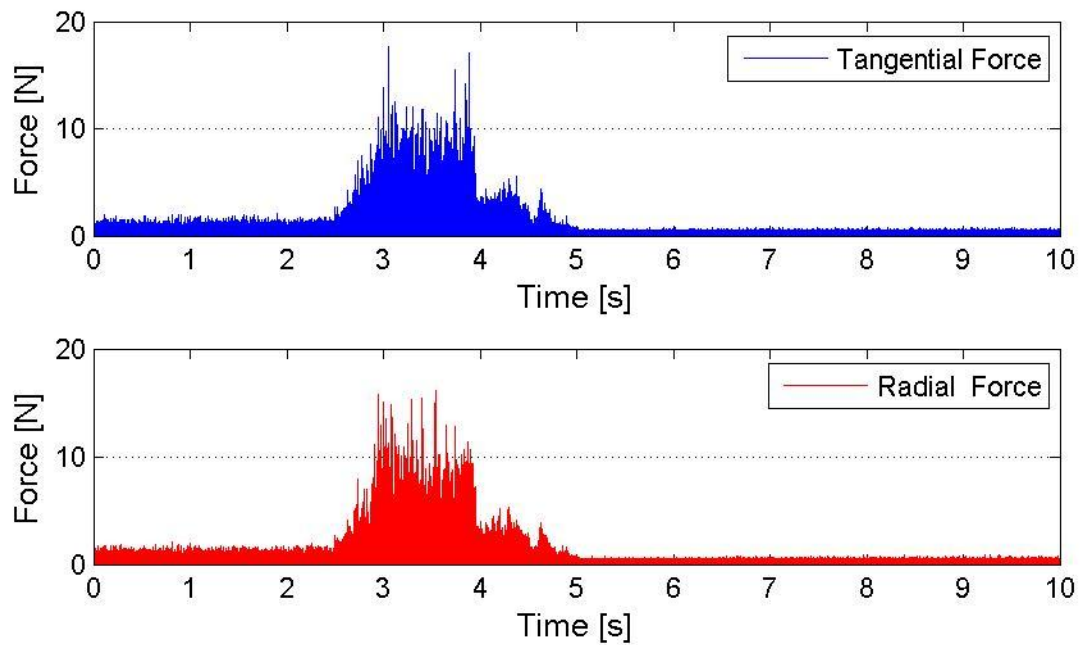


Figure G-239: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

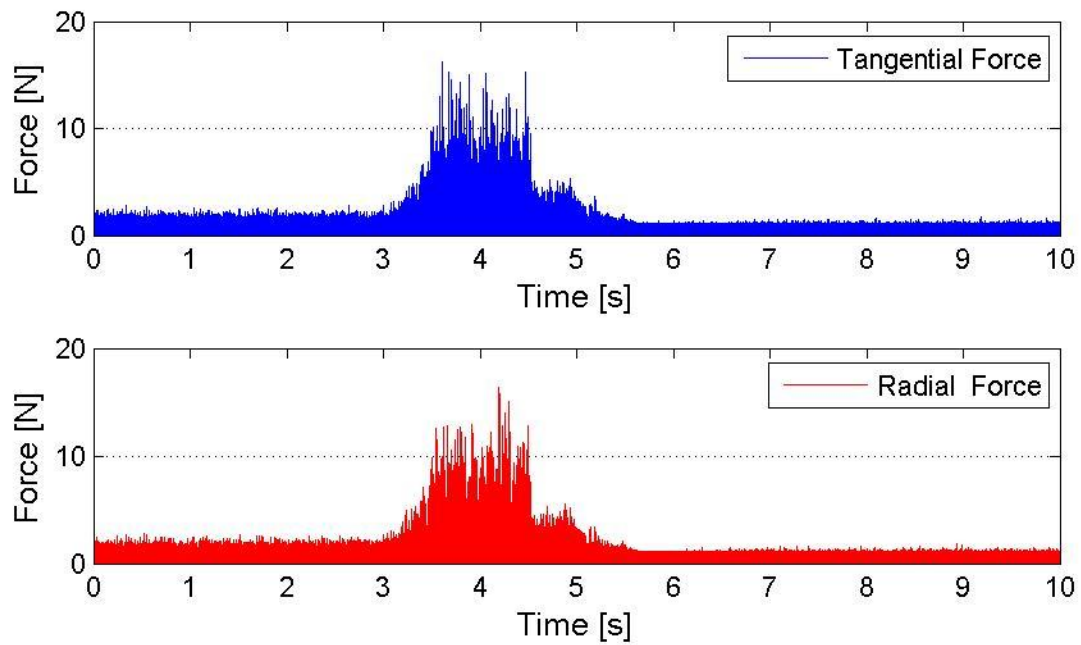


Figure G-240: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

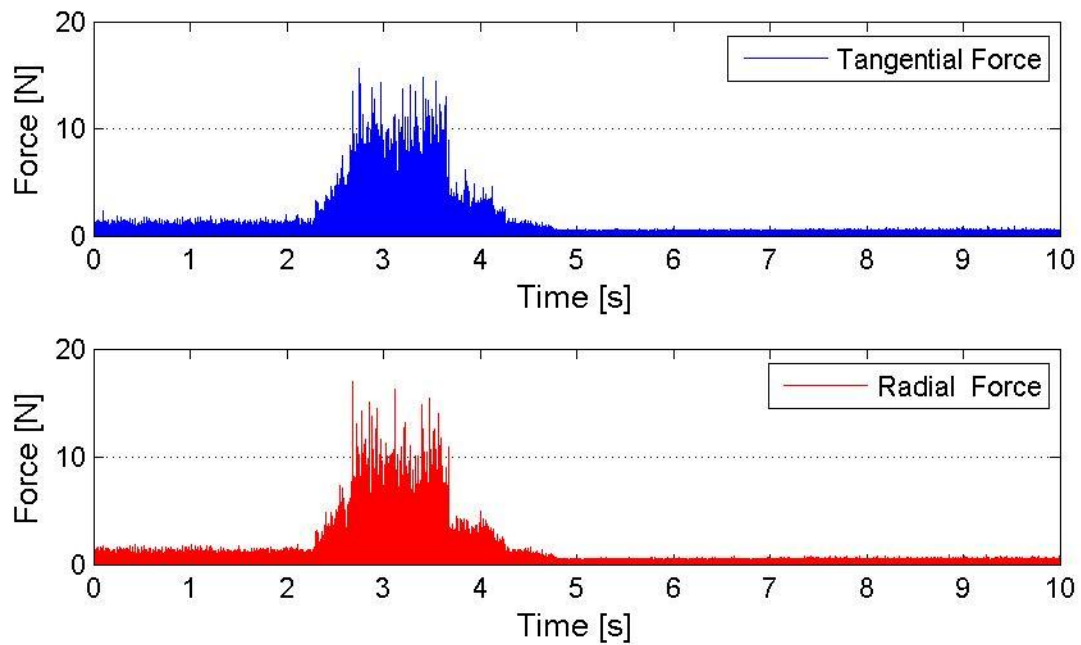


Figure G-241: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

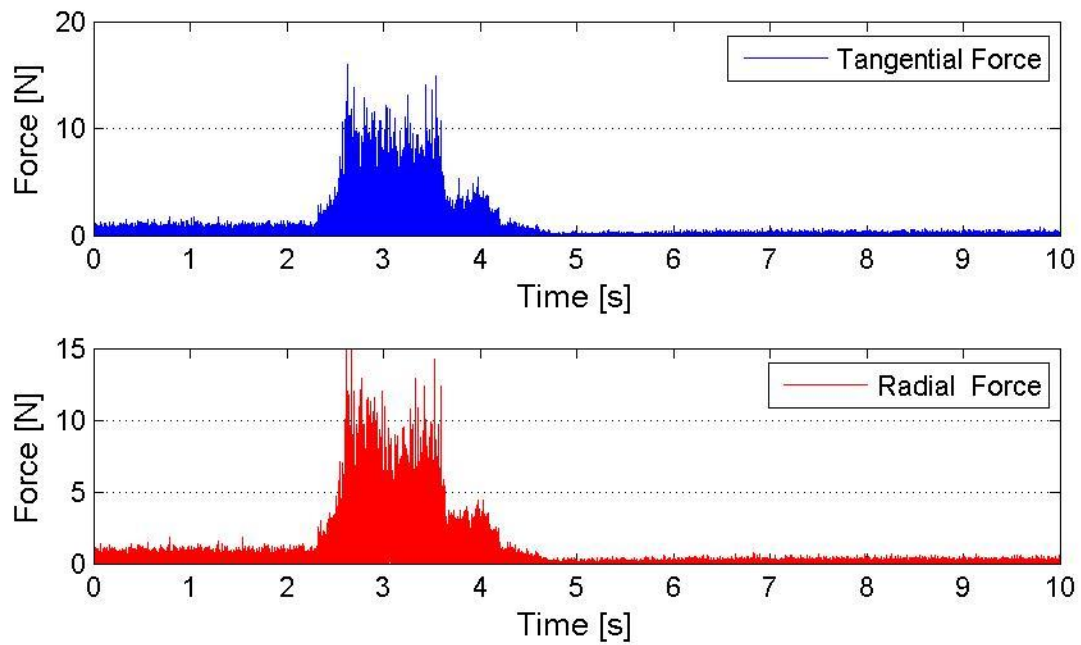


Figure G-242: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

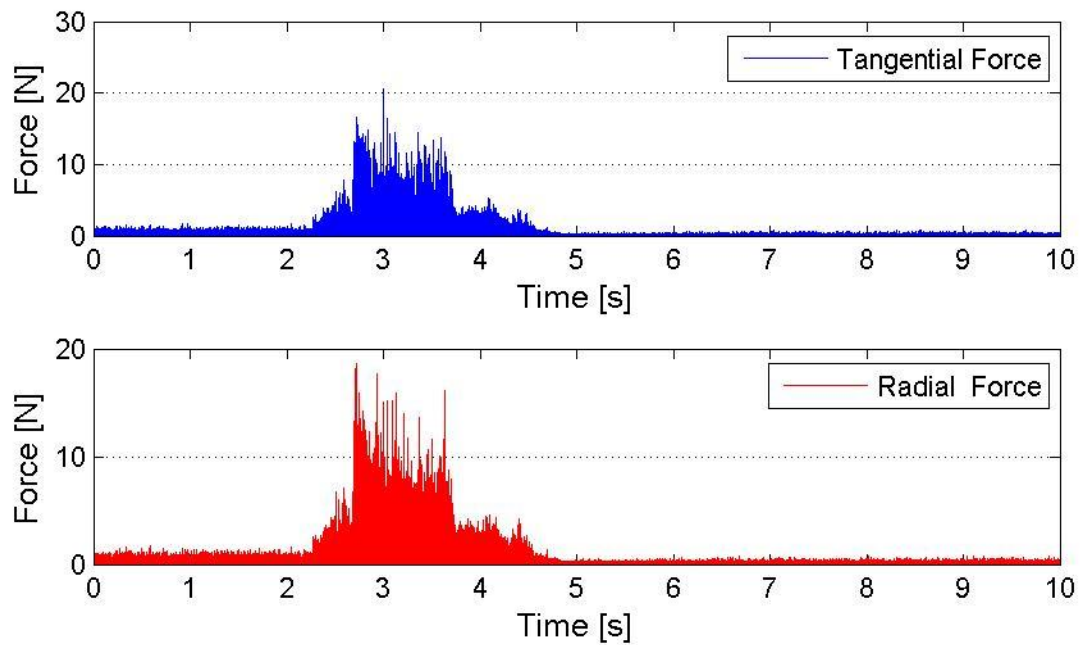


Figure G-243: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

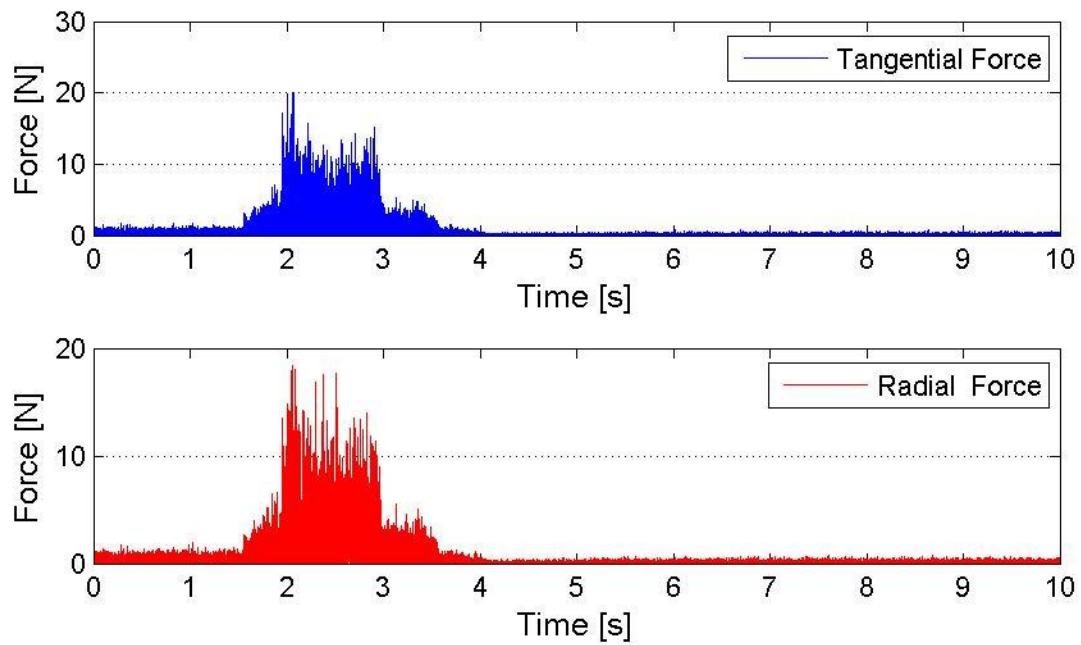


Figure G-244: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

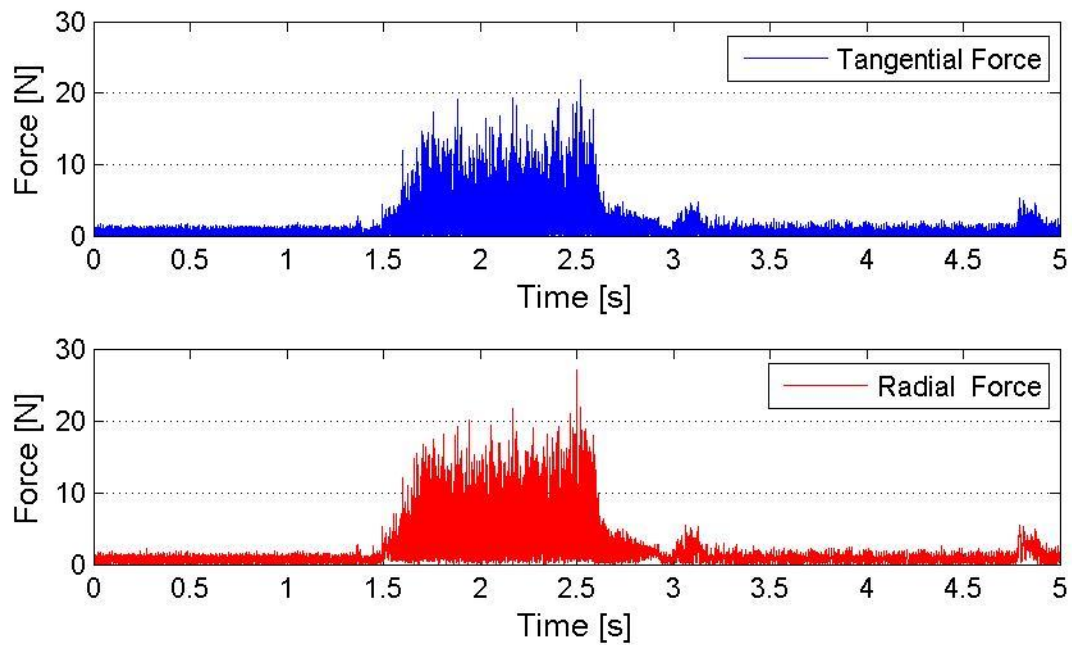


Figure G-245: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

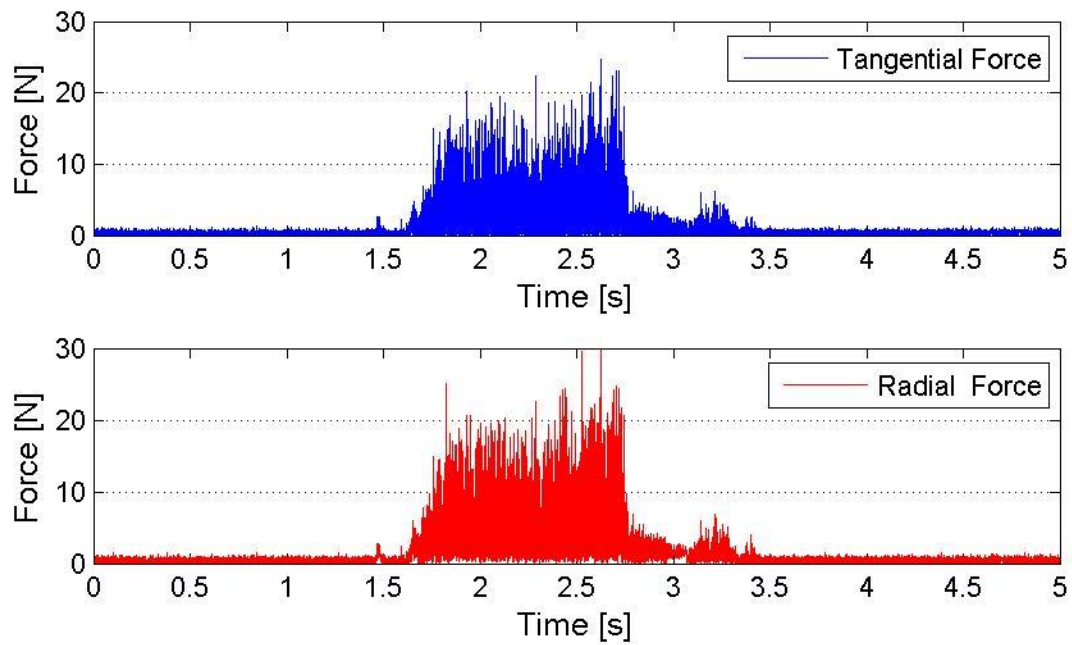


Figure G-246: Tangential and radial cutting force of Cfoam at 4000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

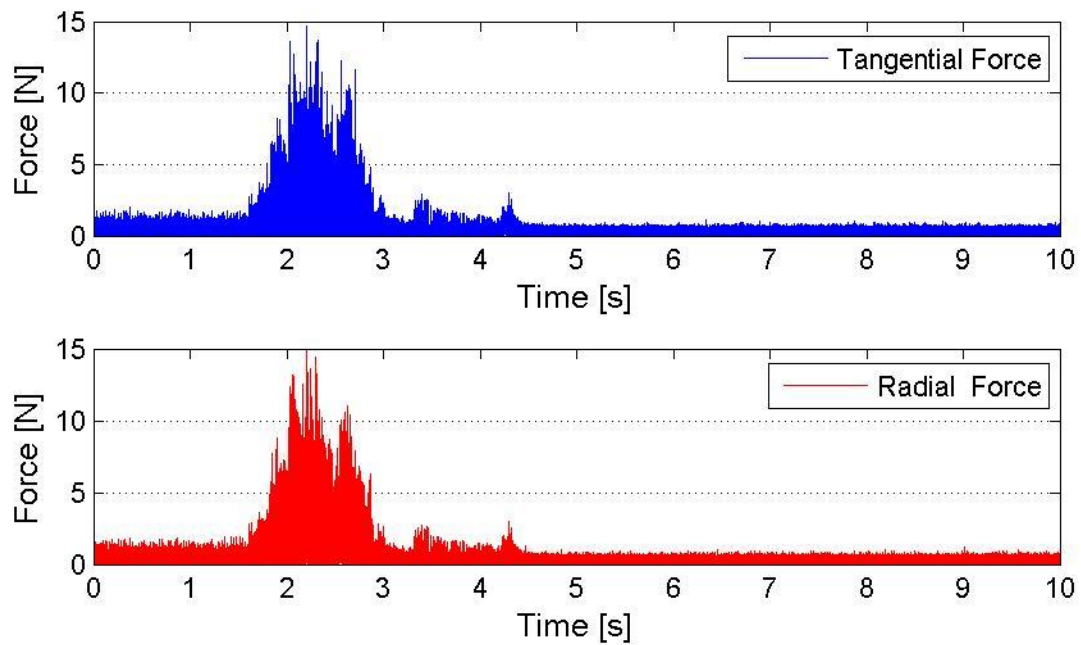


Figure G-247: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

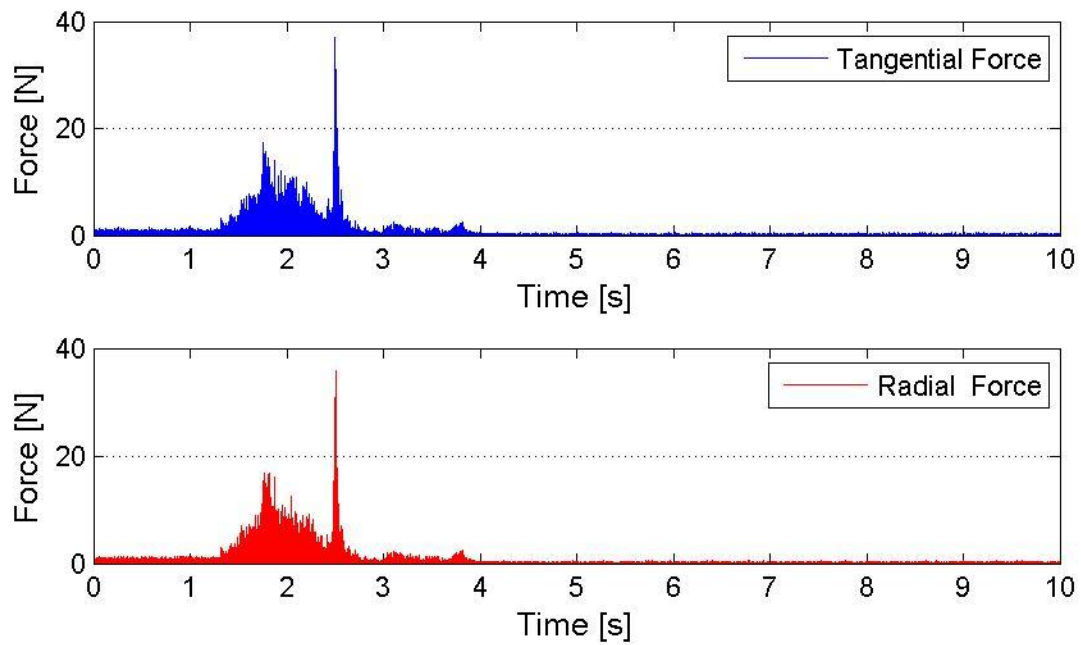


Figure G-248: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

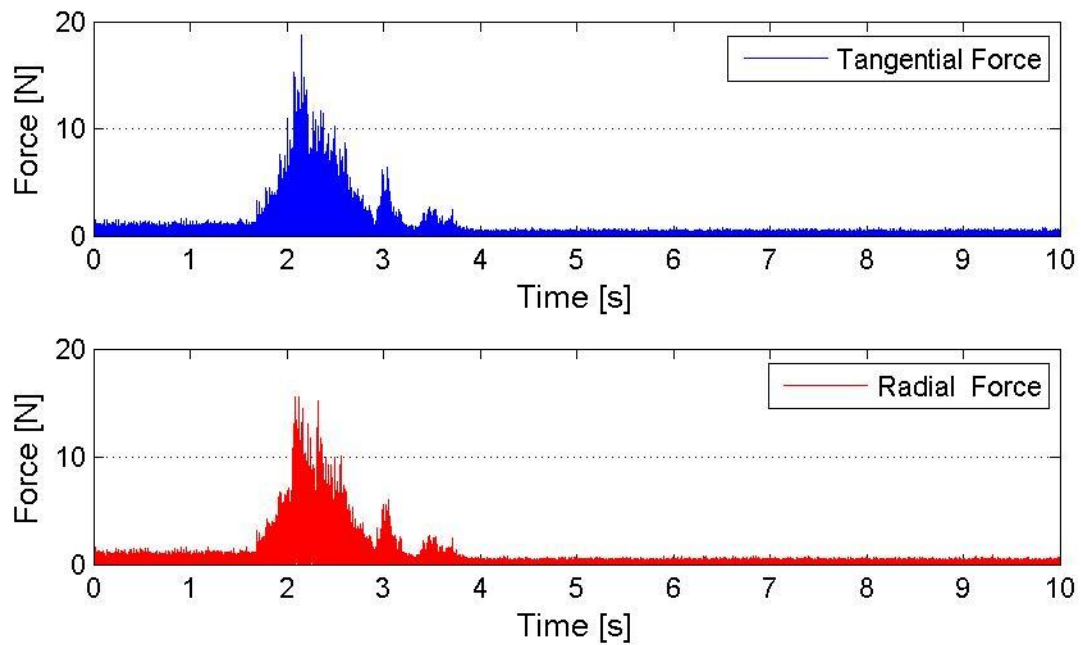


Figure G-249: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

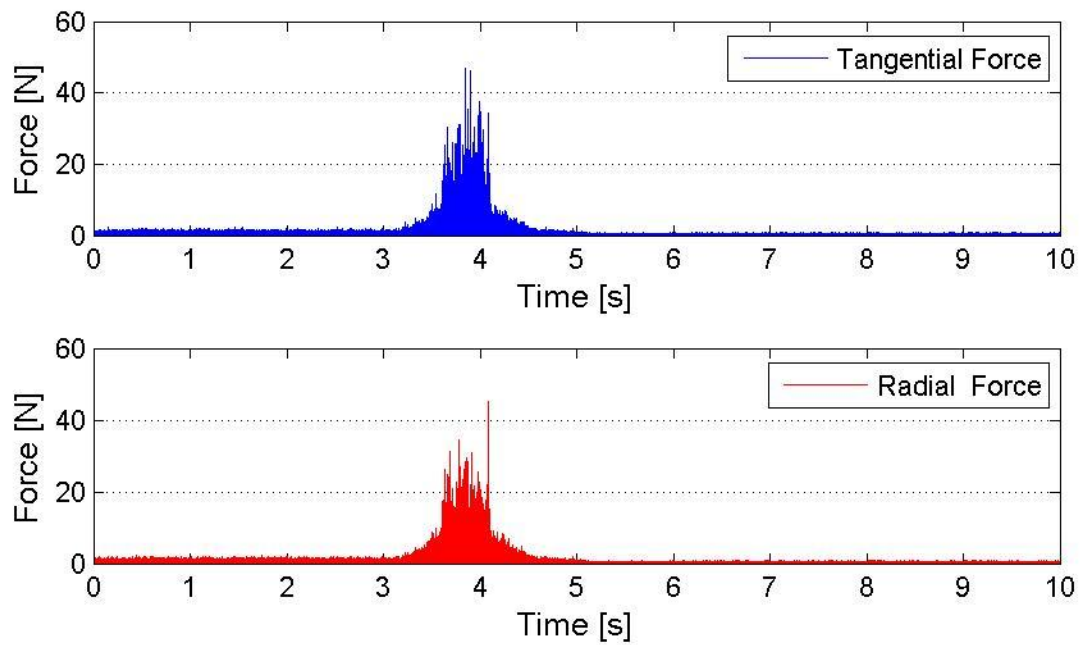


Figure G-250: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

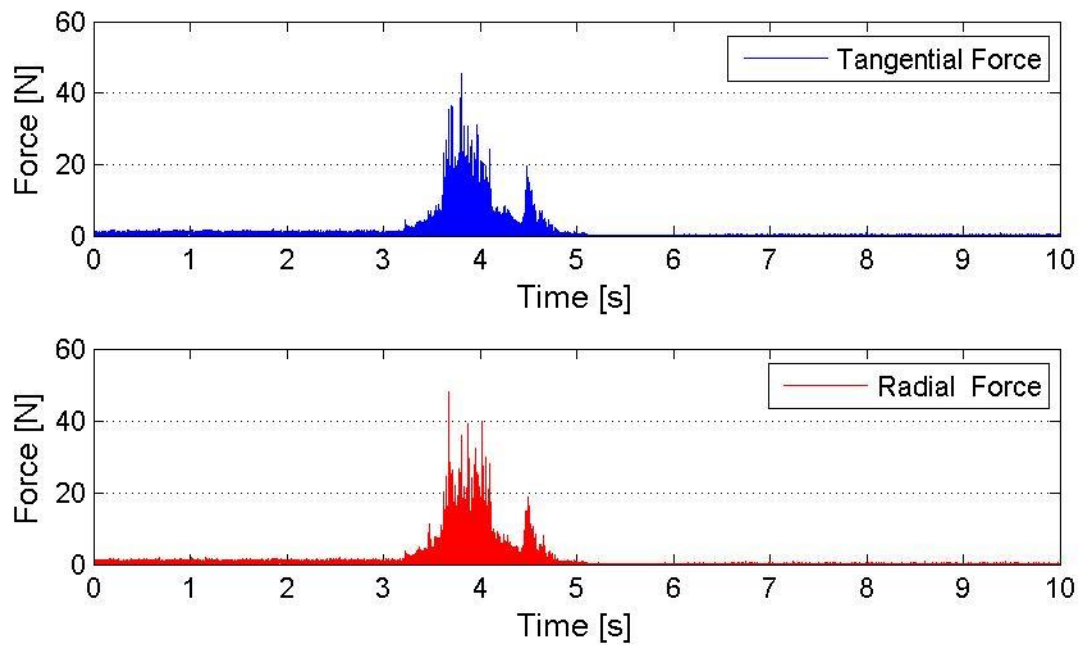


Figure G-251: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

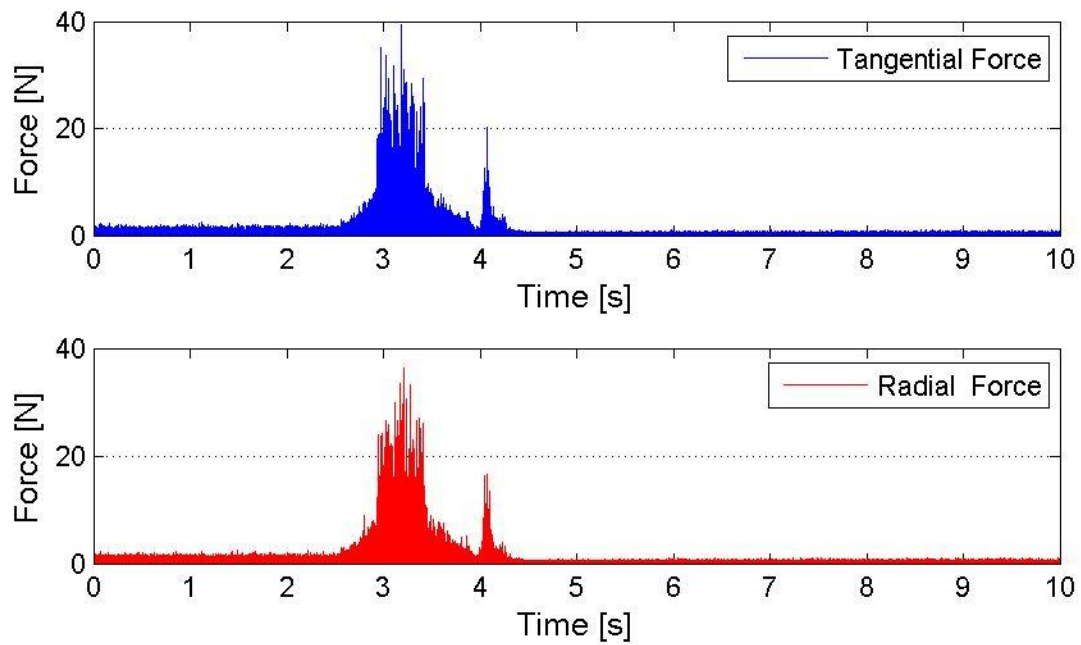


Figure G-252: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

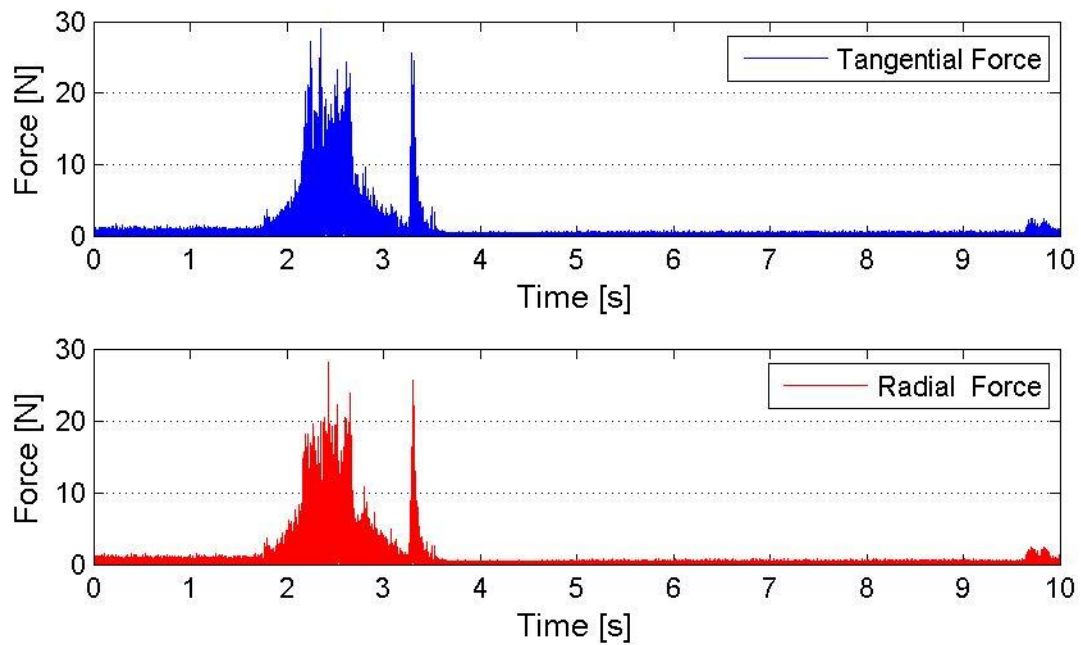


Figure G-253: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

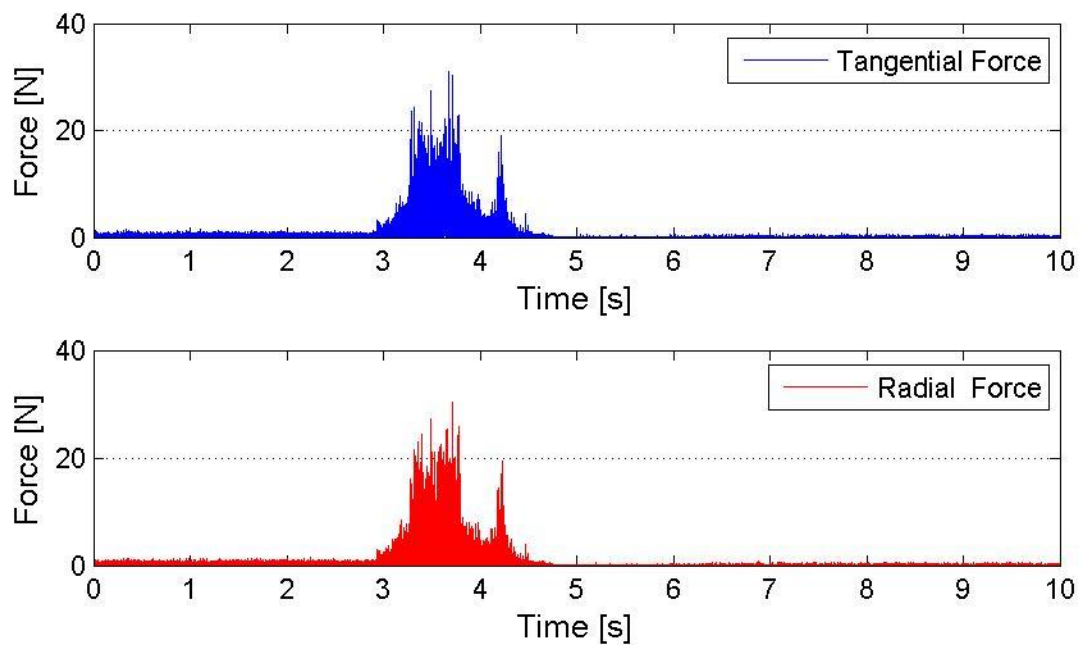


Figure G-254: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

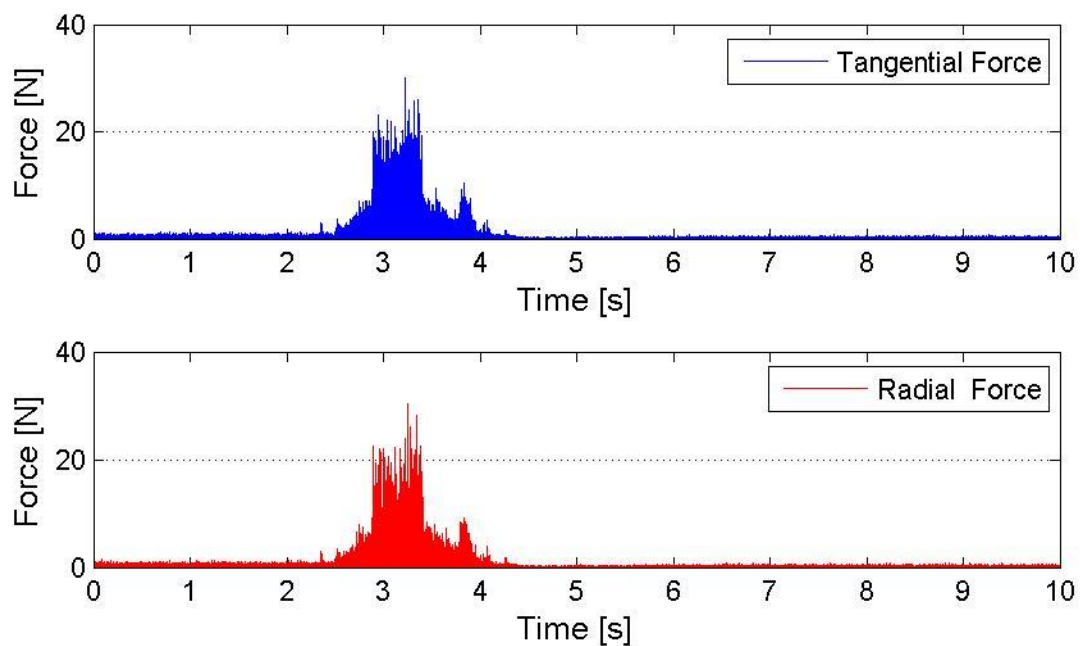


Figure G-255: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

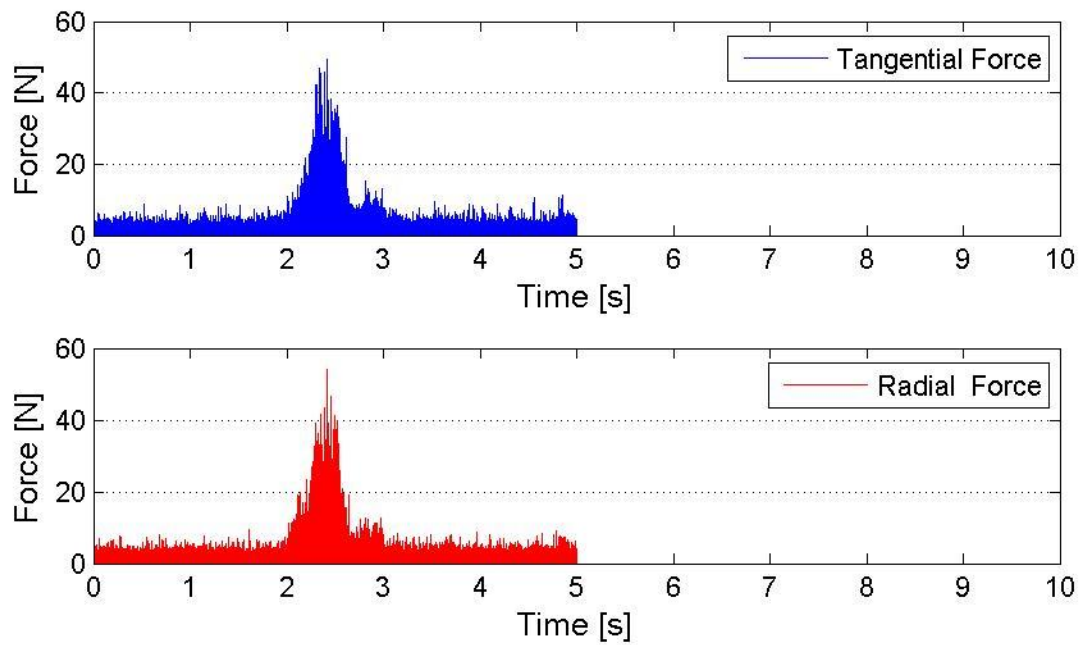


Figure G-256: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

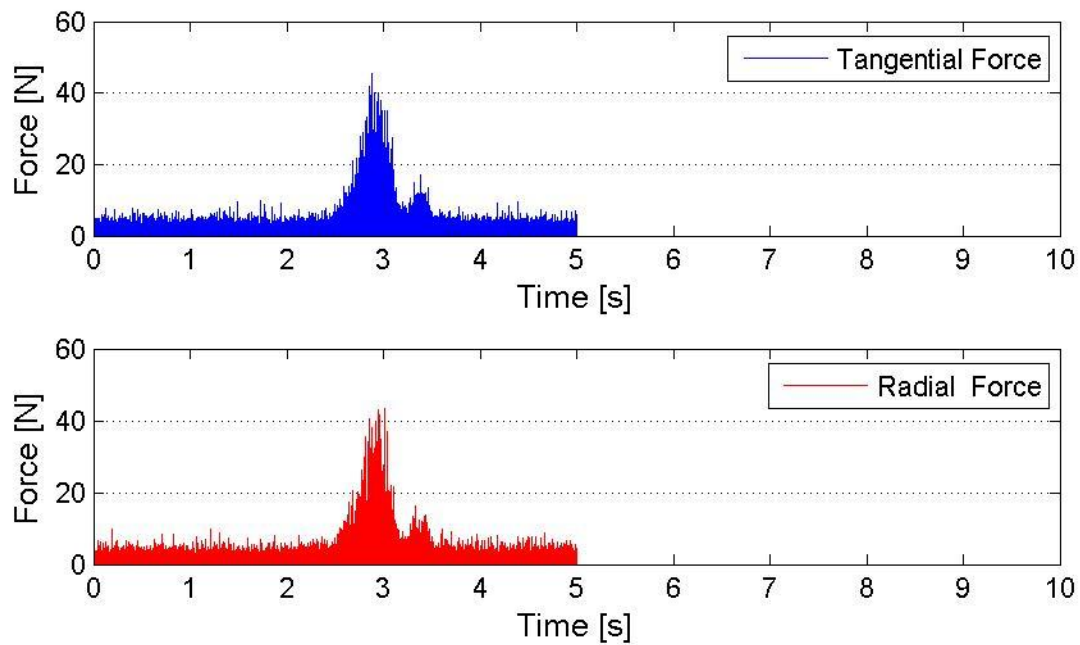


Figure G-257: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

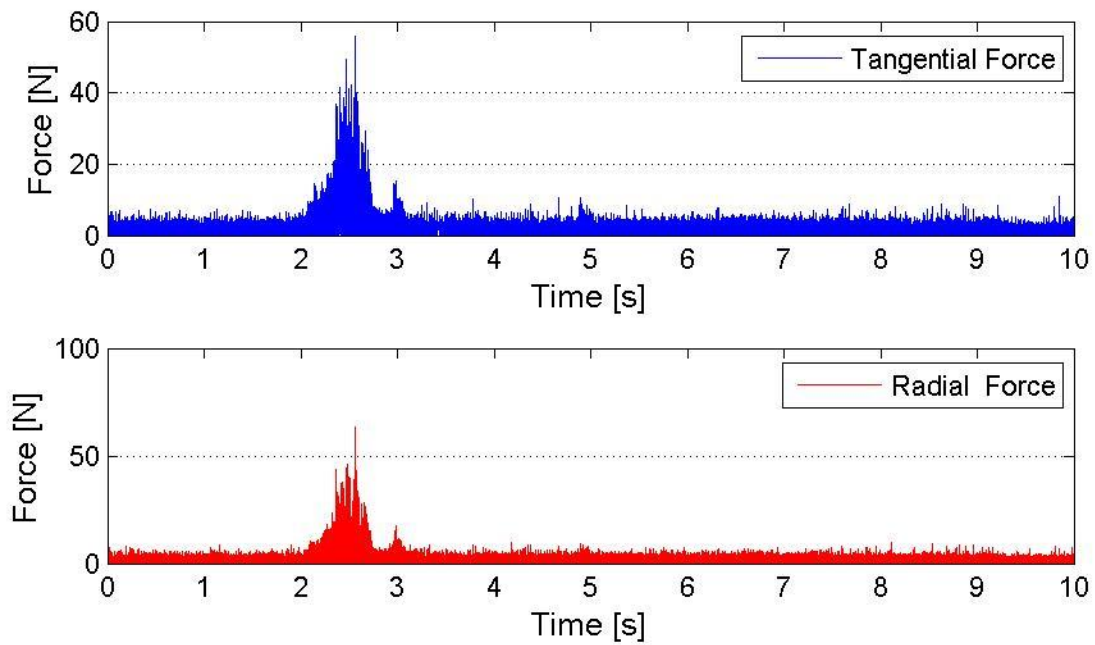


Figure G-258: Tangential and radial cutting force of Cfoam at 4000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

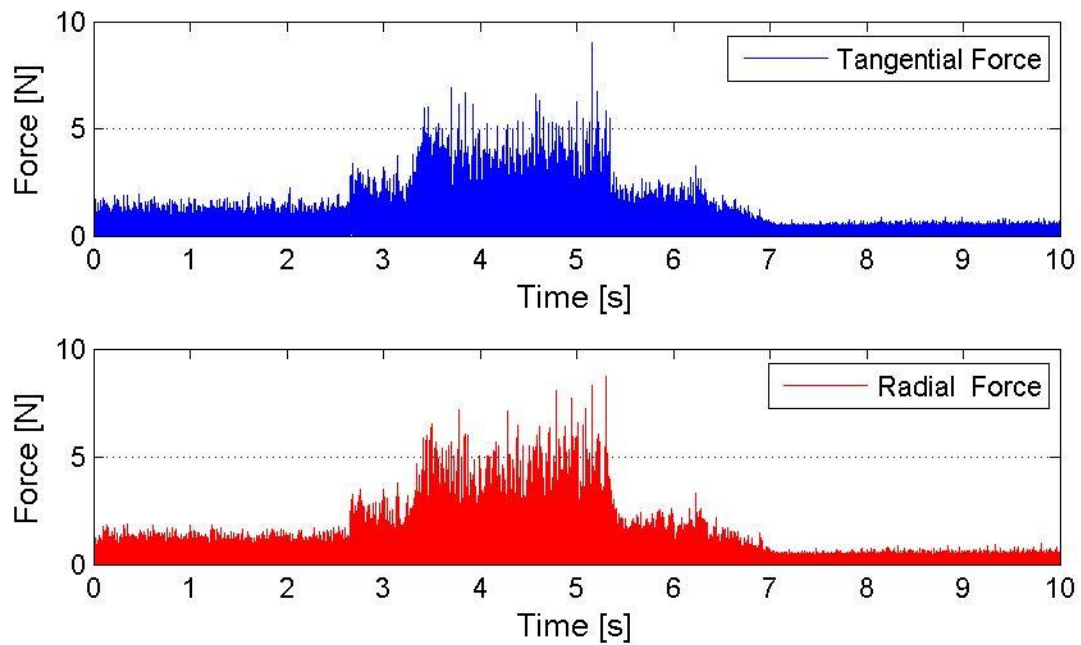


Figure G-259: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

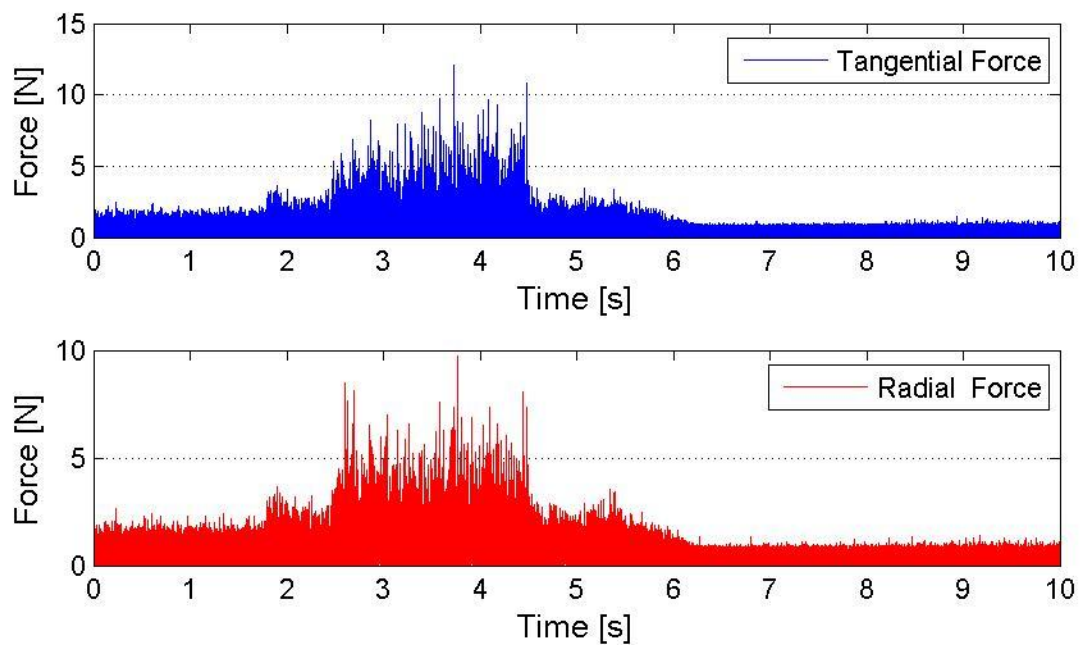


Figure G-260: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

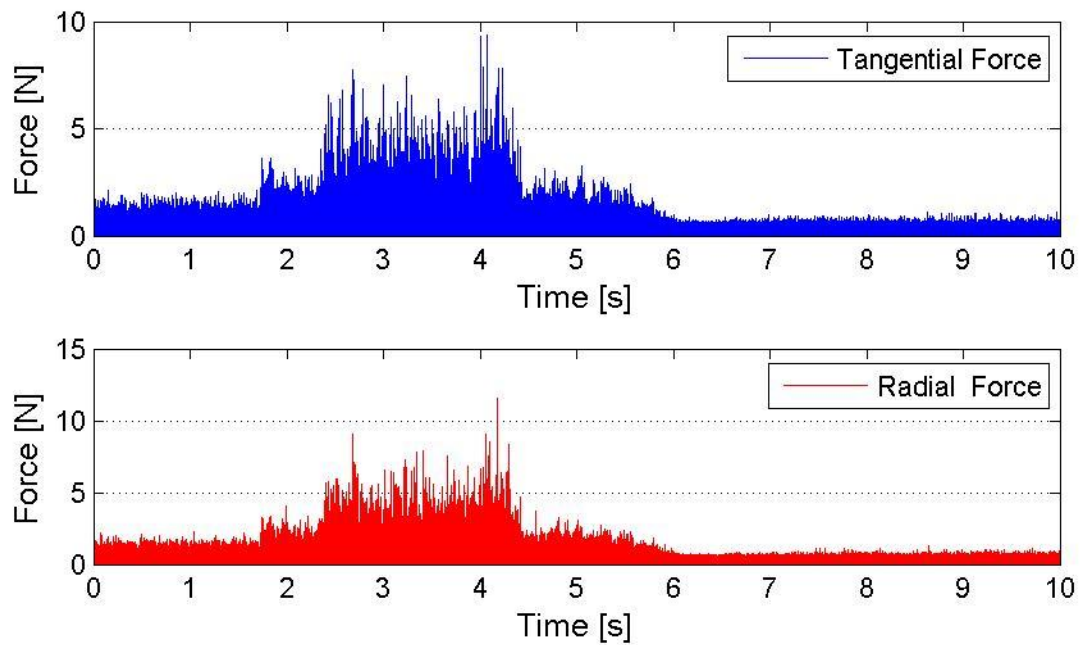


Figure G-261: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

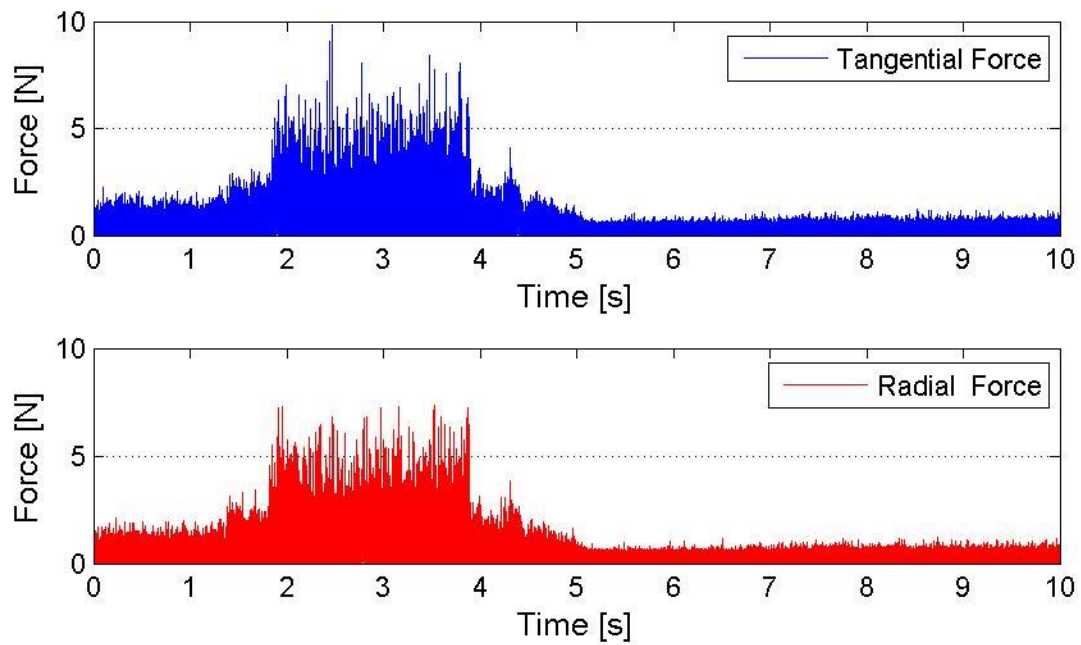


Figure G-262: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

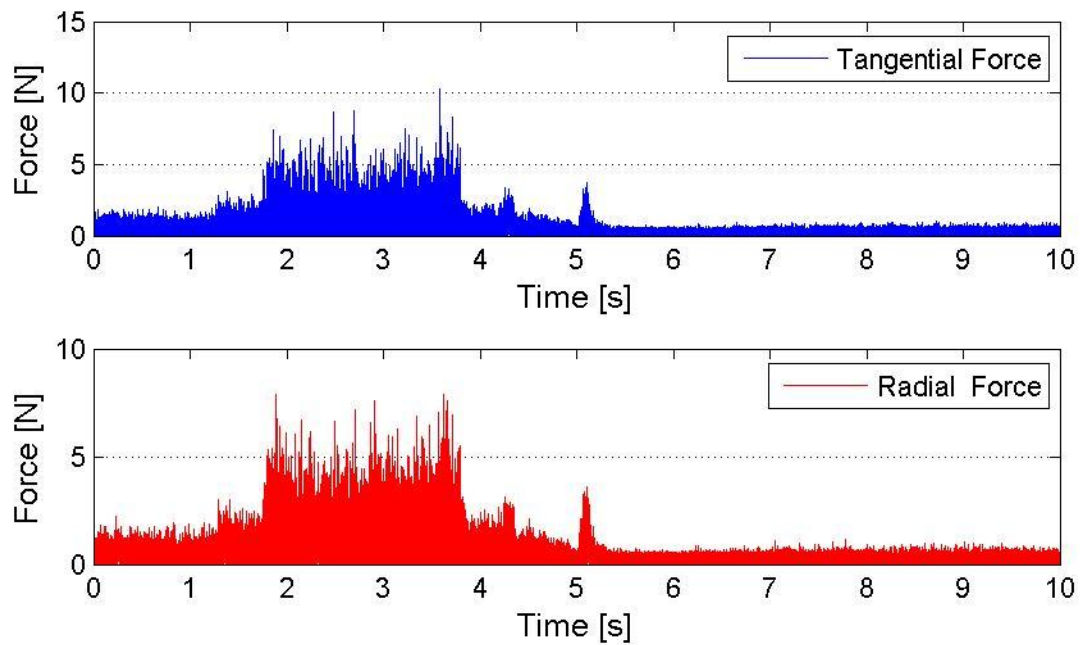


Figure G-263: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

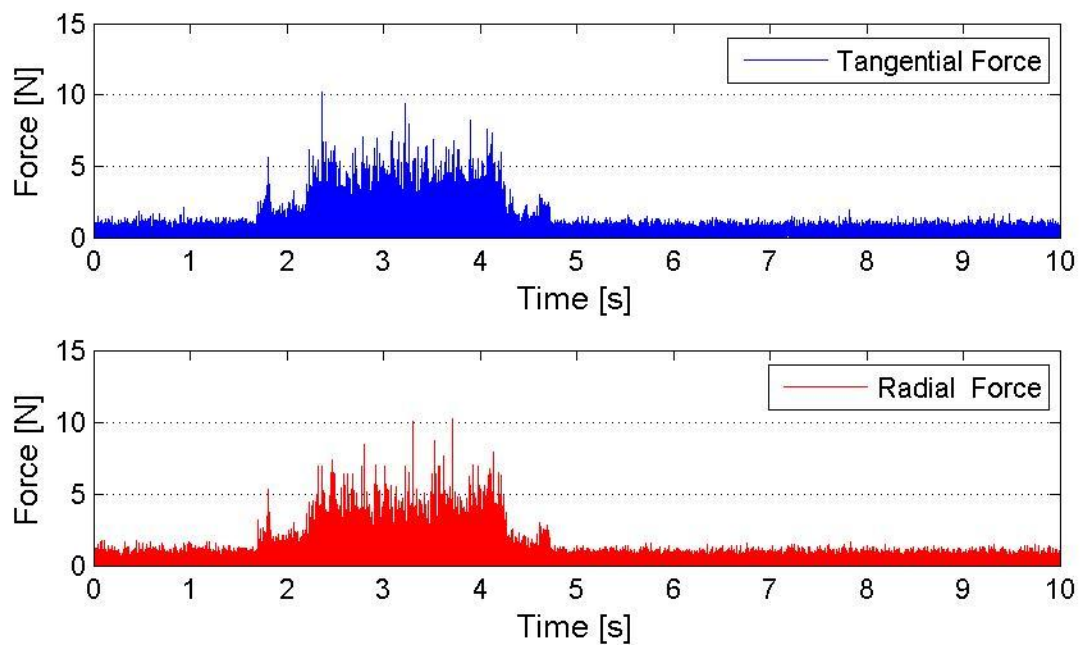


Figure G-264: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

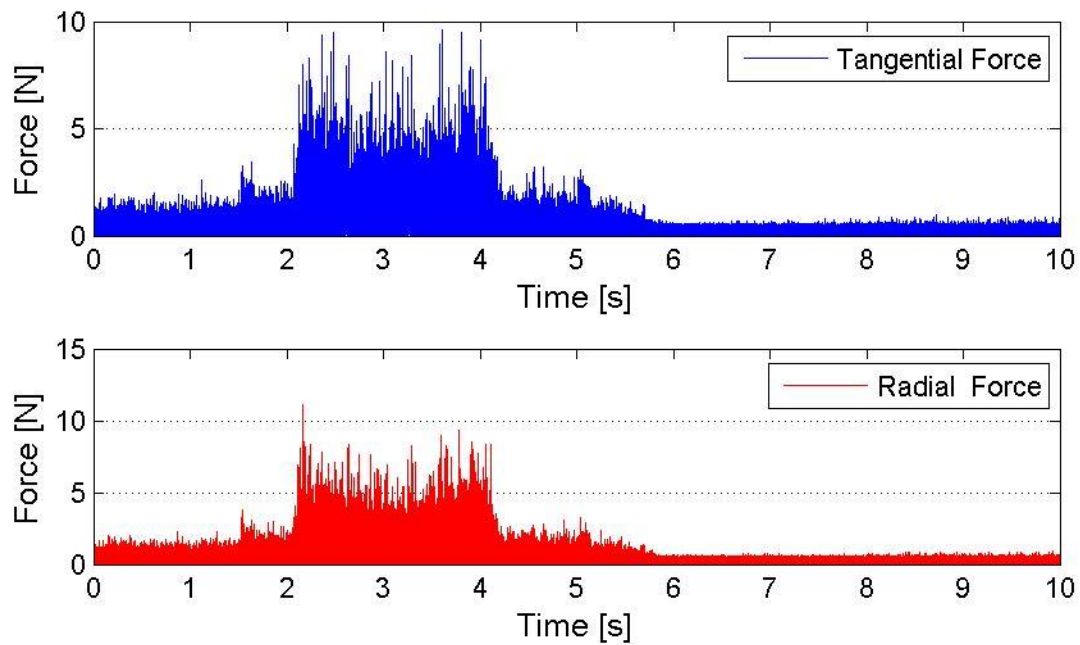


Figure G-265: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

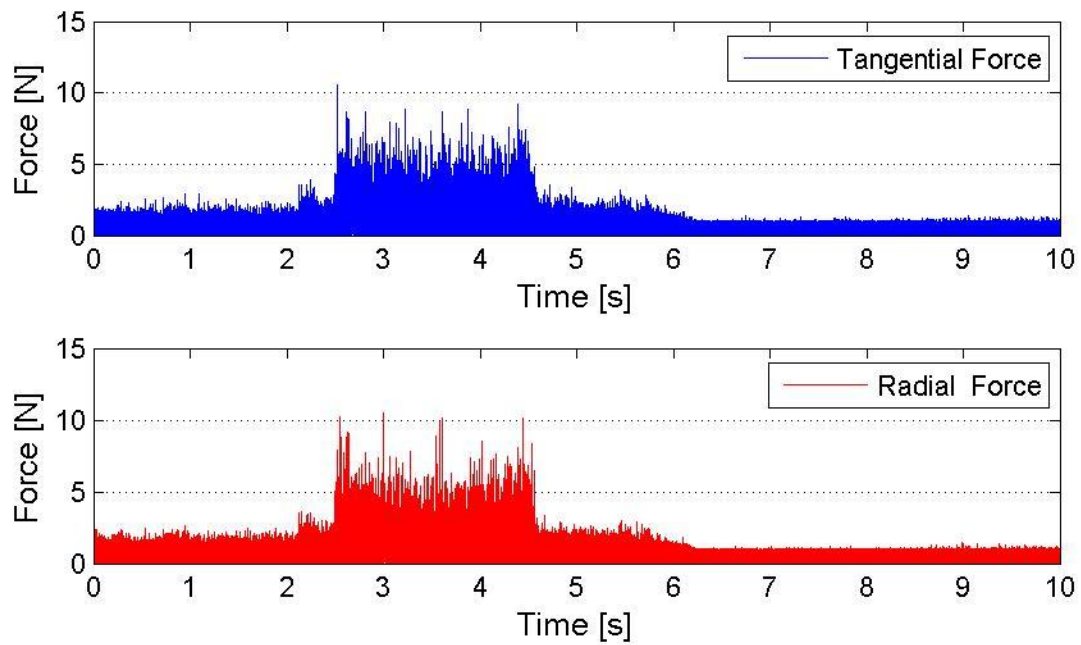


Figure G-266: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

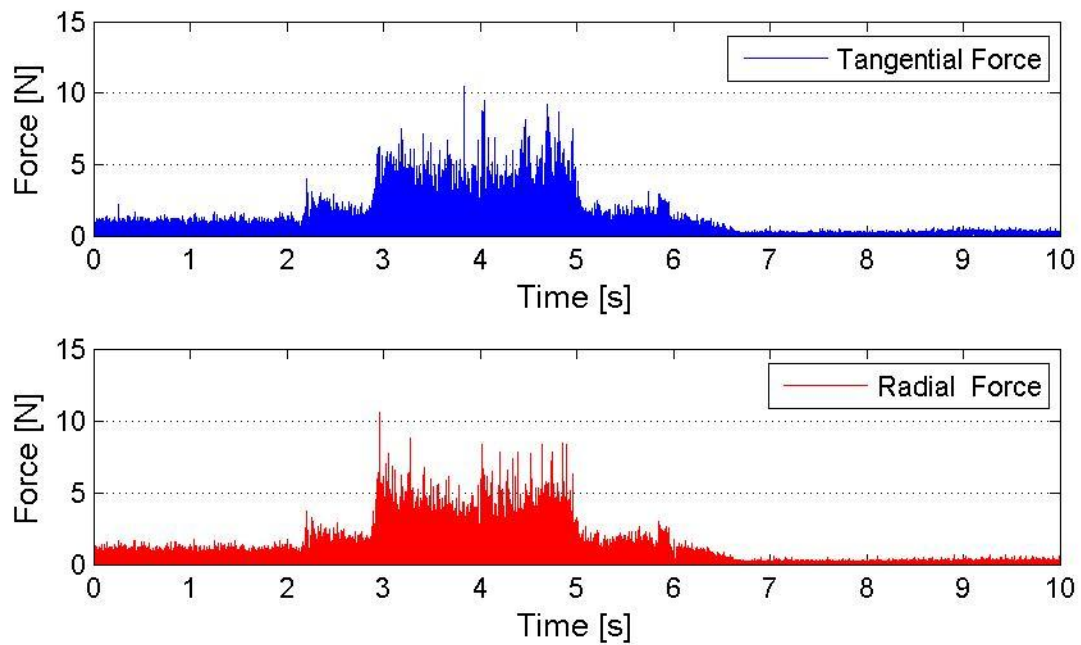


Figure G-267: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

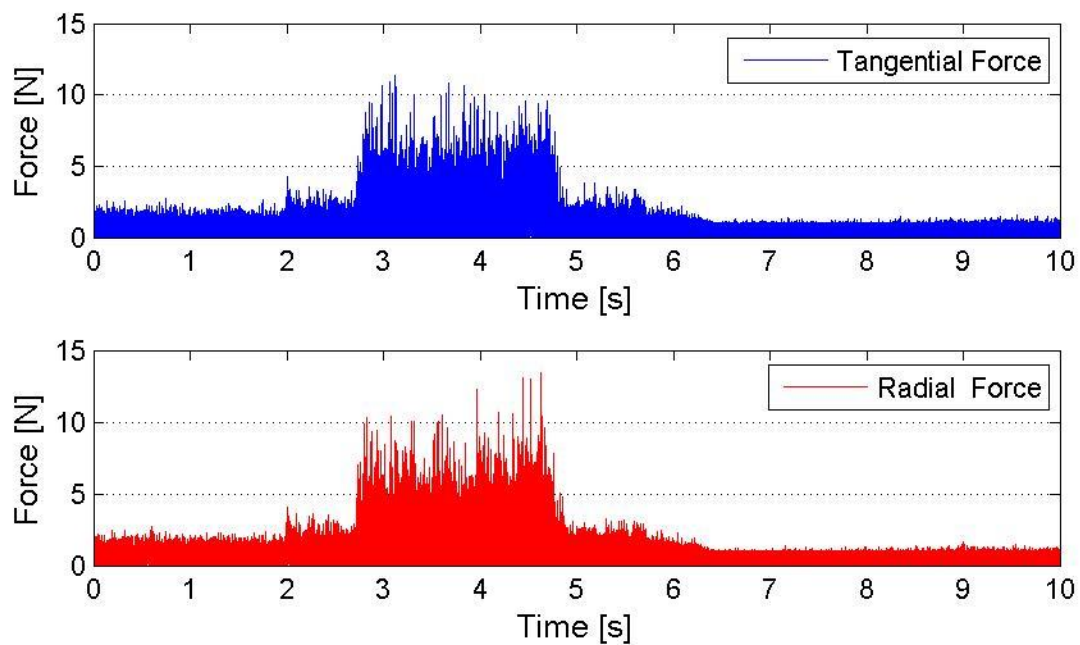


Figure G-268: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

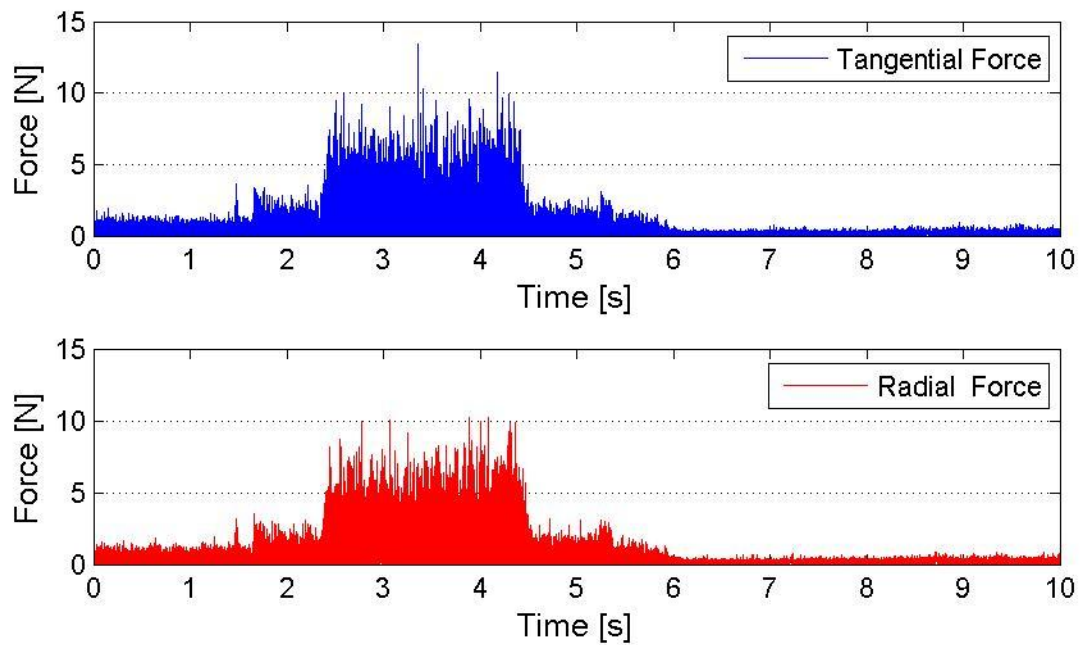


Figure G-269: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

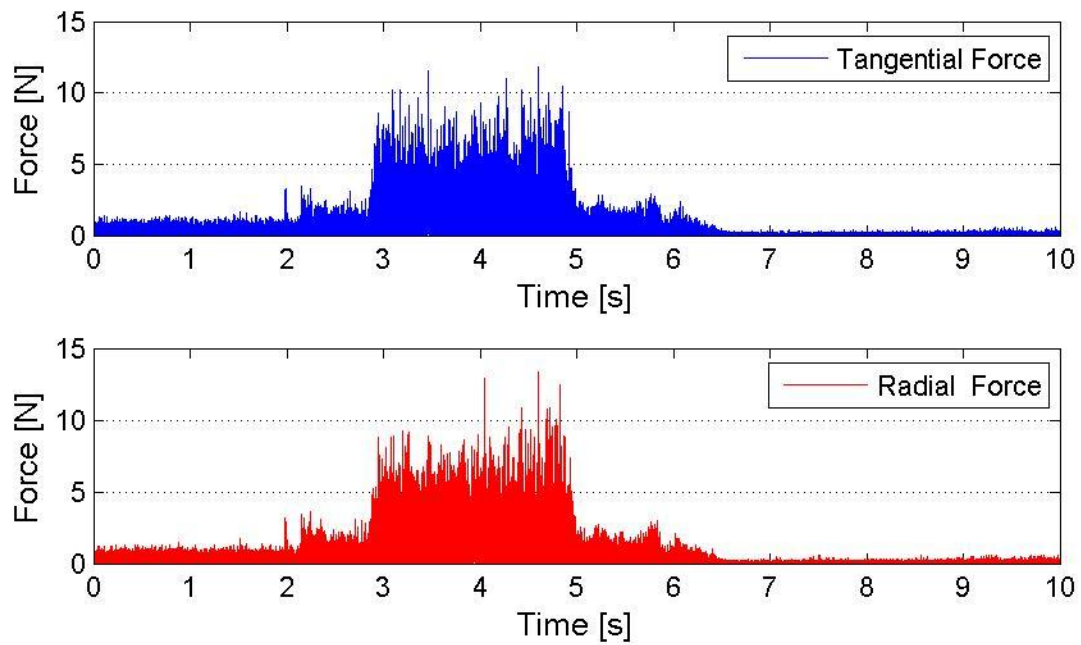


Figure G-270: Tangential and radial cutting force of Cfoam at 5000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

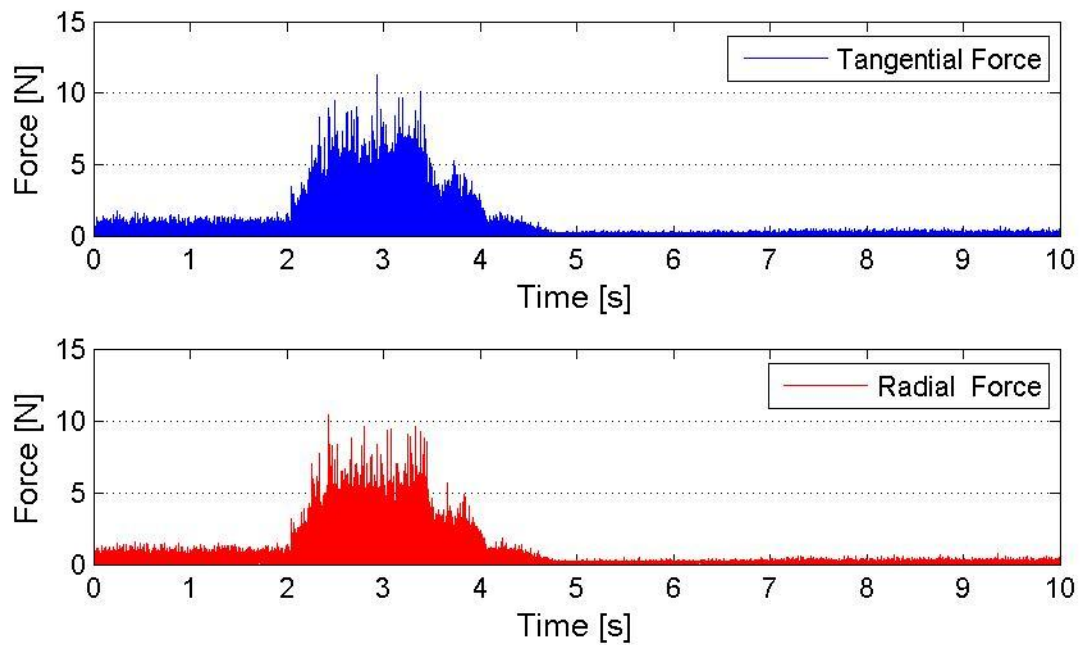


Figure G-271: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

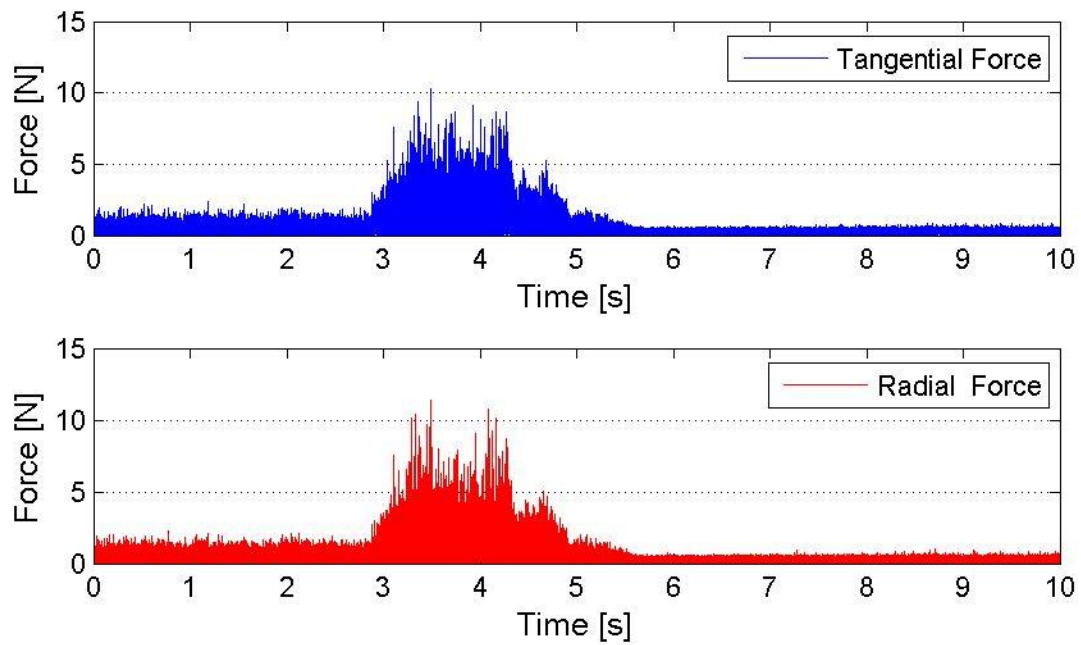


Figure G-272: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

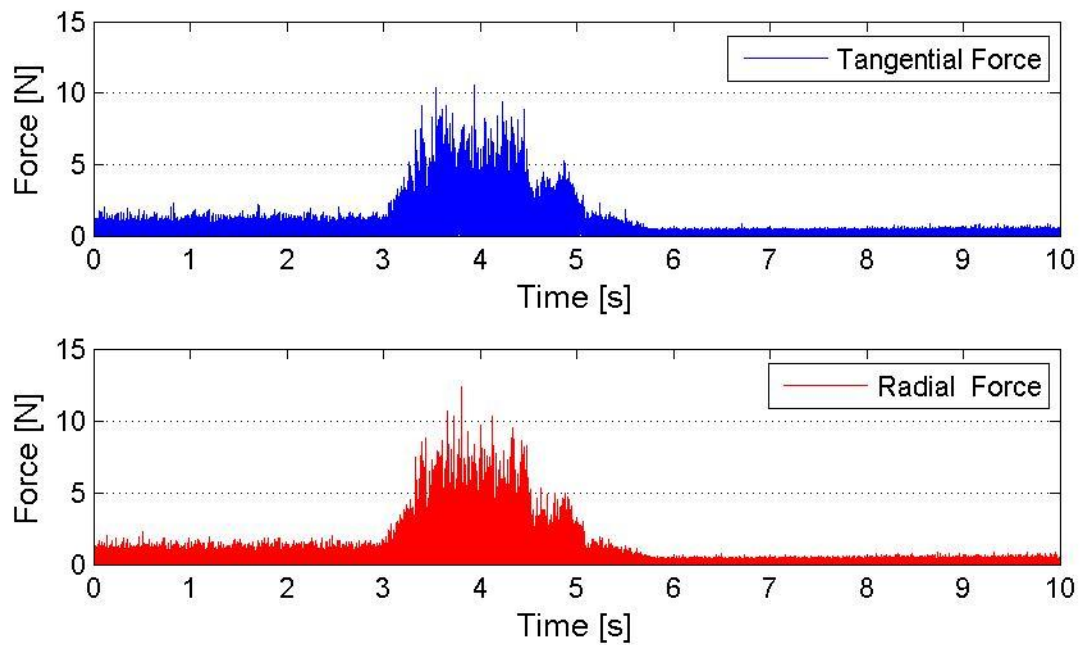


Figure G-273: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

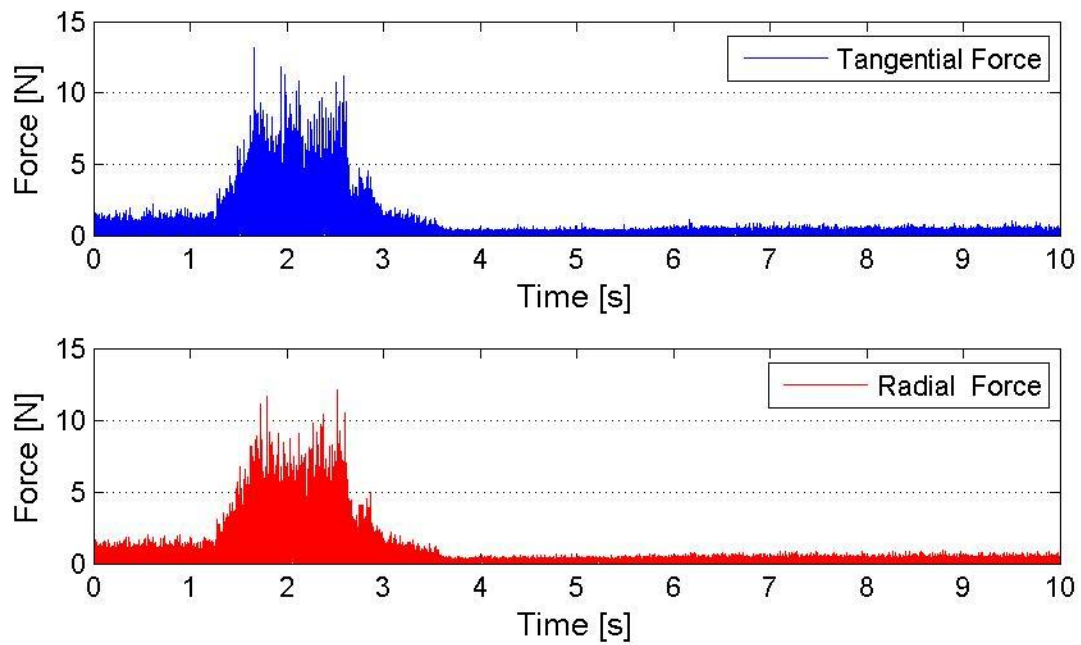


Figure G-274: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

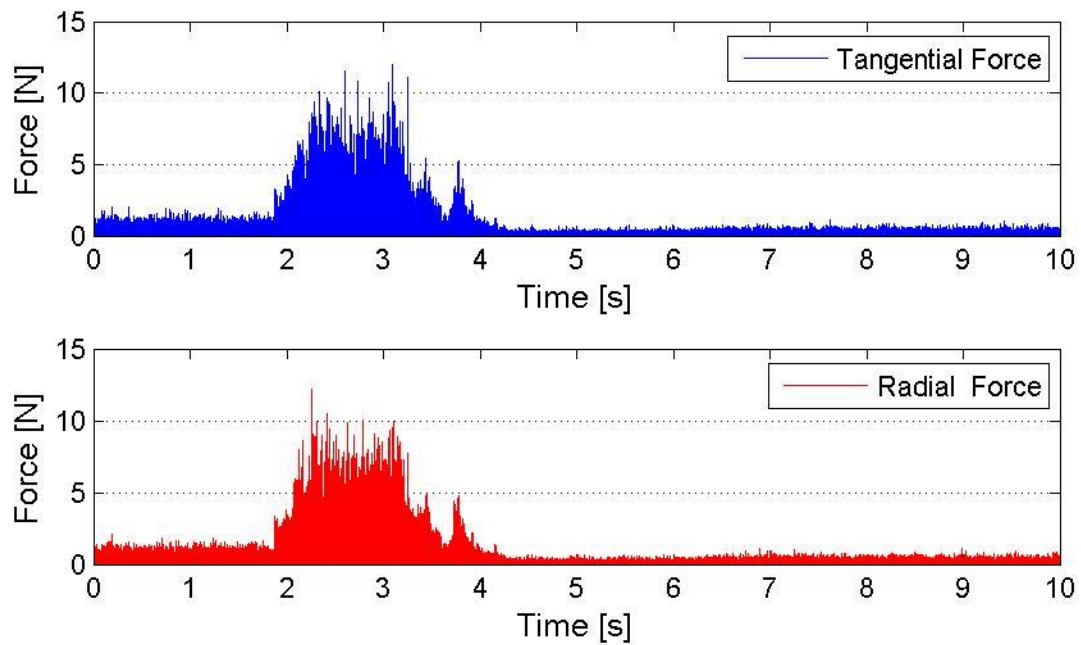


Figure G-275: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

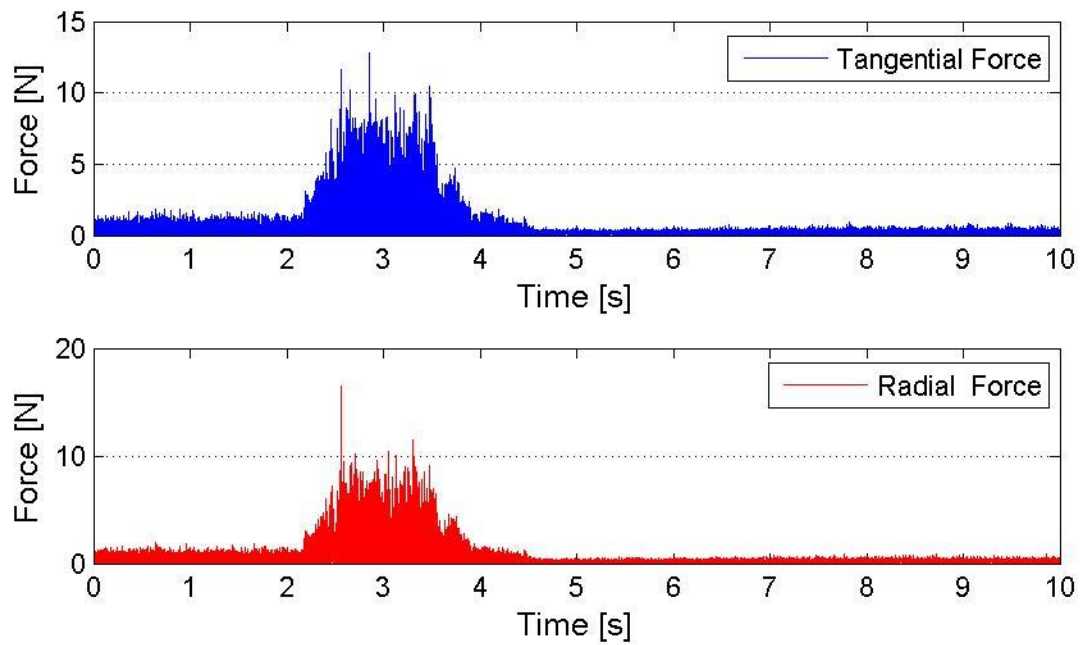


Figure G-276: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

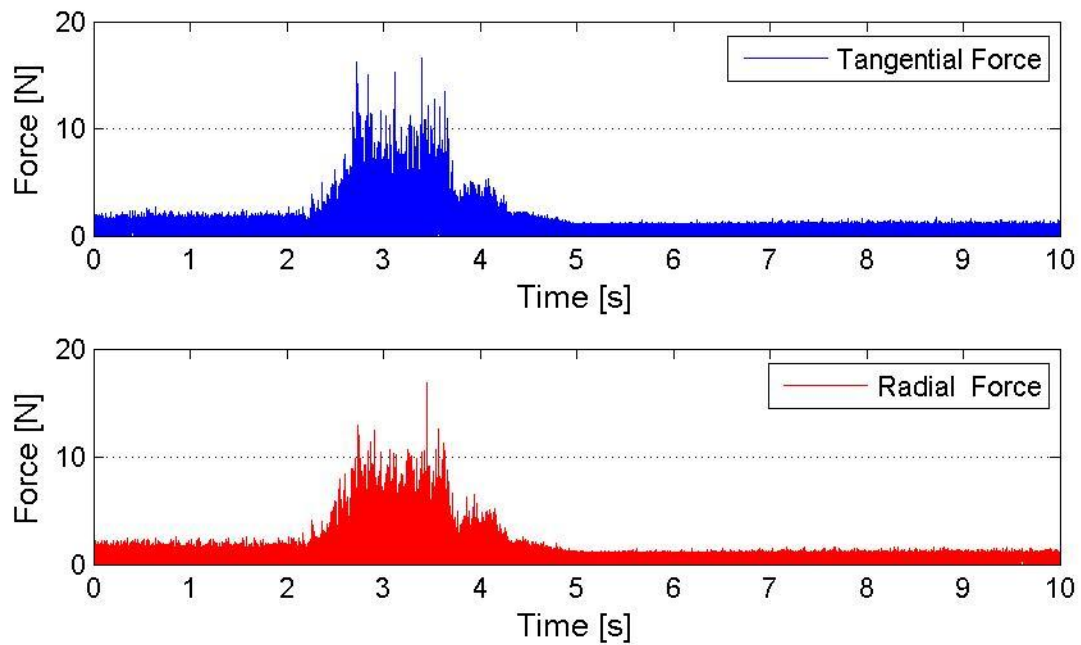


Figure G-277: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

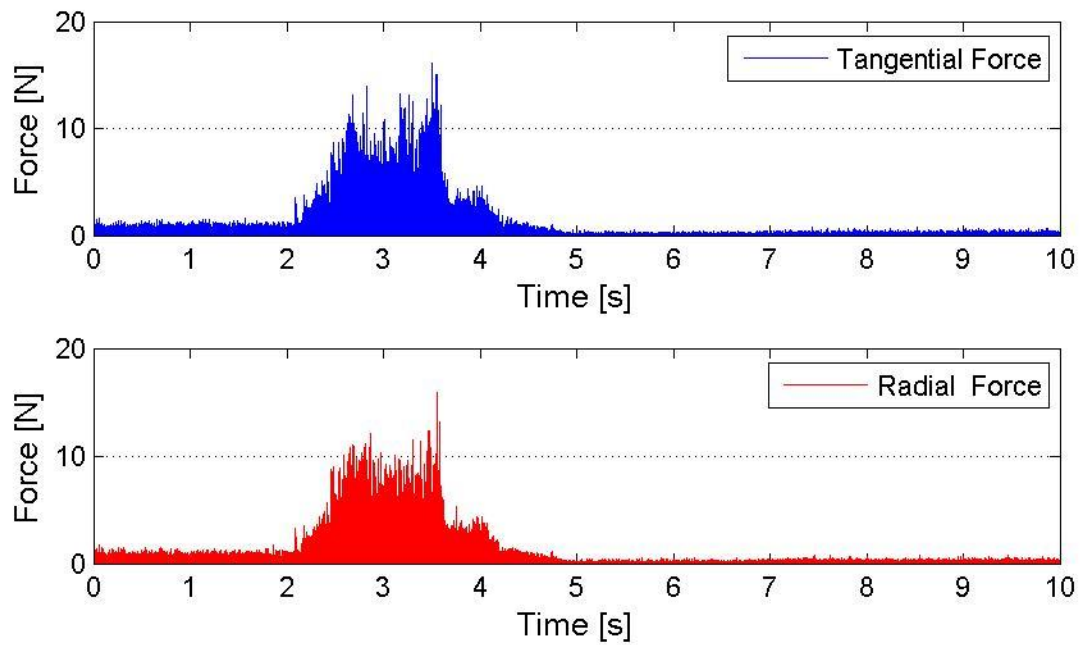


Figure G-278: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

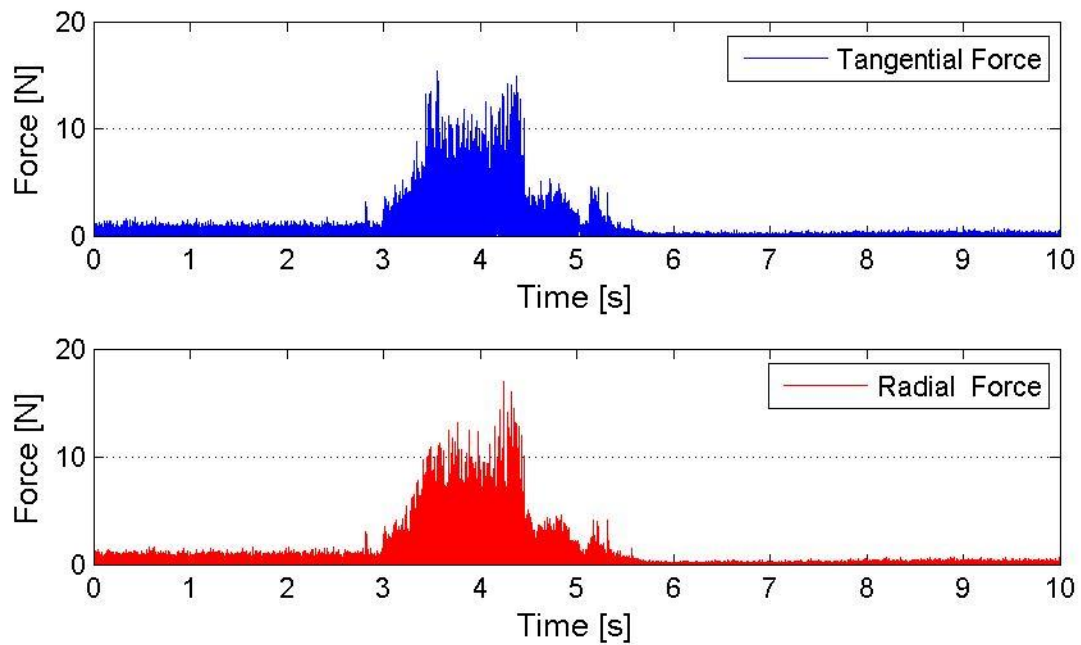


Figure G-279: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

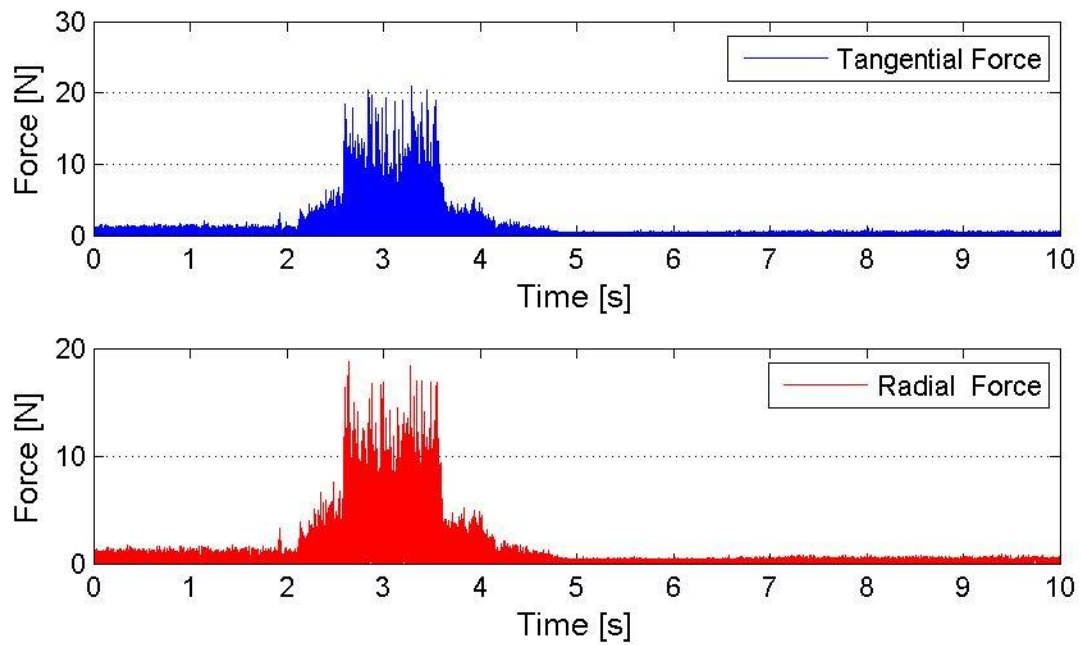


Figure G-280: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

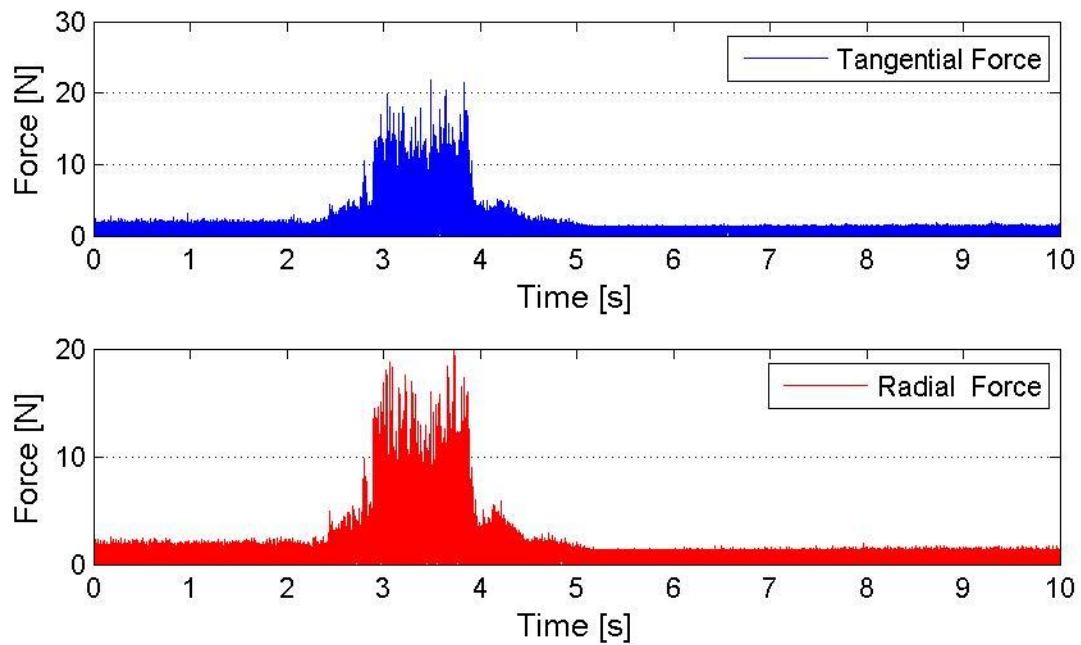


Figure G-281: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

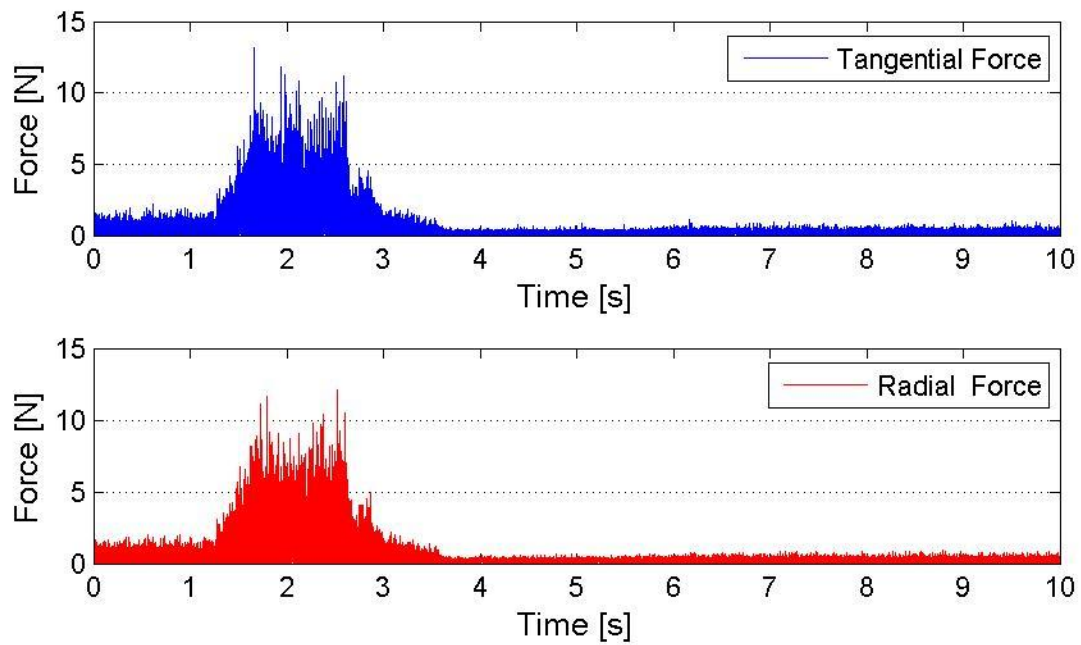


Figure G-282: Tangential and radial cutting force of Cfoam at 5000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

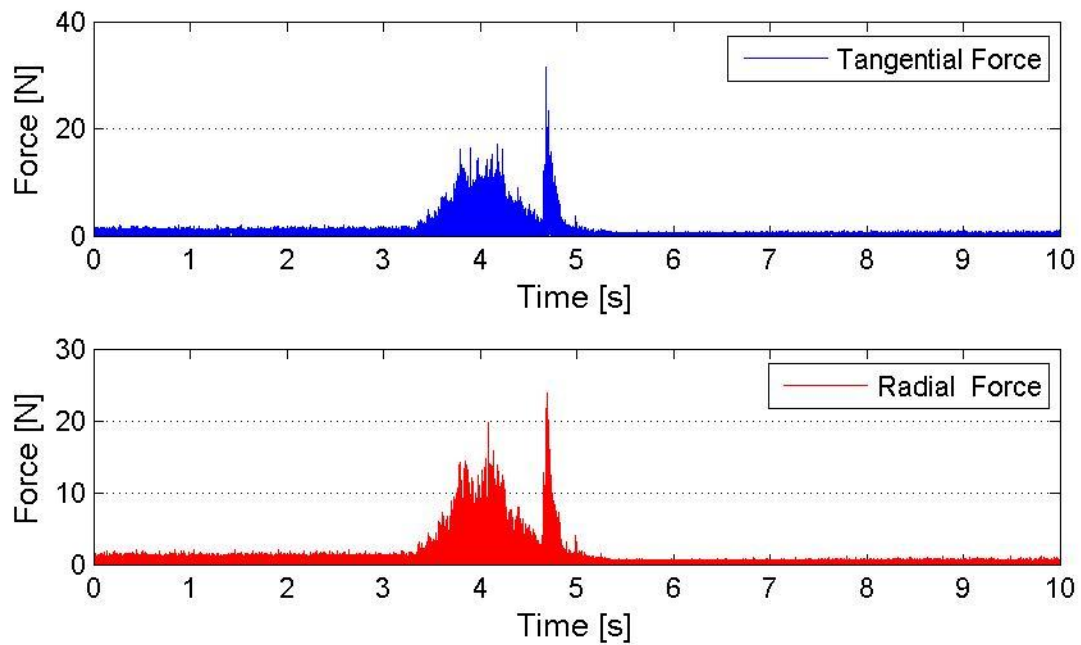


Figure G-283: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

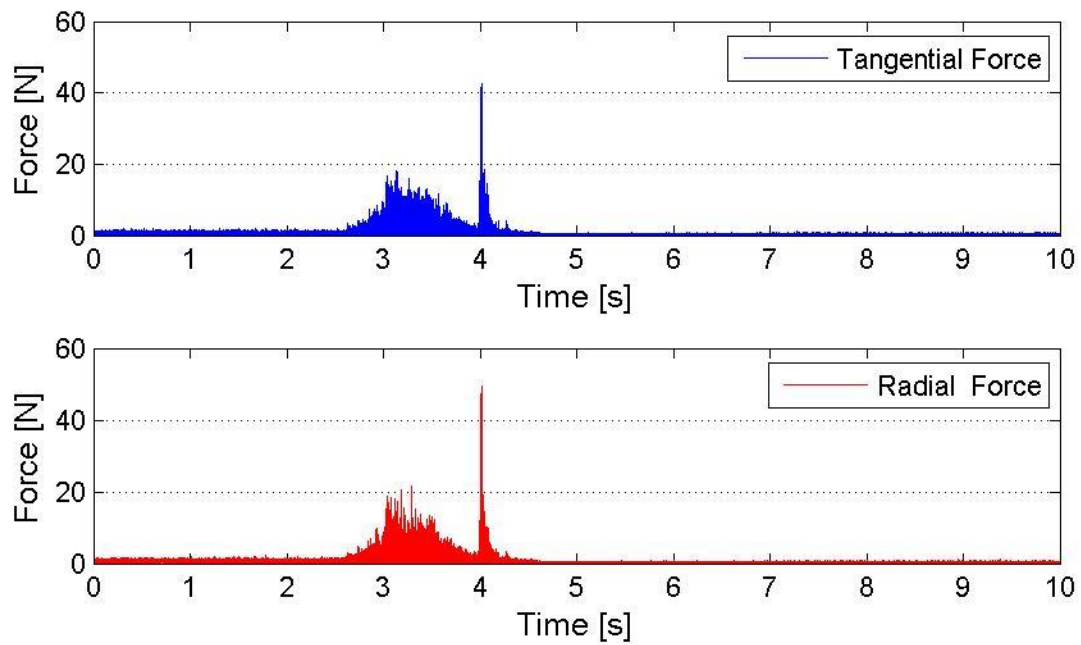


Figure G-284: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

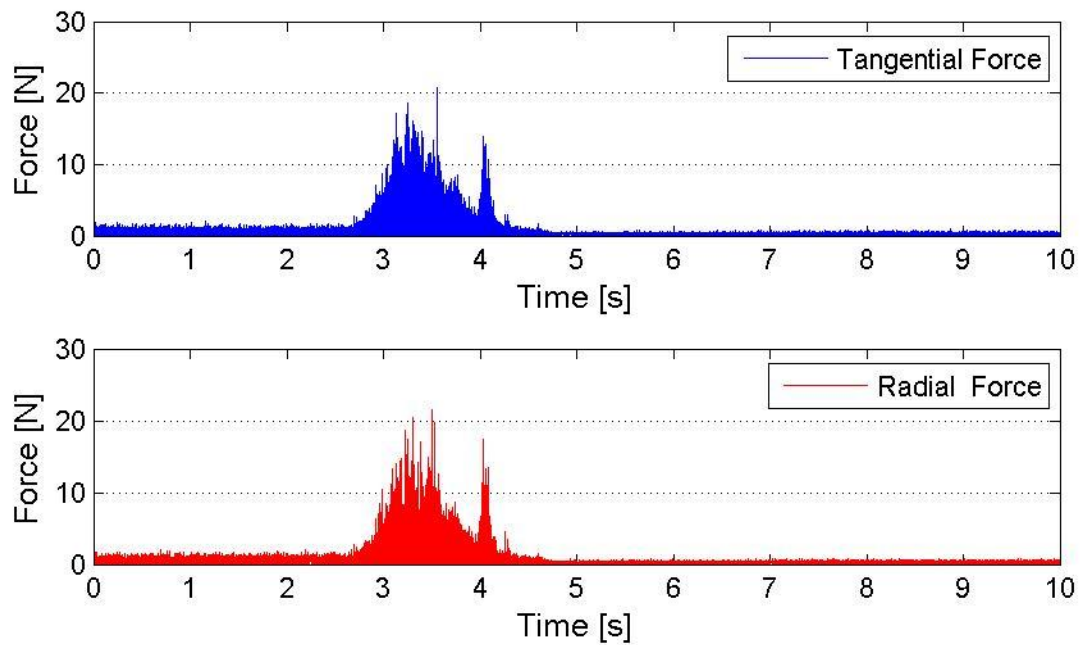


Figure G-285: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

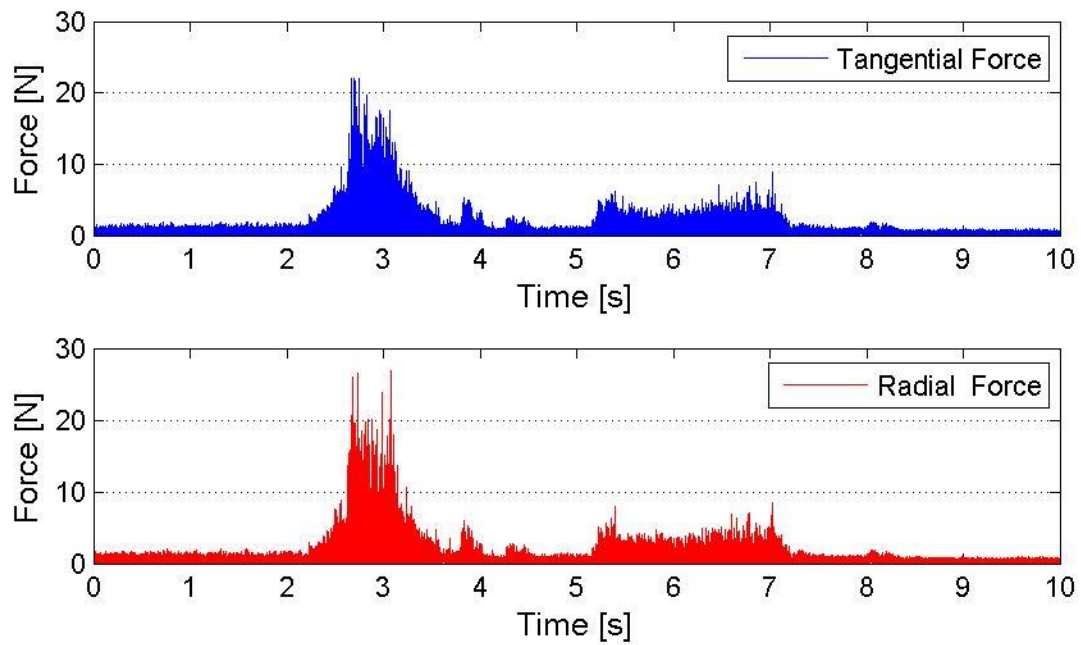


Figure G-286: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

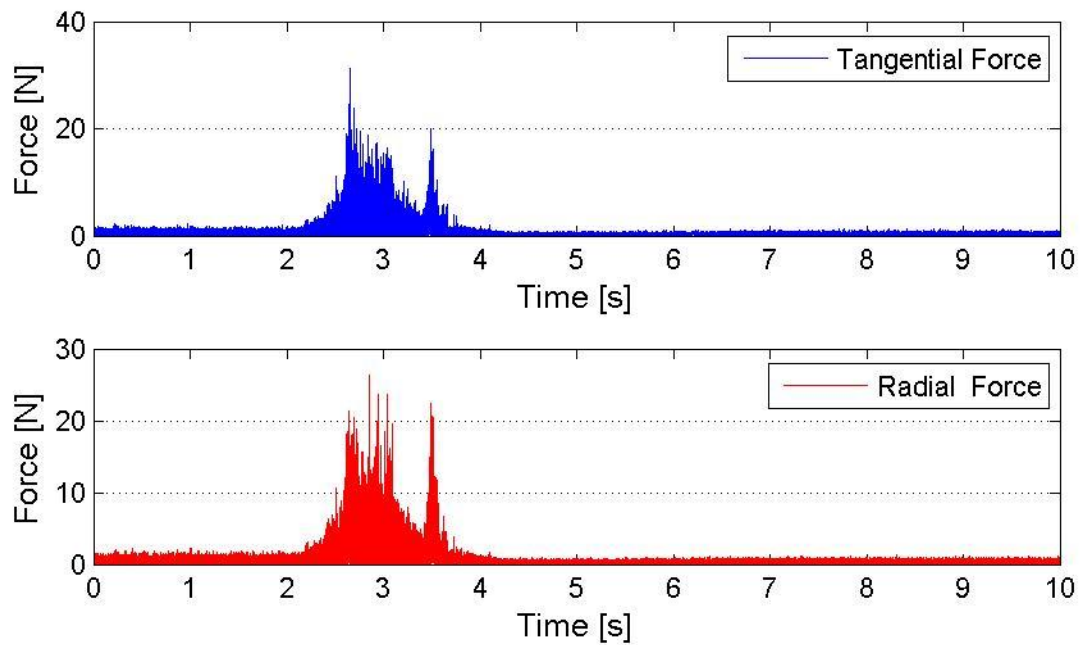


Figure G-287: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

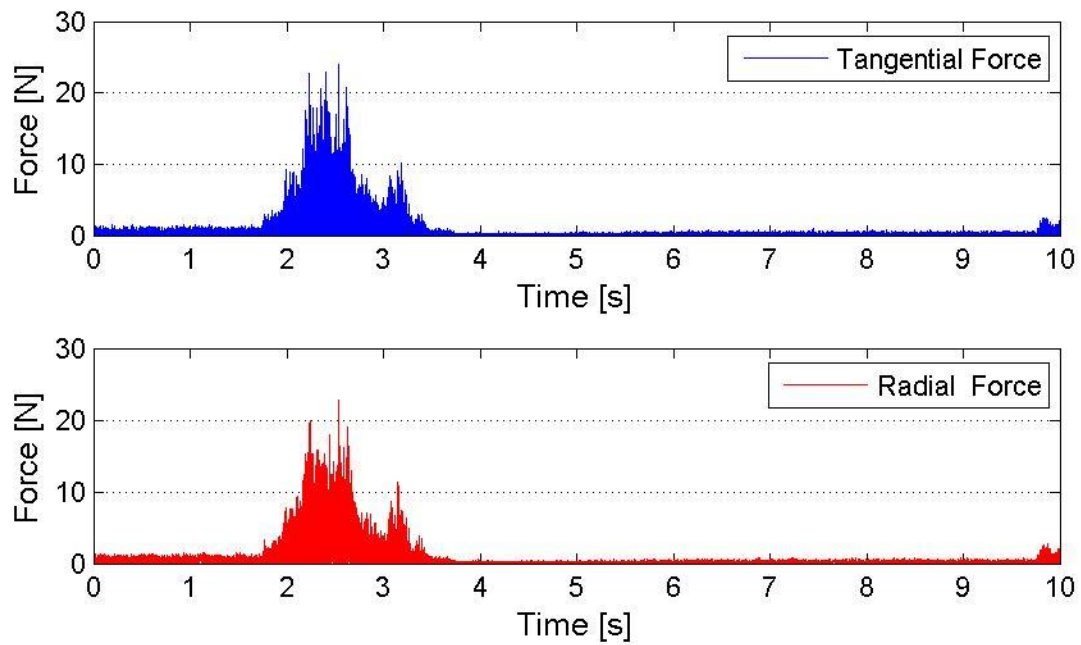


Figure G-288: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

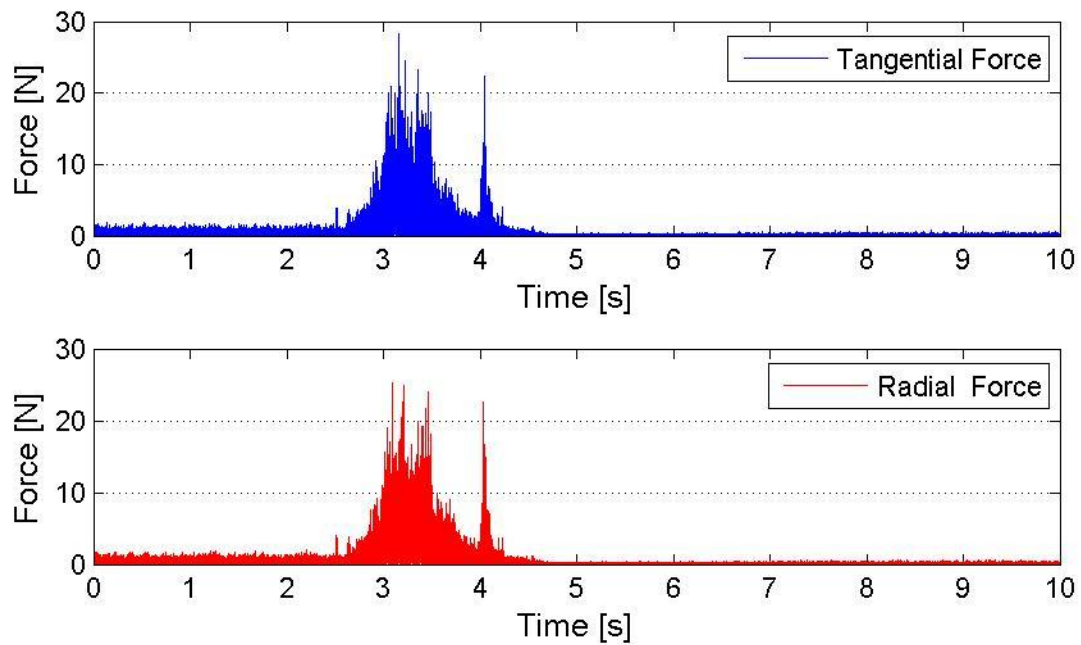


Figure G-289: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

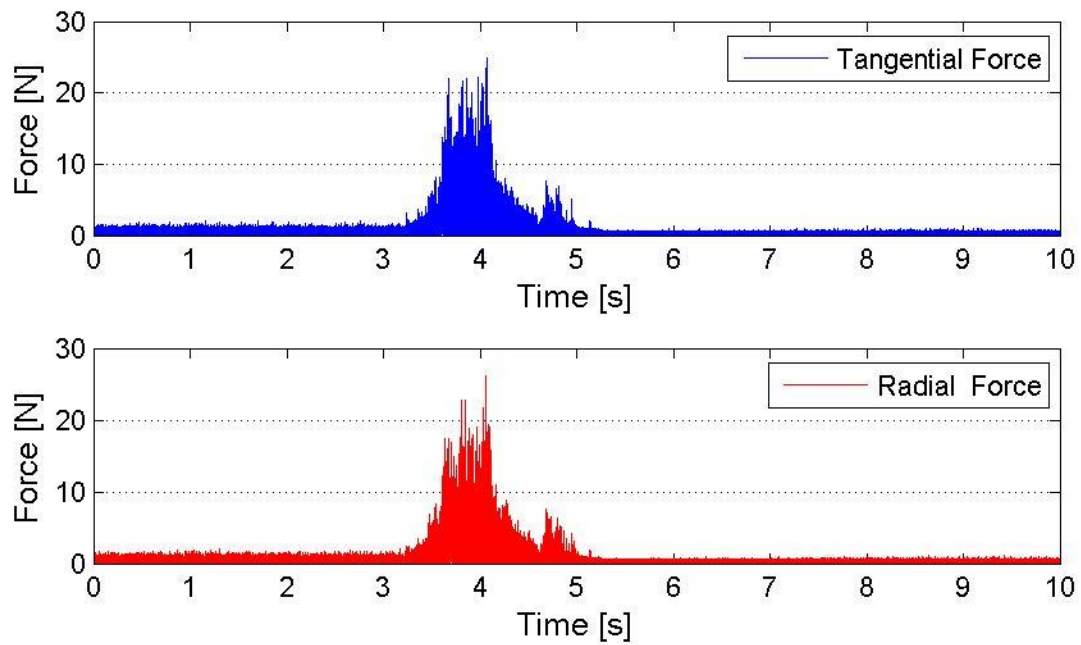


Figure G-290: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

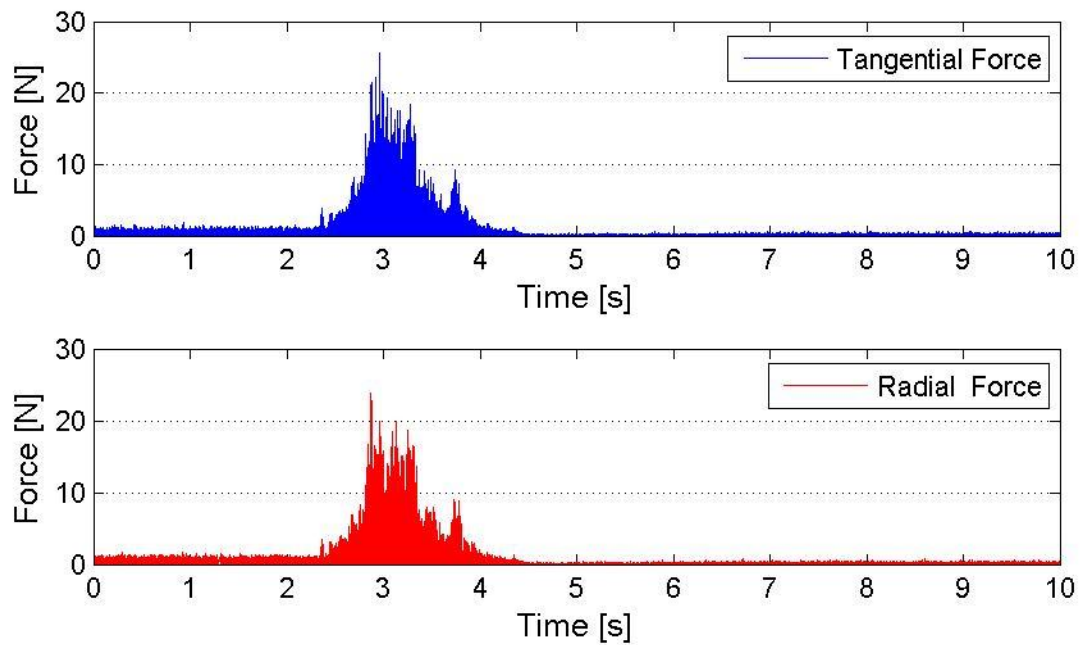


Figure G-291: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

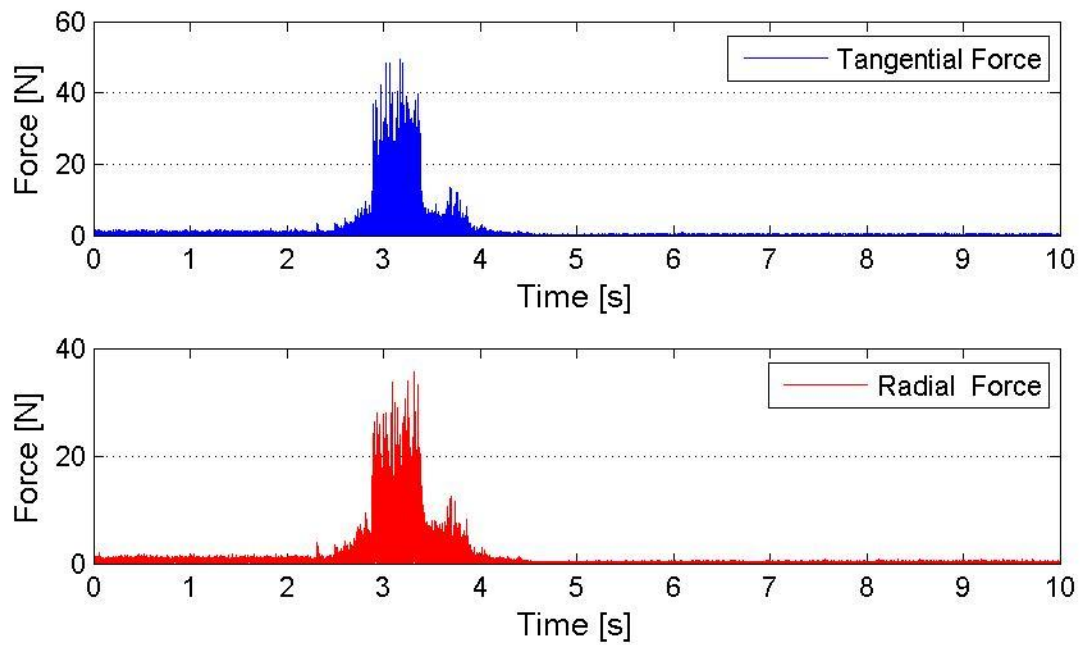


Figure G-292: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

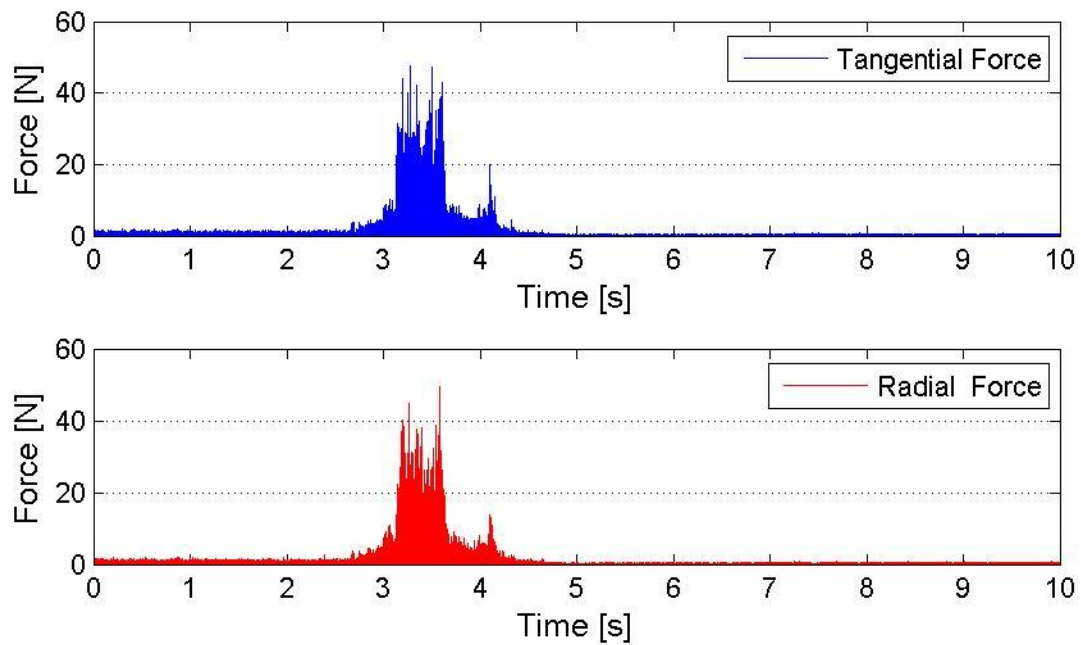


Figure G-293: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

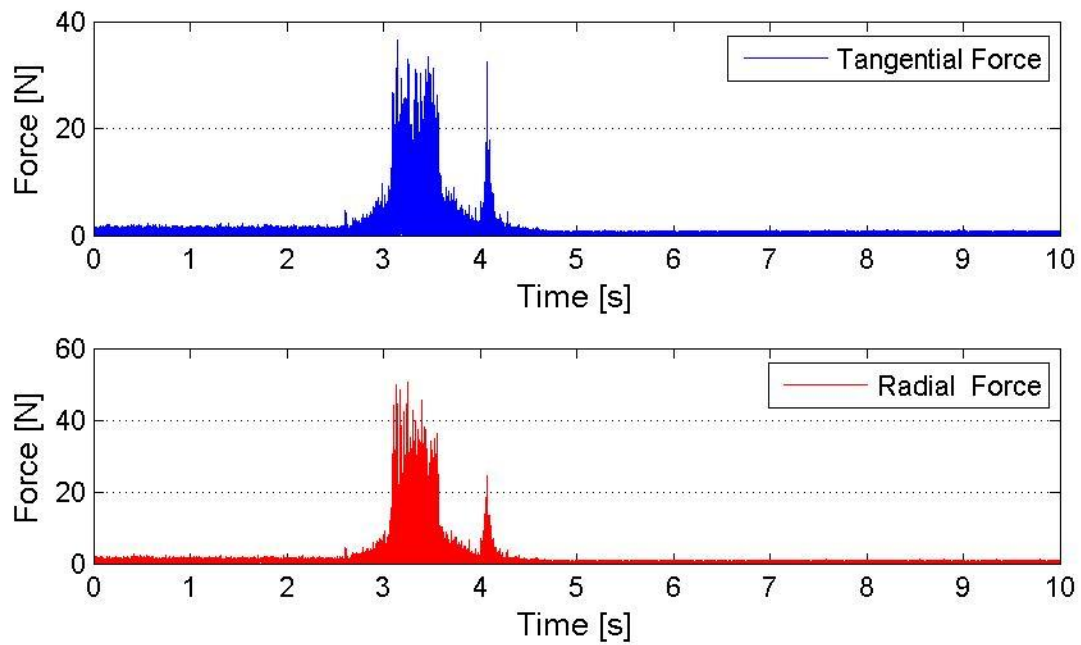


Figure G-294: Tangential and radial cutting force of Cfoam at 5000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

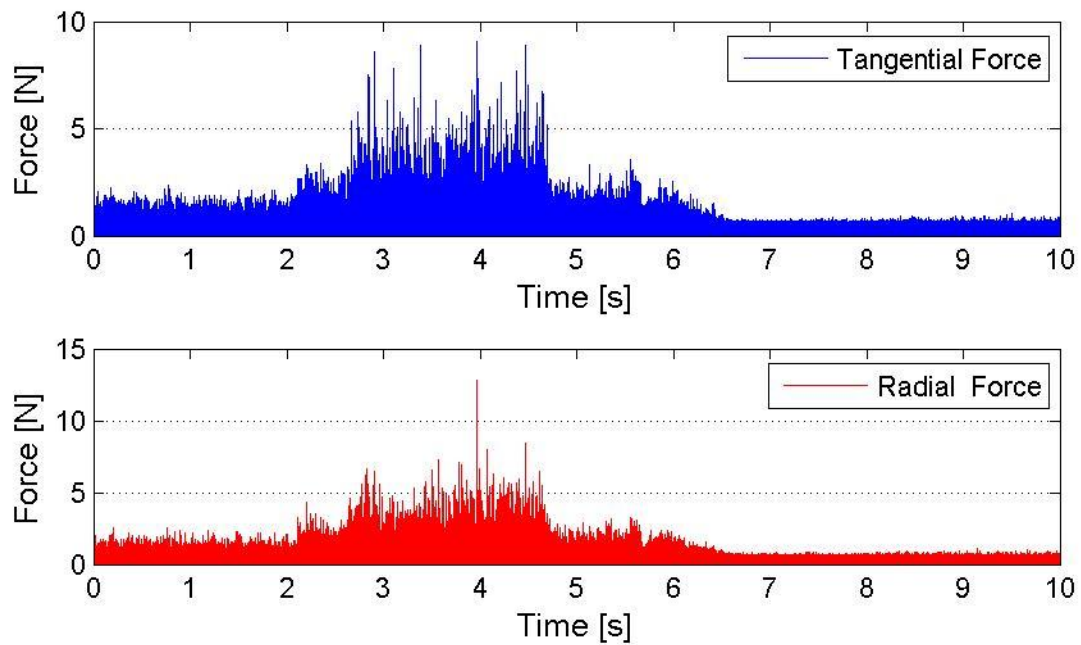


Figure G-295: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

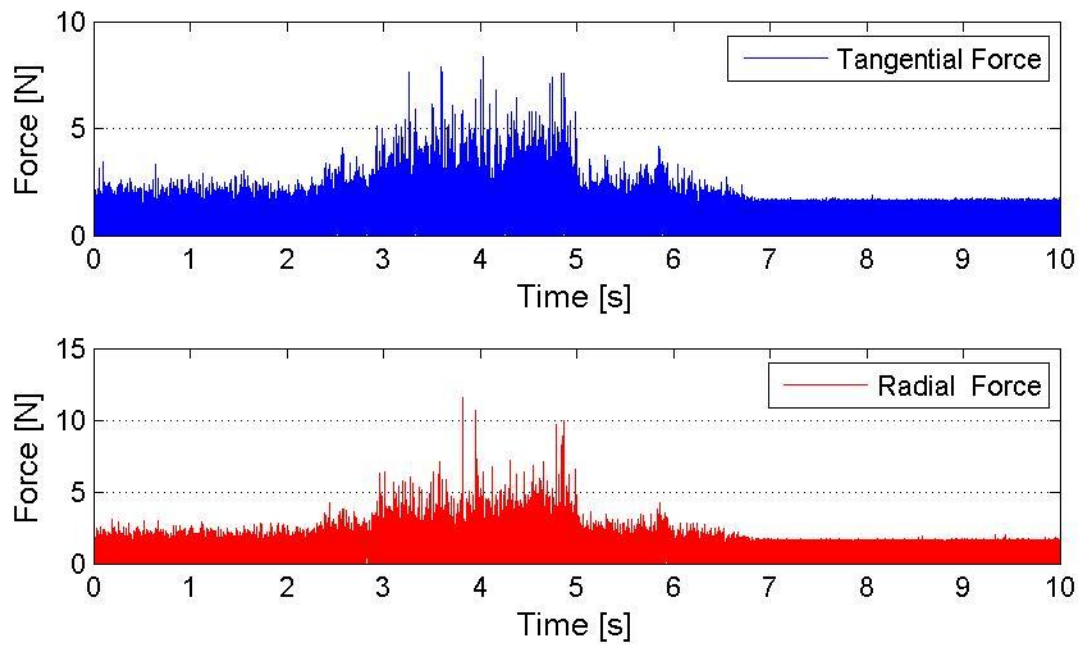


Figure G-296: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

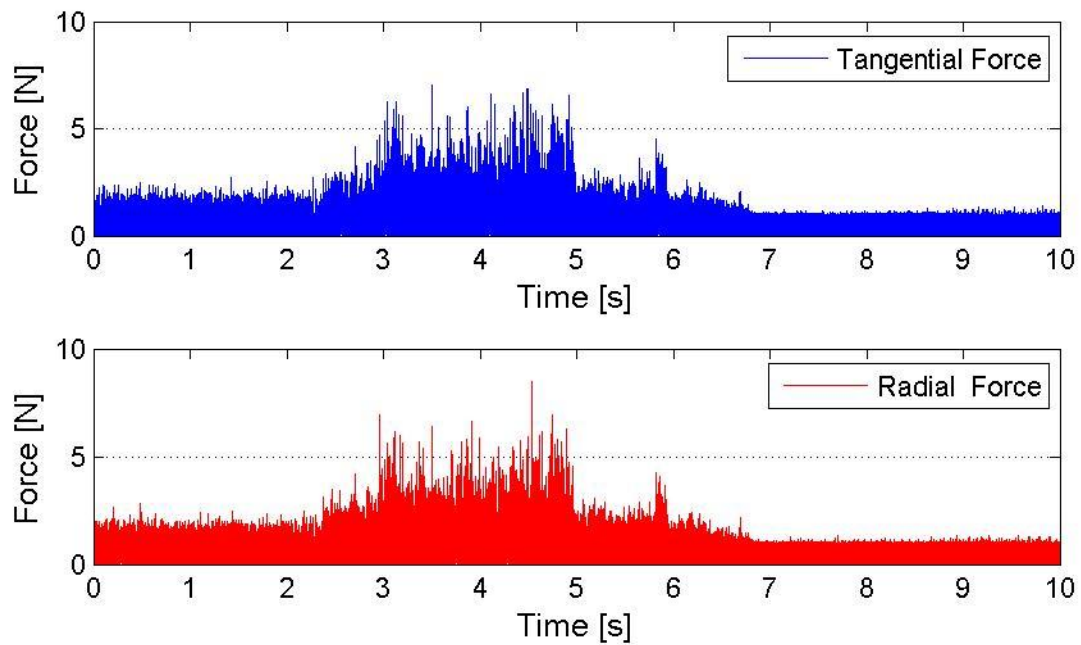


Figure G-297: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

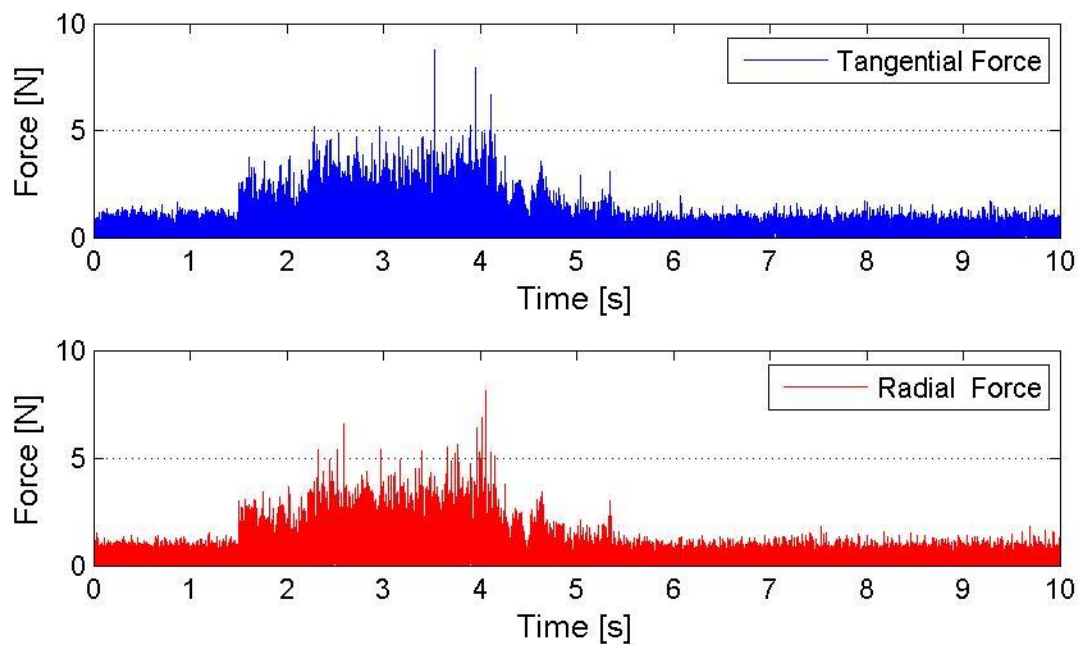


Figure G-298: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

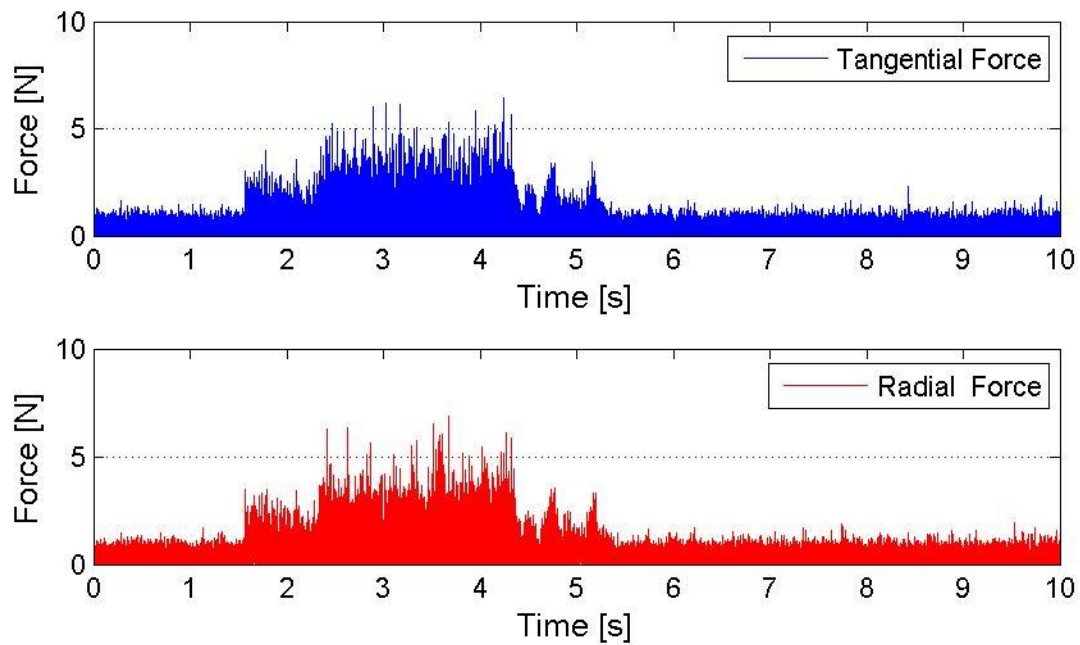


Figure G-299: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

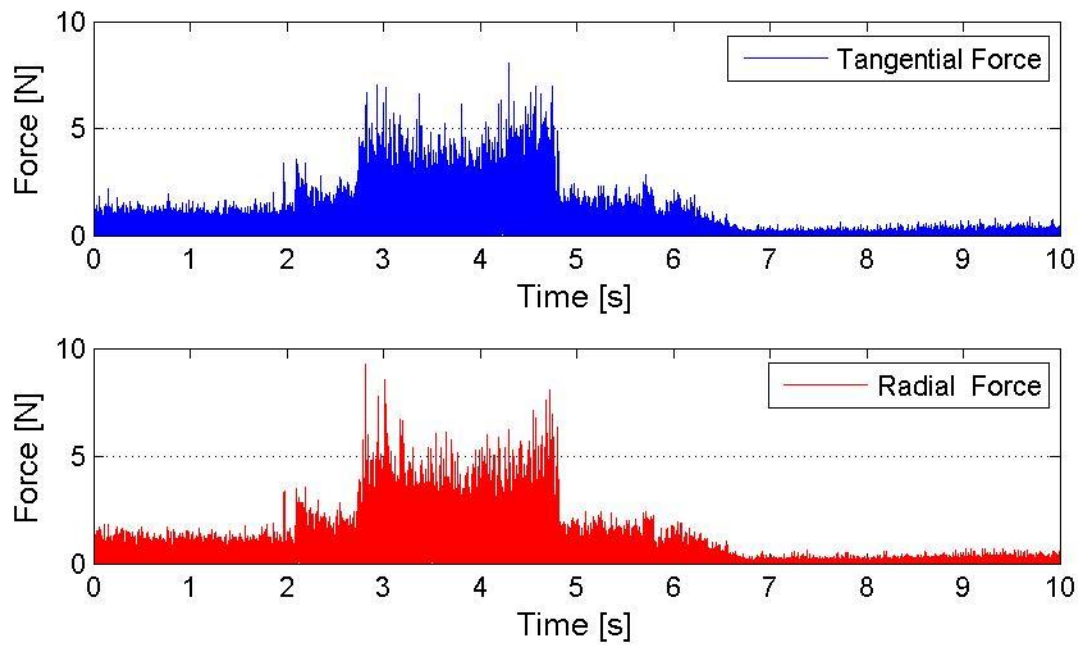


Figure G-300: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

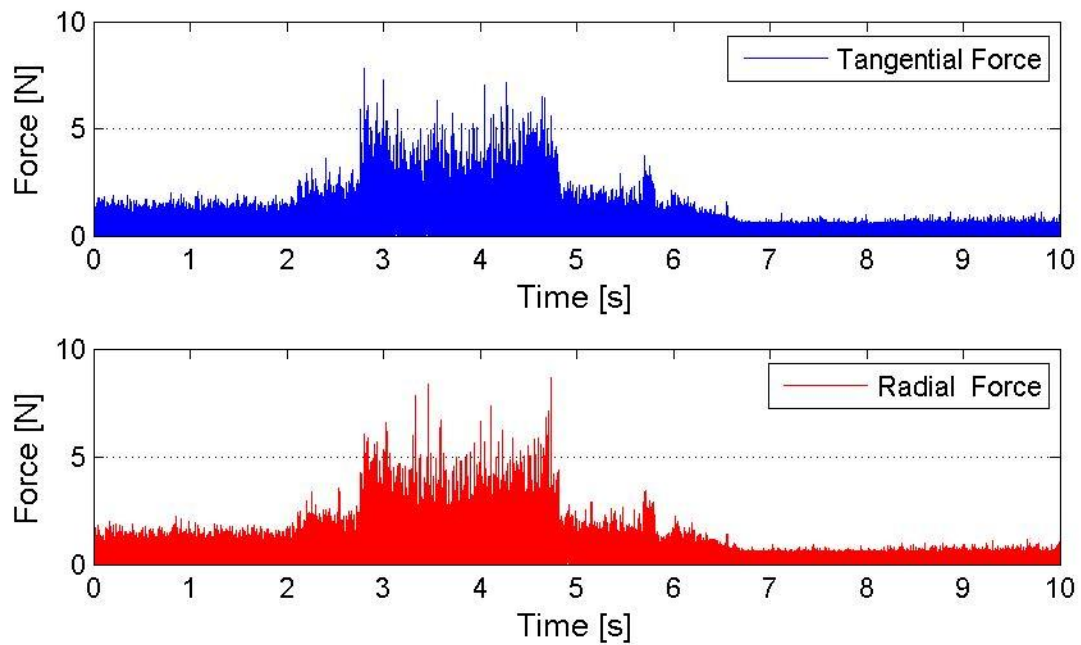


Figure G-301: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

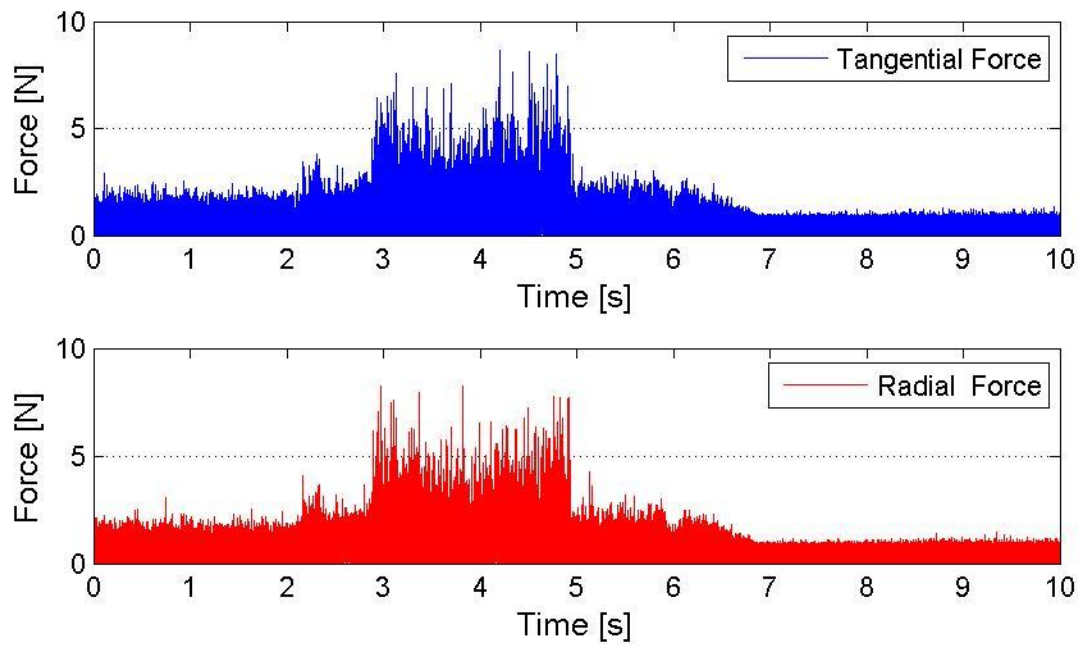


Figure G-302: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

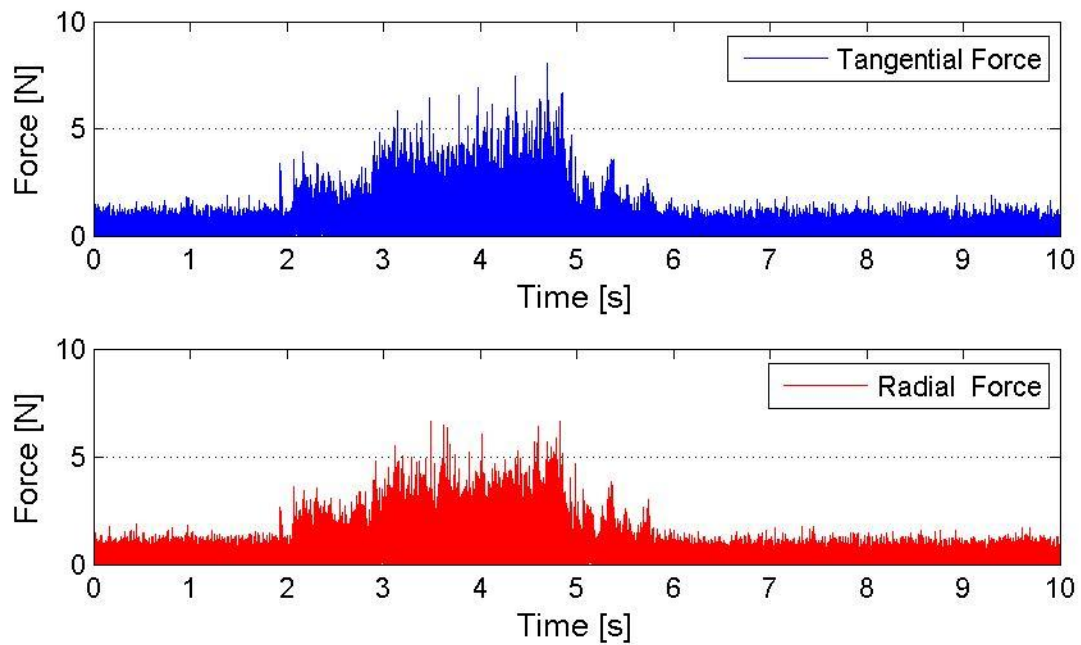


Figure G-303: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

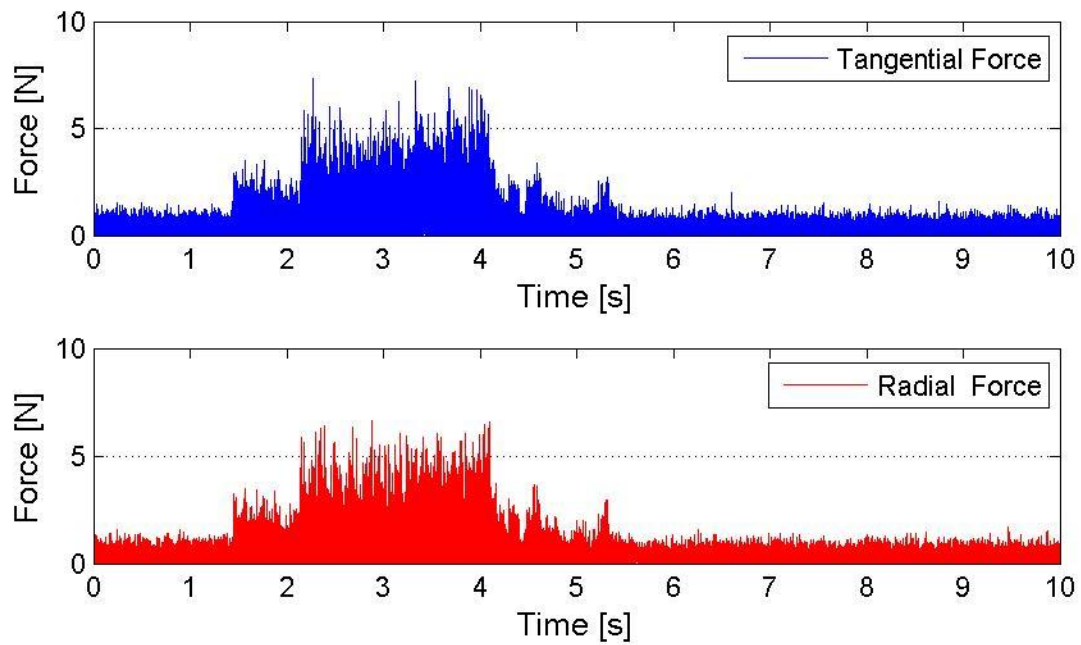


Figure G-304: Tangential and radial cutting force of Cfoam at 6000 RPM, 2.54 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

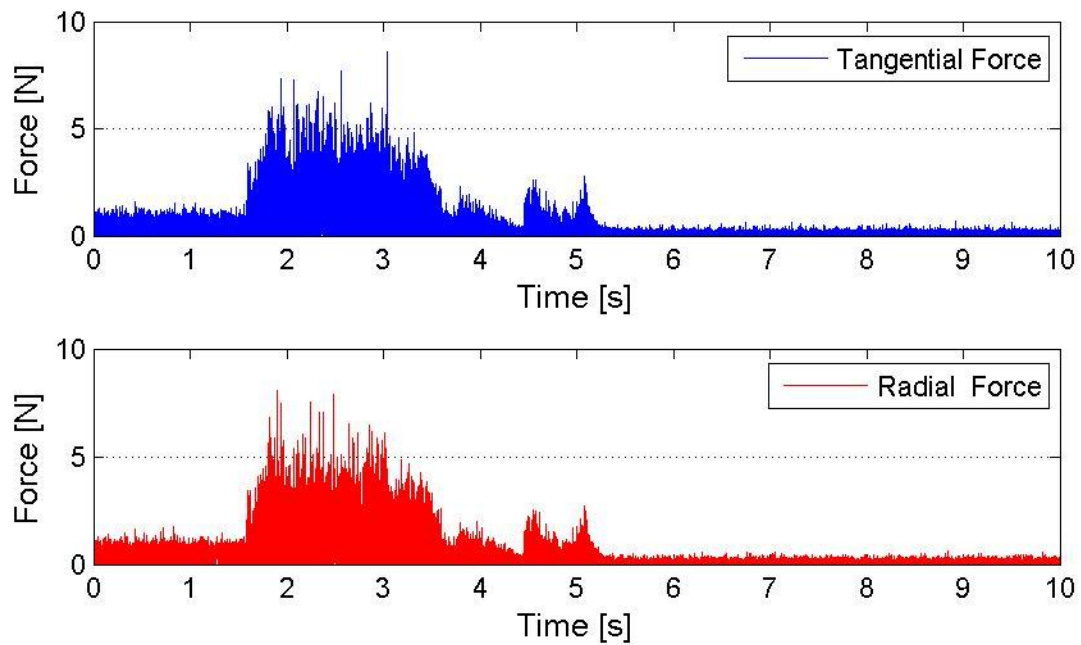


Figure G-305: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

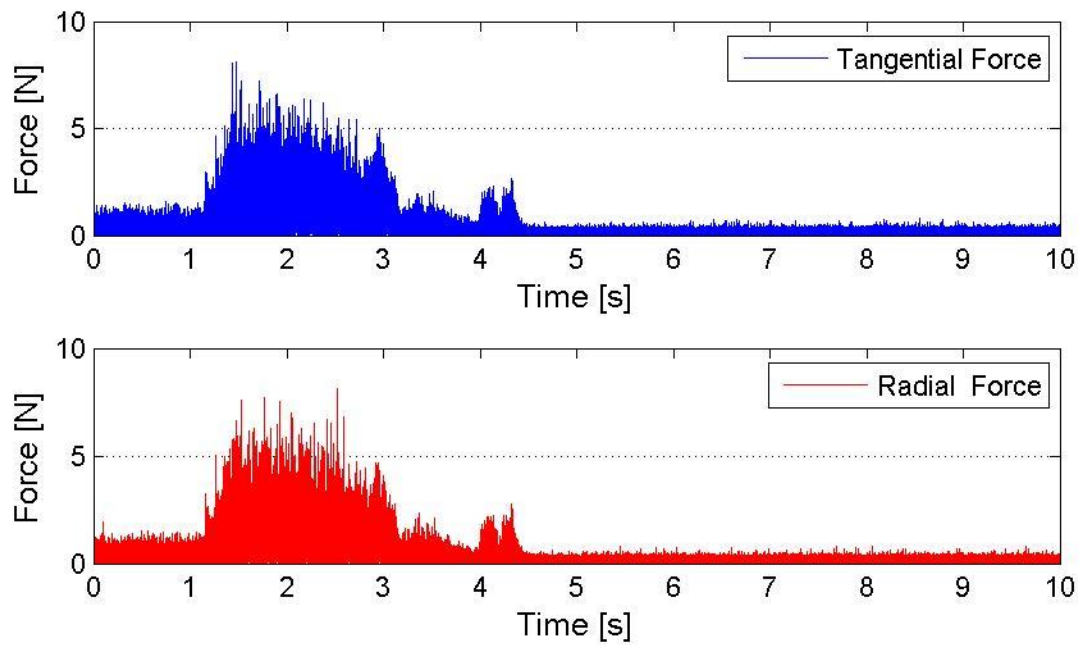


Figure G-306: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

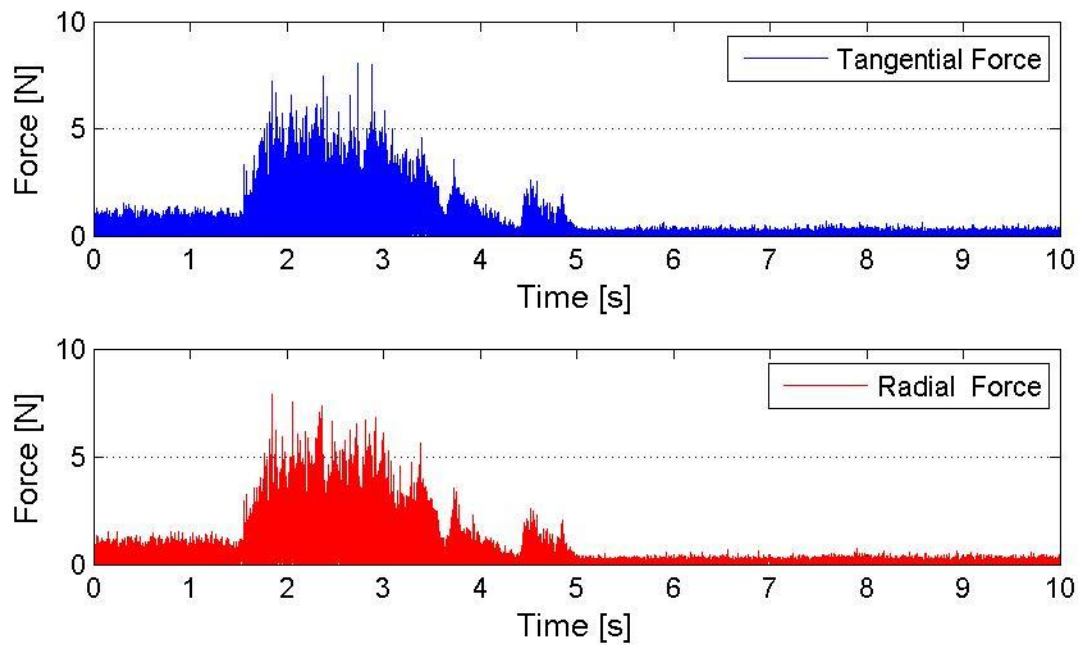


Figure G-307: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

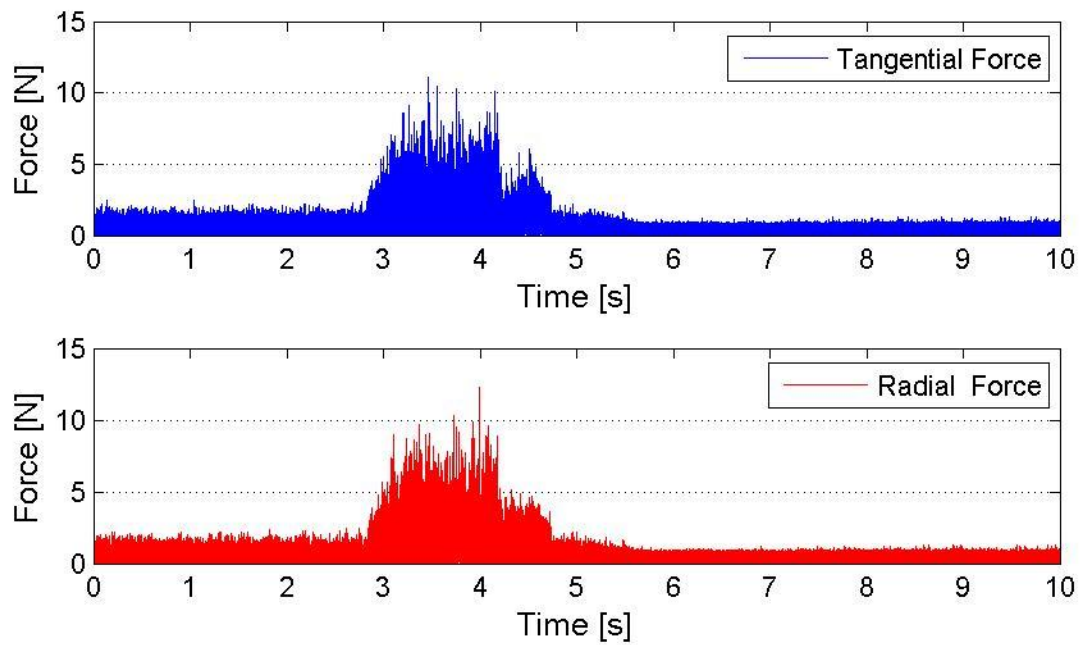


Figure G-308: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

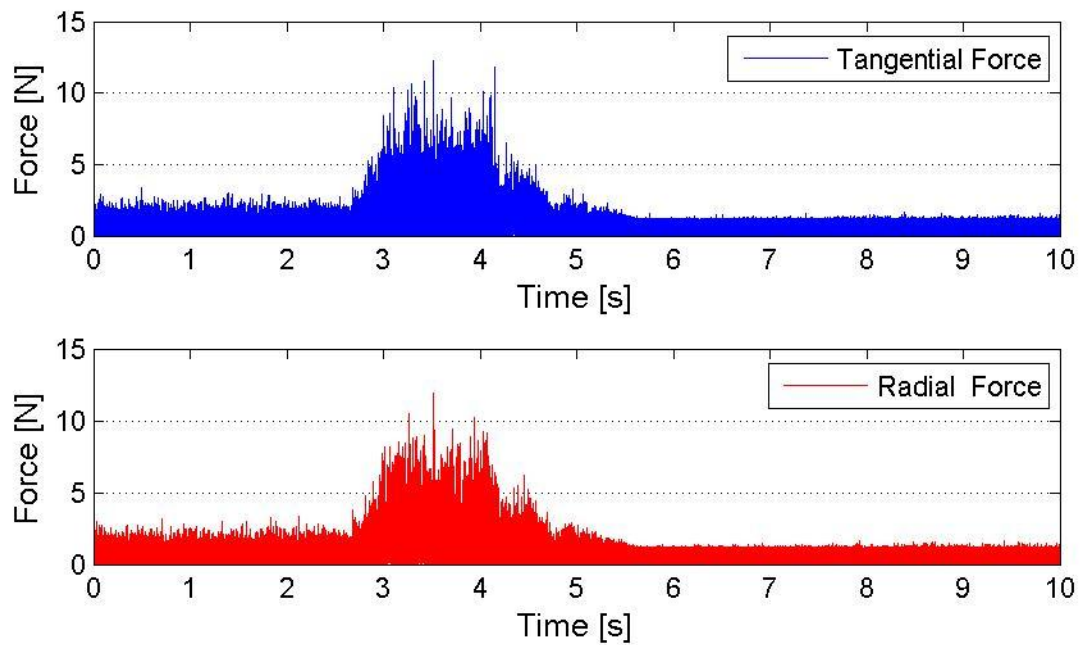


Figure G-309: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

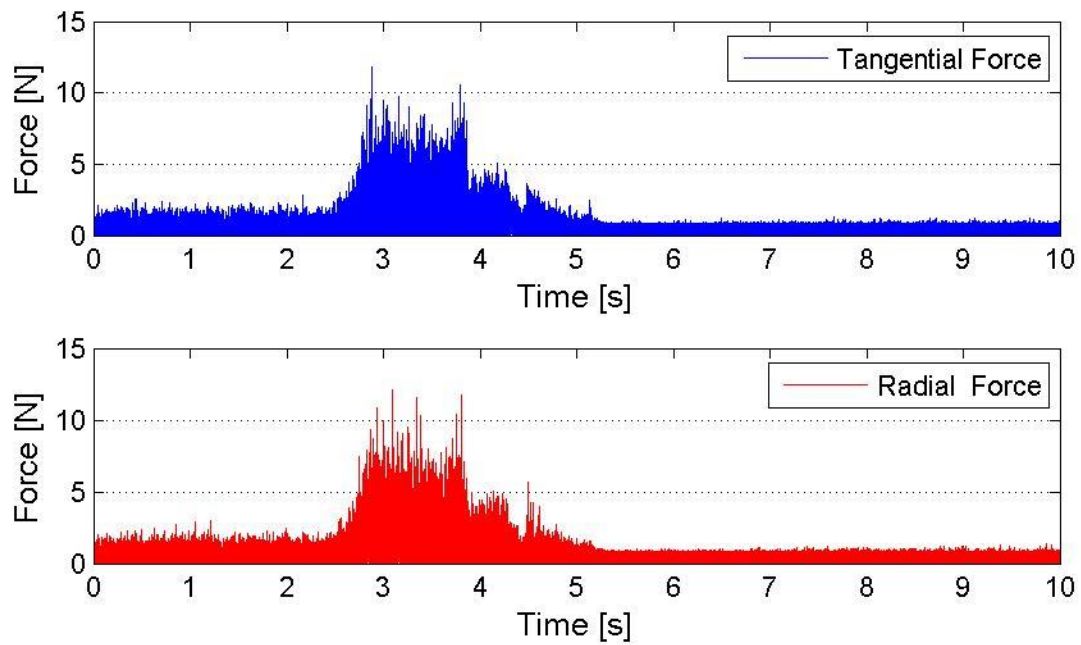


Figure G-310: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

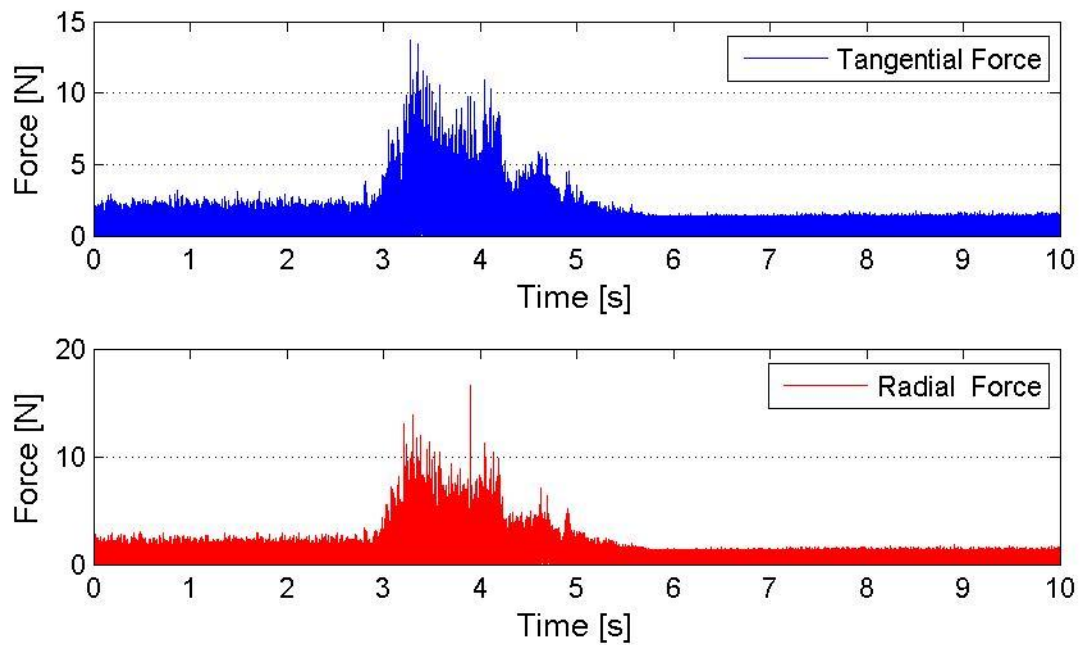


Figure G-311: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

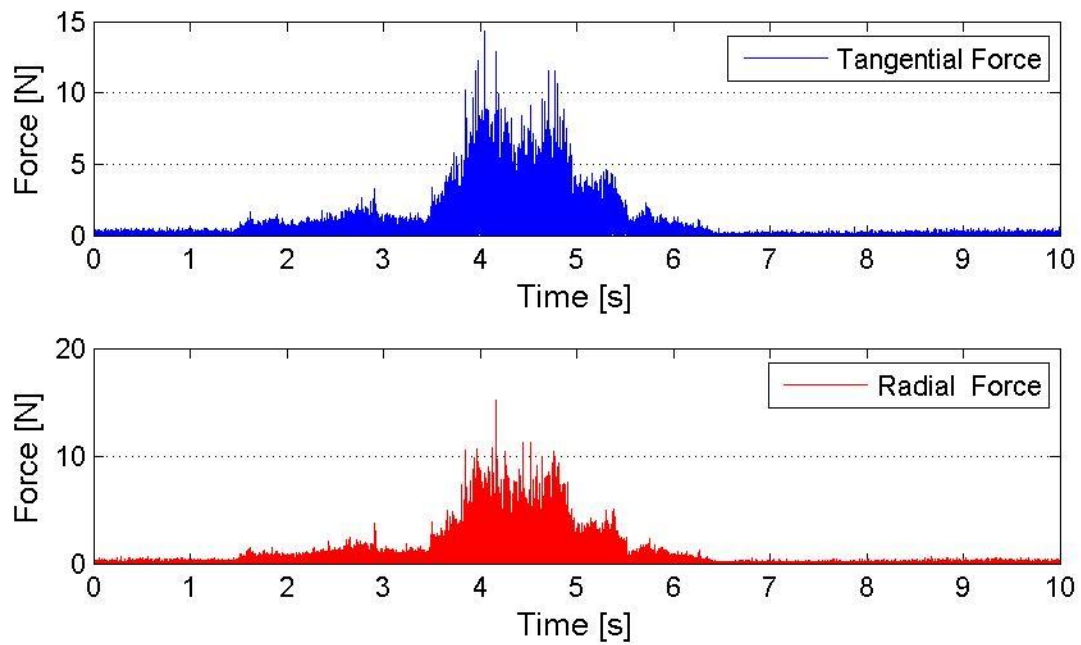


Figure G-312: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

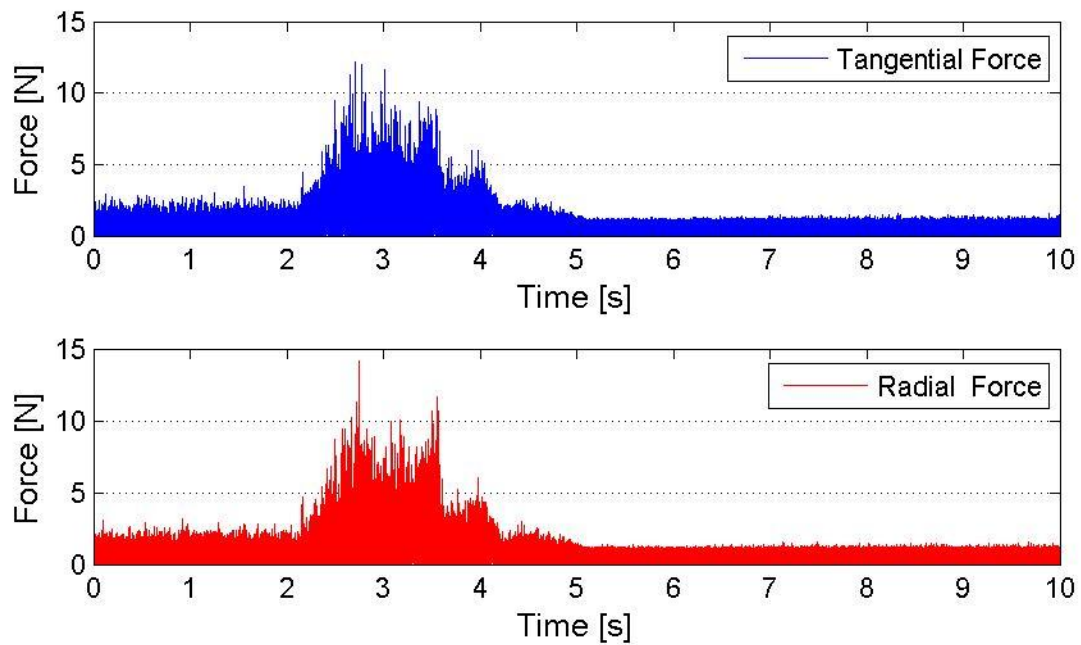


Figure G-313: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

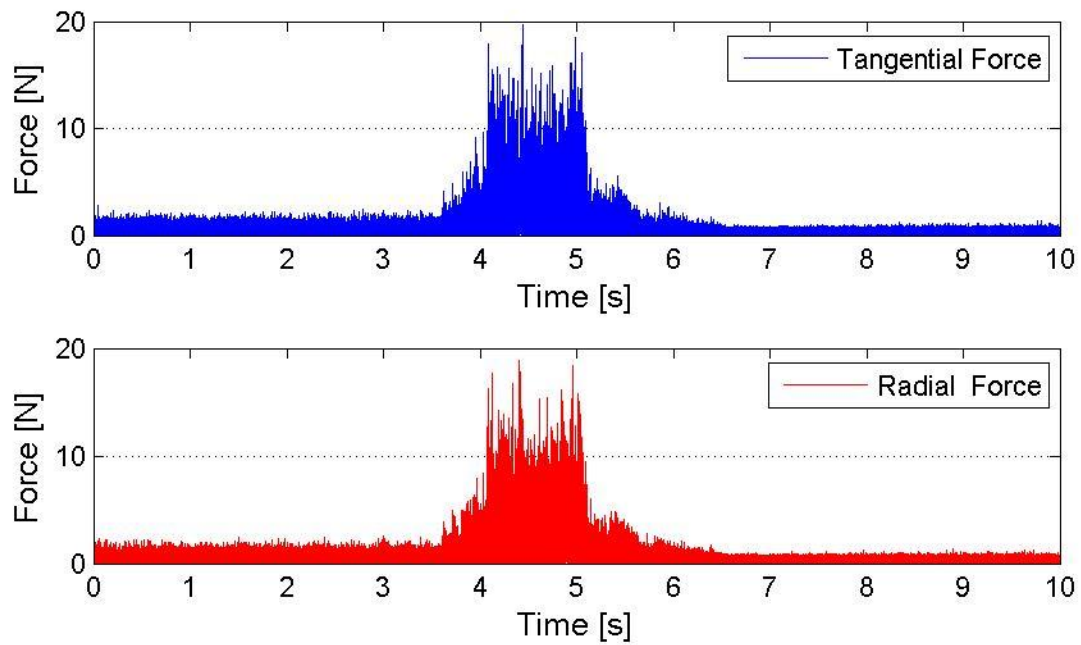


Figure G-314: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

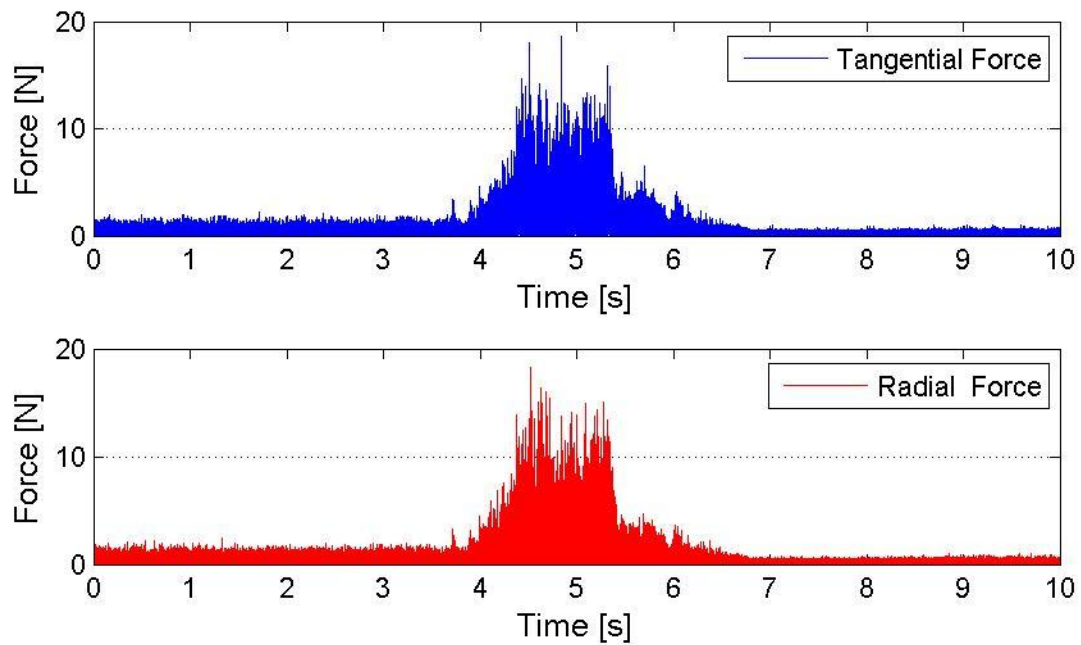


Figure G-315: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

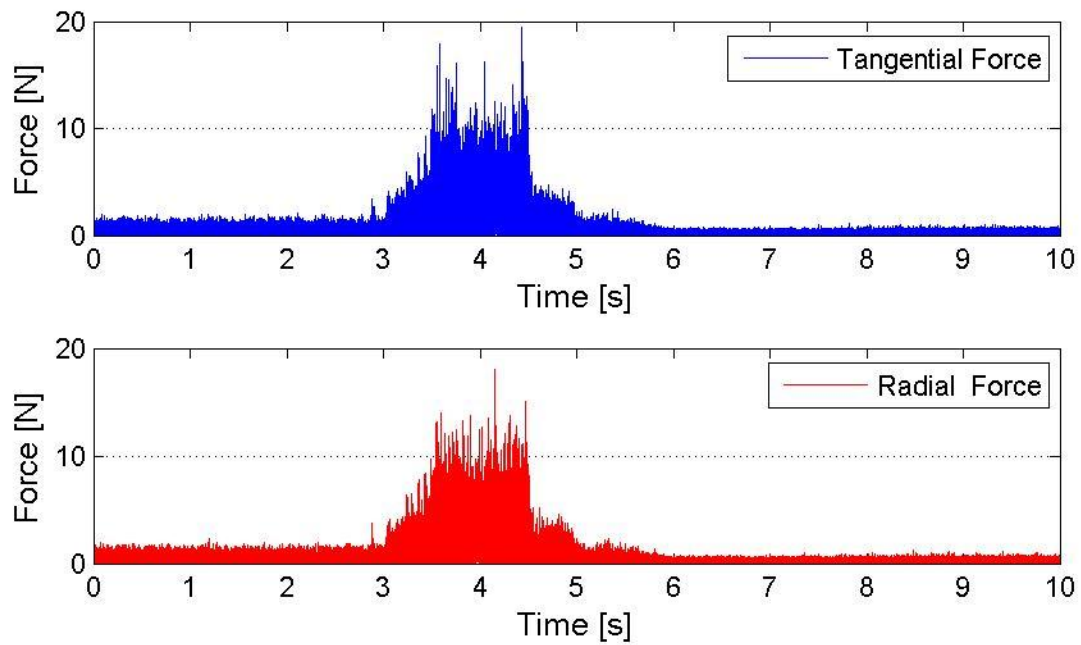


Figure G-316: Tangential and radial cutting force of Cfoam at 6000 RPM, 5.08 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

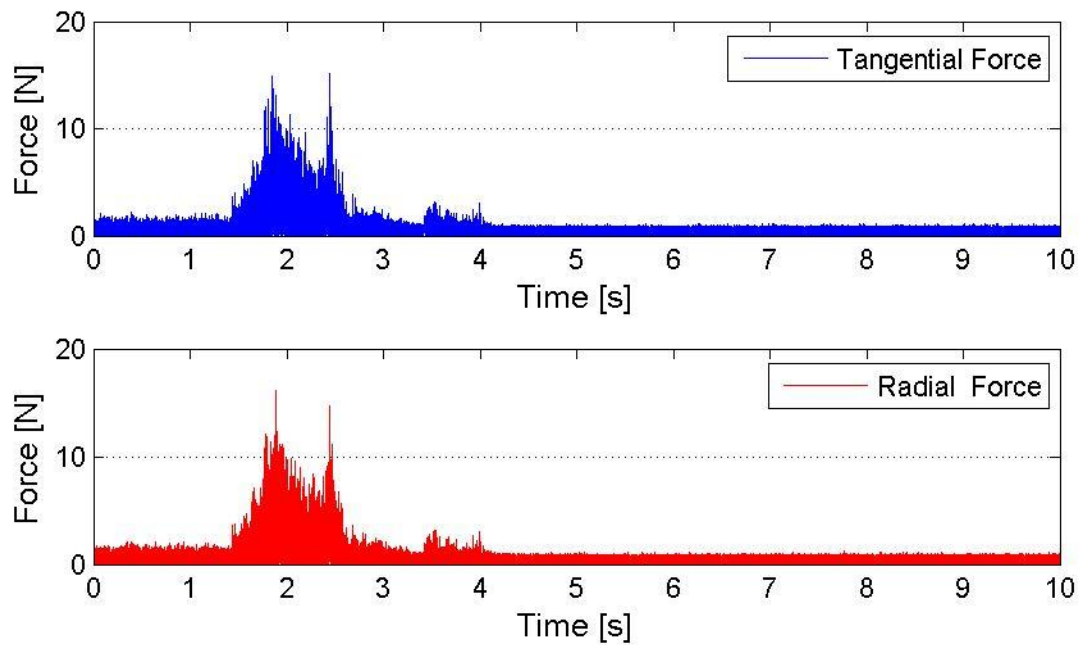


Figure G-317: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

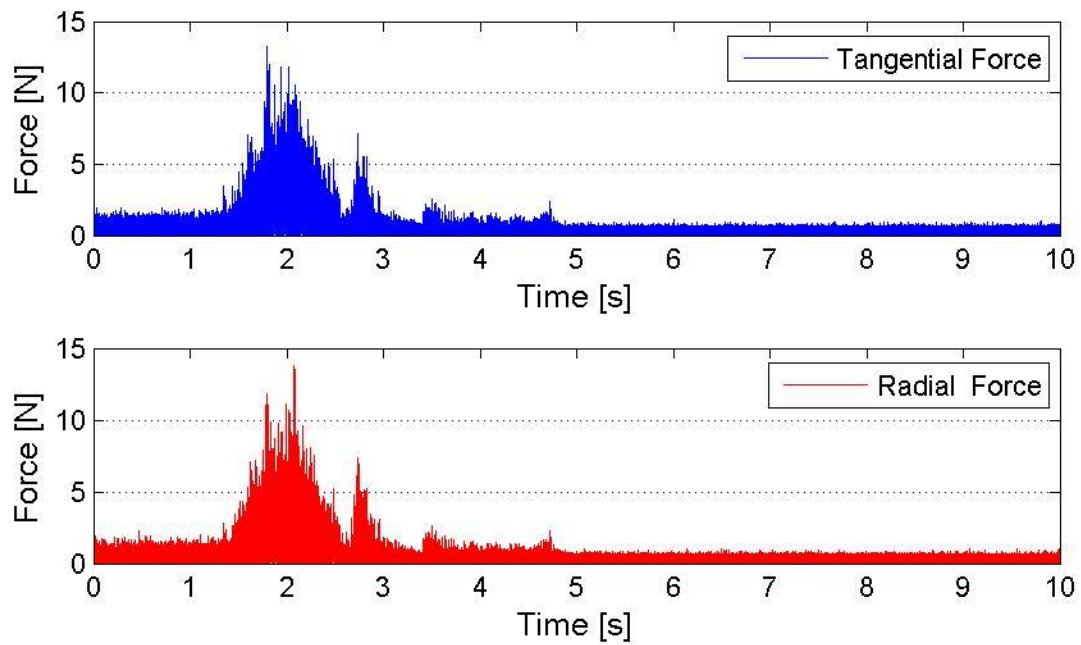


Figure G -318: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

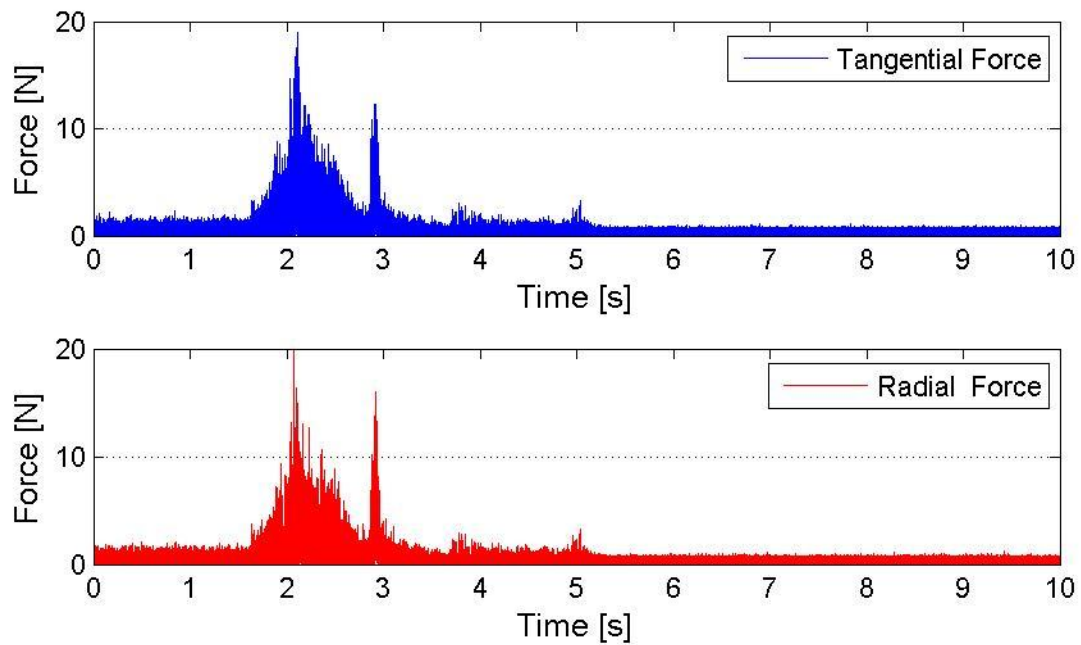


Figure G --319: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

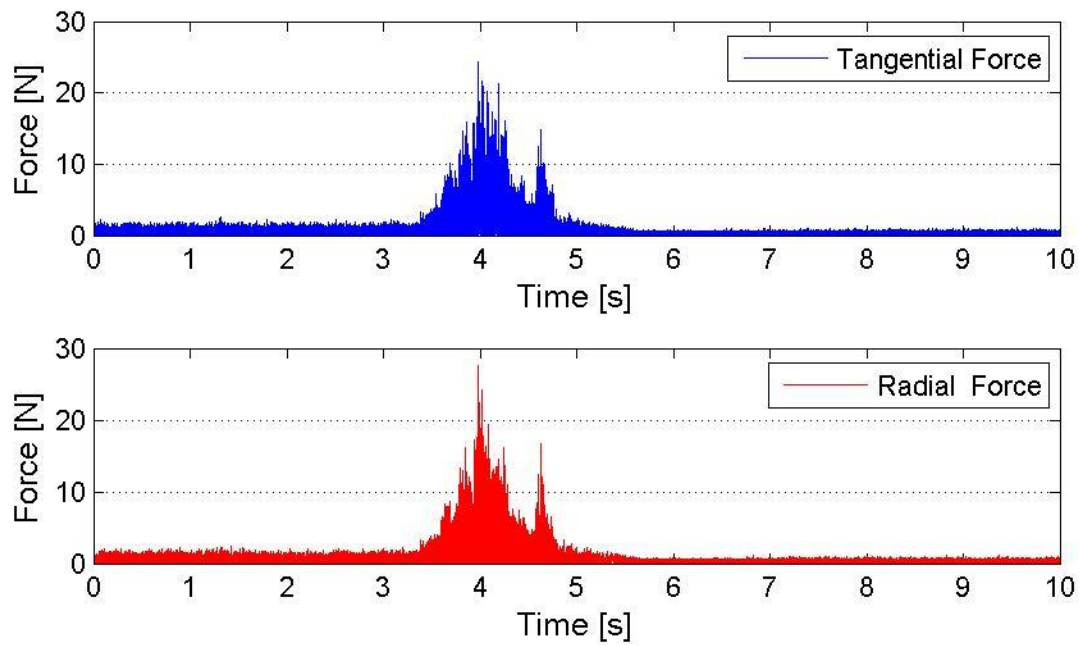


Figure G -320: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

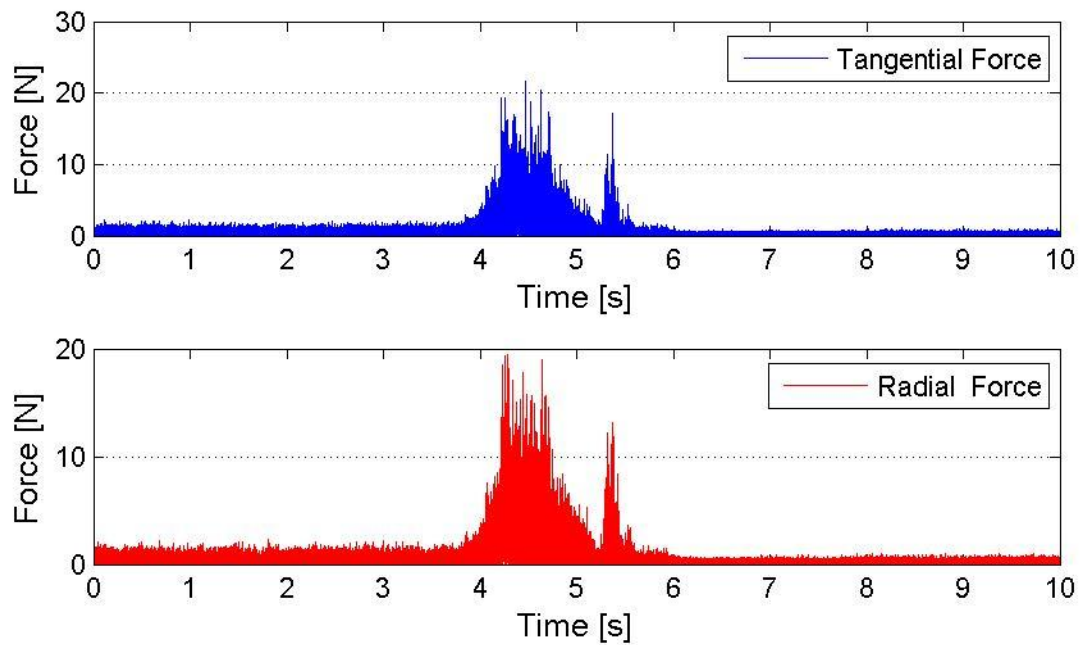


Figure G -321: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

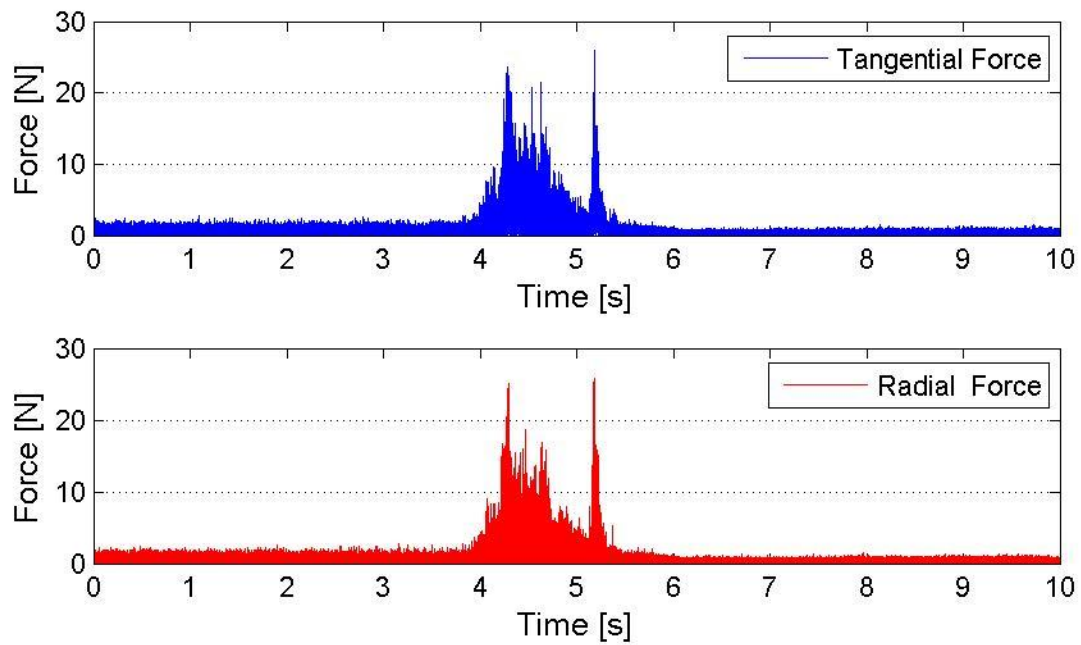


Figure G -322: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 3.18 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

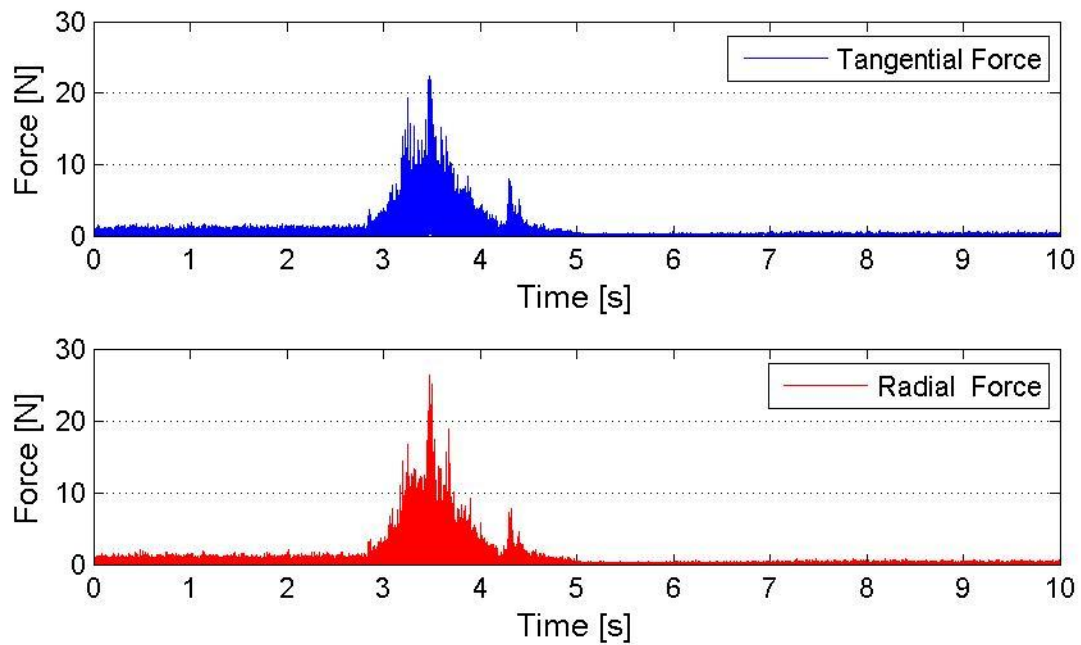


Figure G -323: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 1.

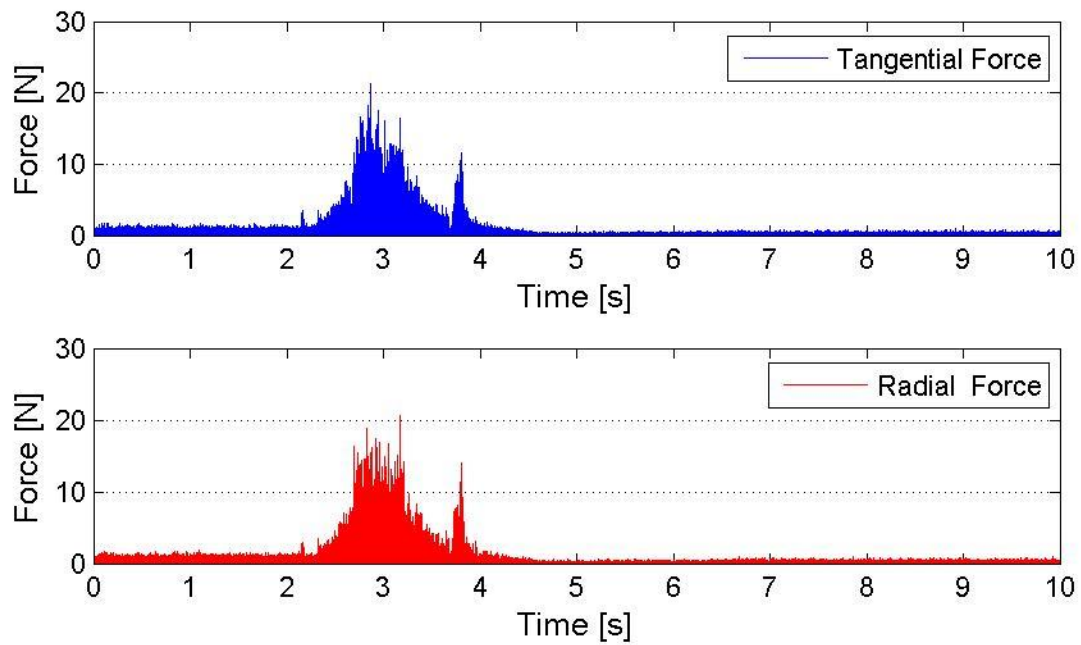


Figure G -324: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 2.

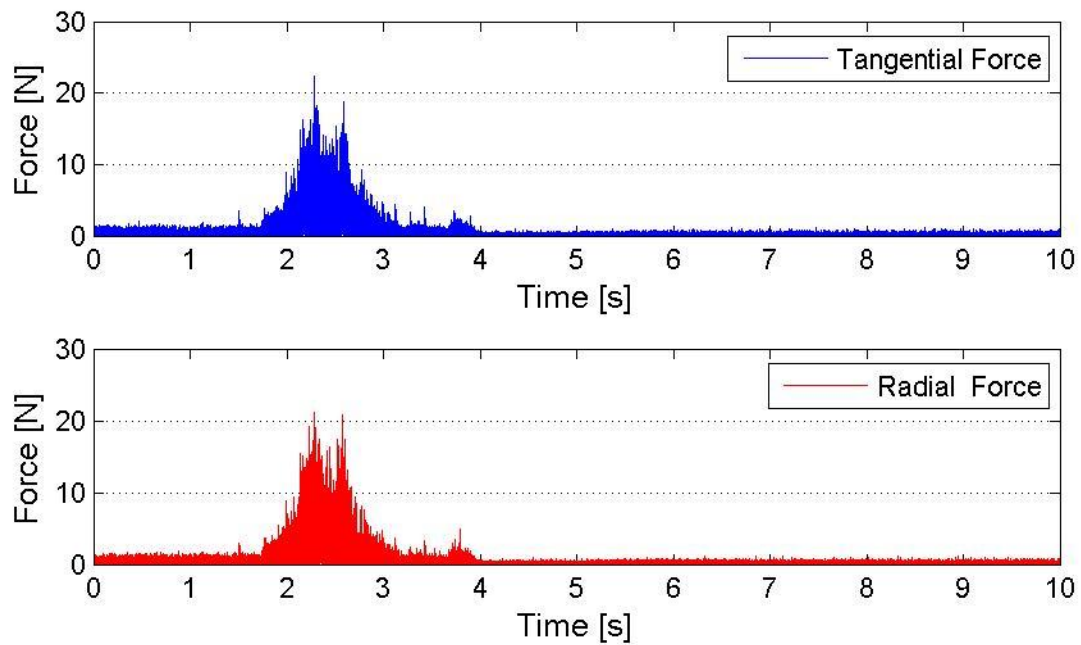


Figure G-325: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 3.18 mm radial depth of cut: test number 3.

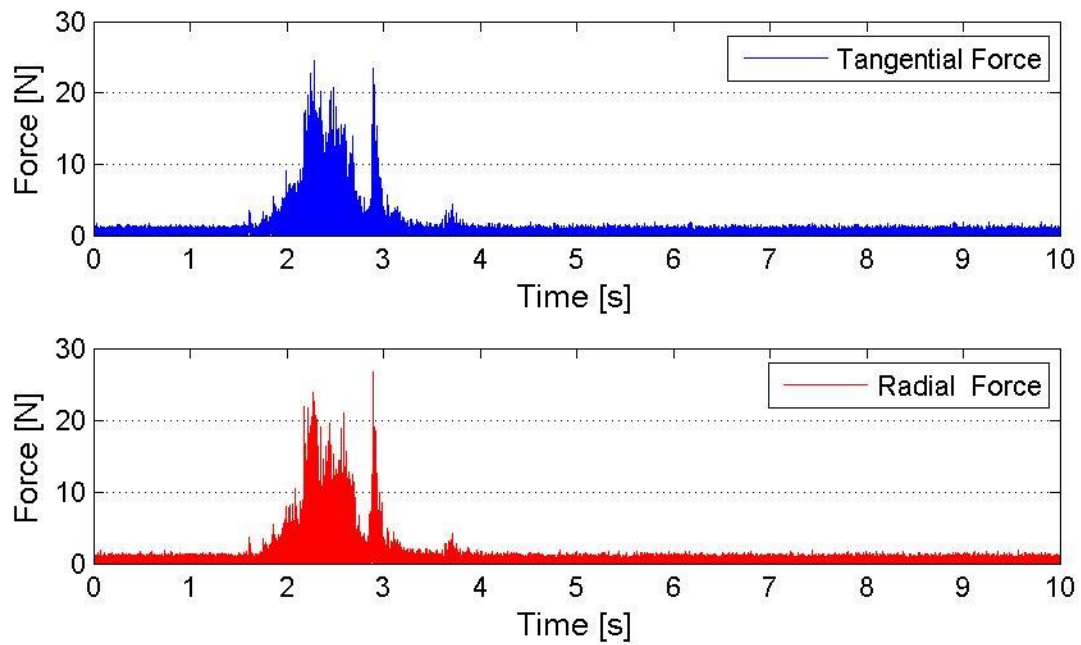


Figure G-326: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 1.

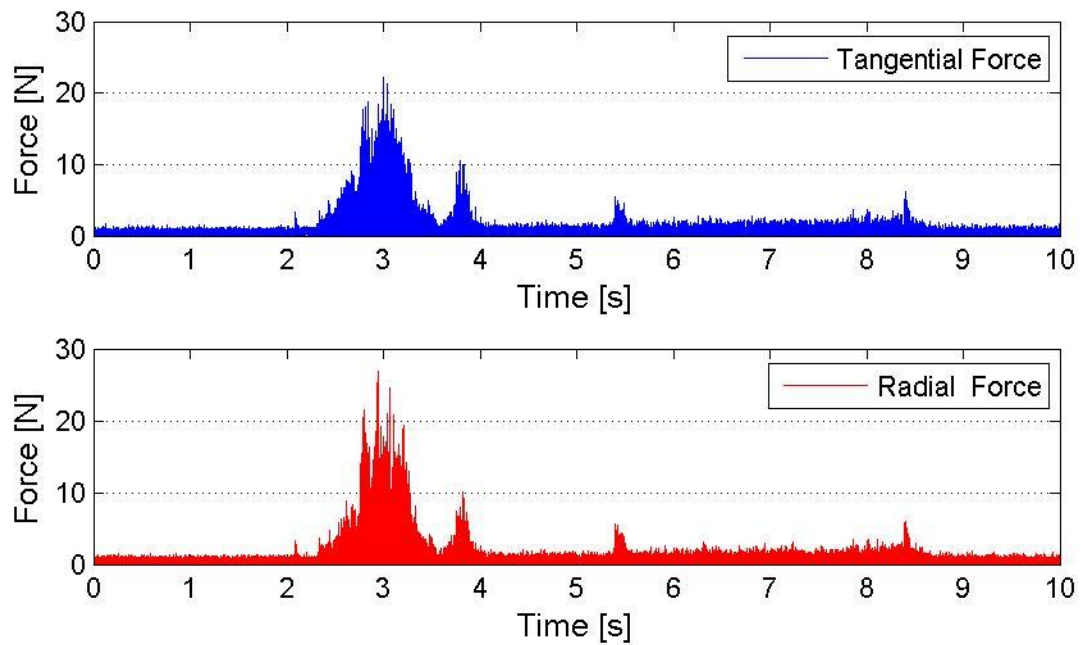


Figure G-327: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 2.

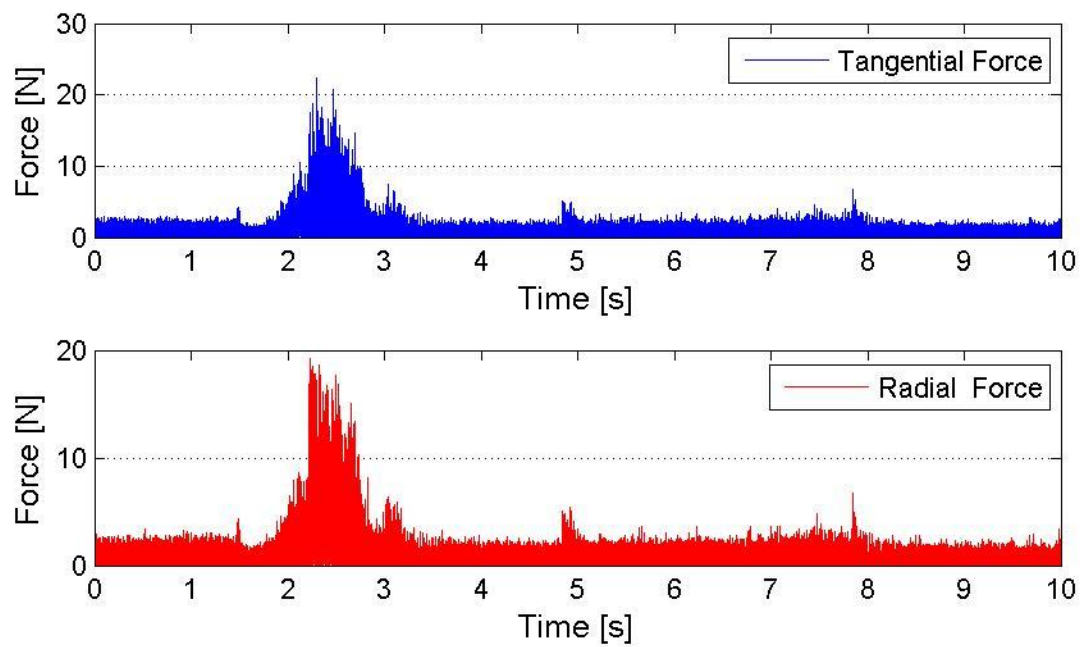


Figure G-328: Tangential and radial cutting force of Cfoam at 6000 RPM, 10.16 m/min, 6.35 mm axial depth of cut and 6.35 mm radial depth of cut: test number 3.

Appendix: H. Surface plots of cutting force DOE

1.) CB1100

◆ Design points above predic
○ Design points below predic
160.2
14.2

X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 6.35
D: ADOC = 6.35

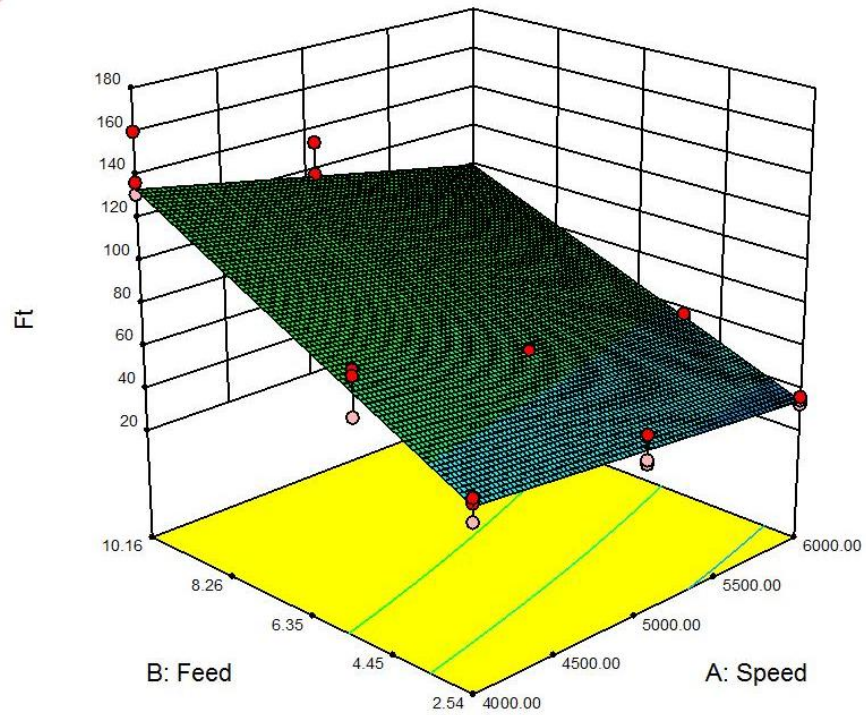


Figure H-329:CB1100 tangential cutting force response surface

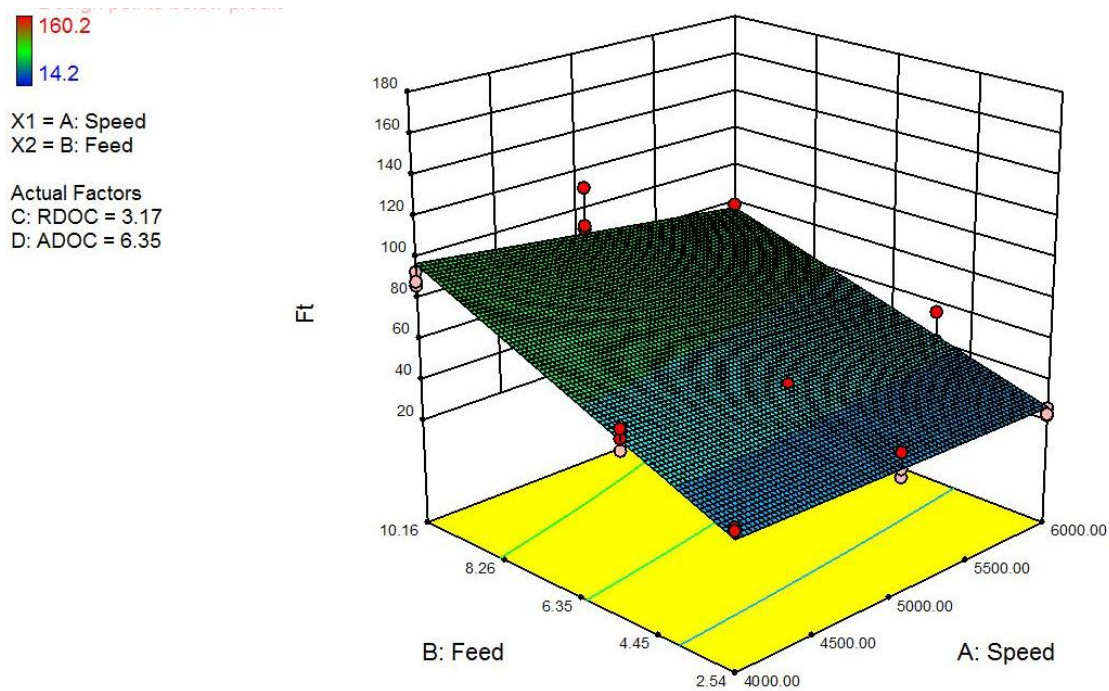


Figure H-330:CB1100 tangential cutting force response surface

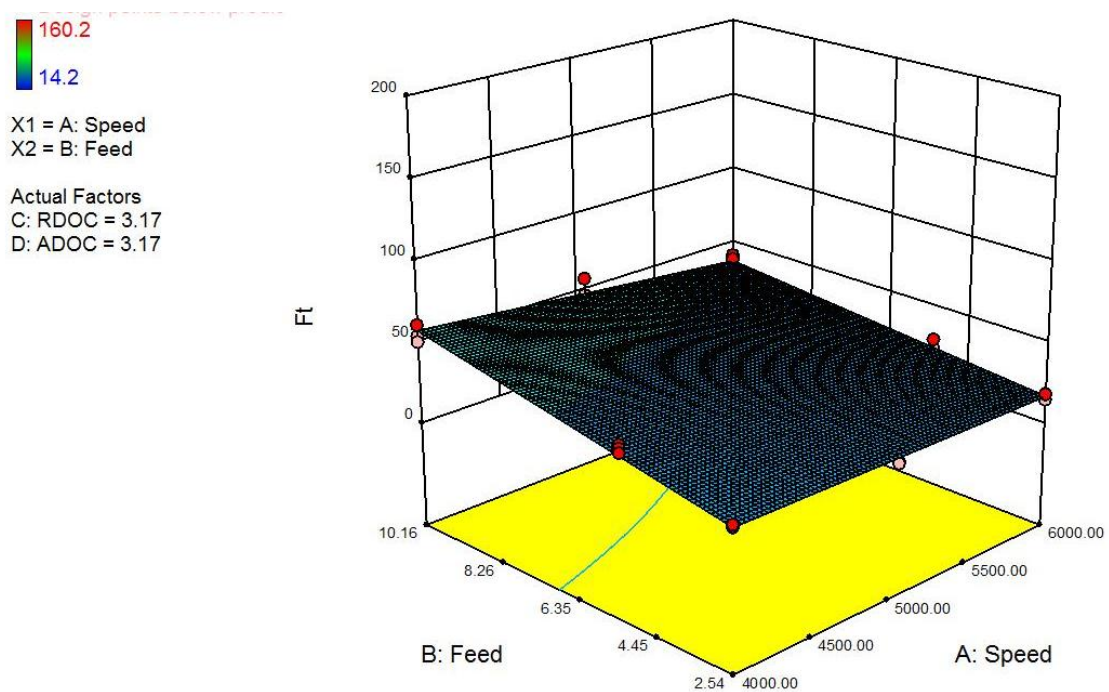


Figure H-331:CB1100 tangential cutting force response surface

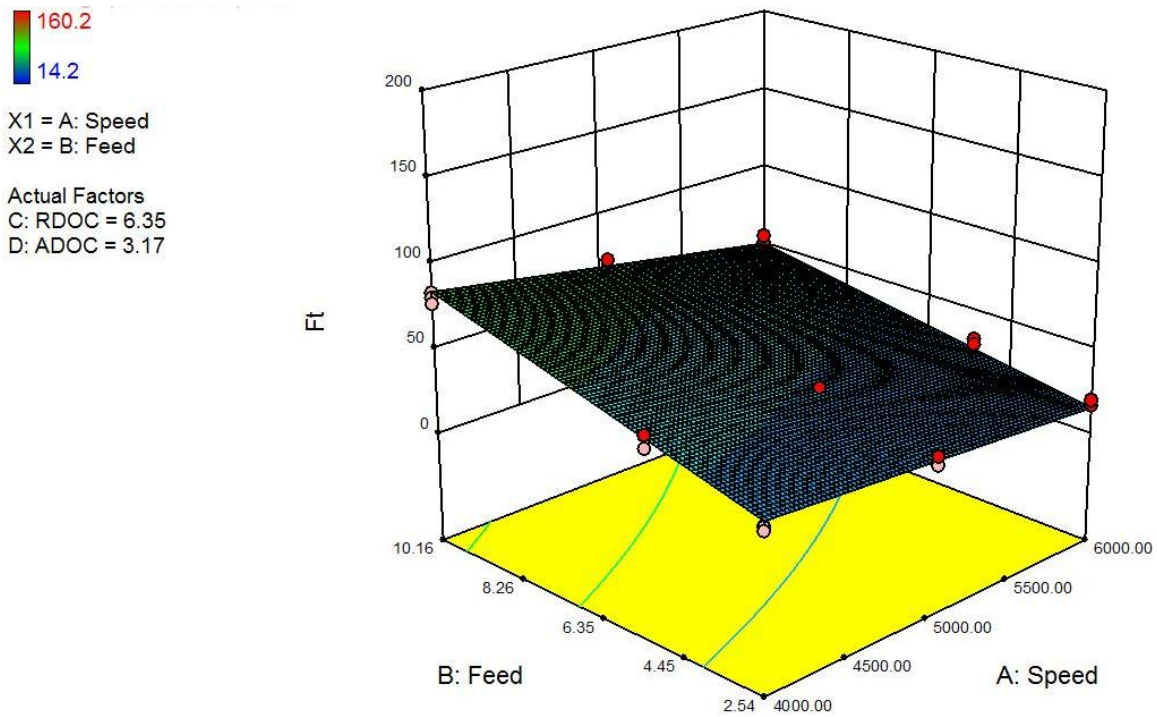


Figure H-332:CB1100 tangential cutting force response surface

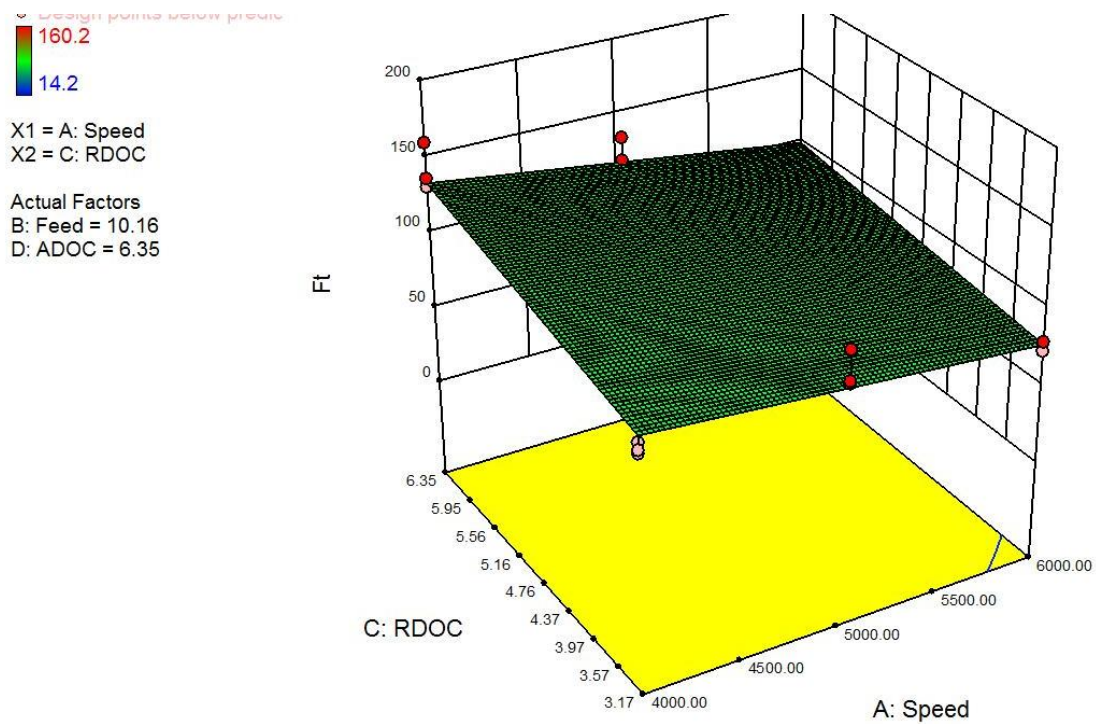


Figure H-333:CB1100 tangential cutting force response surface

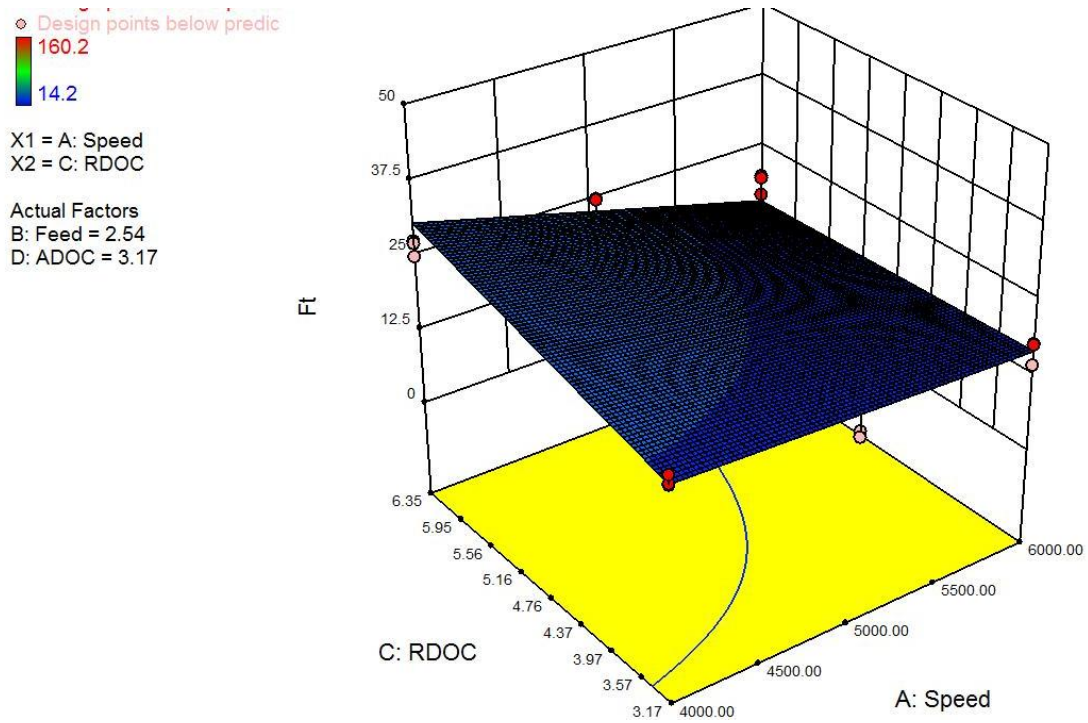


Figure H-334:CB1100 tangential cutting force response surface

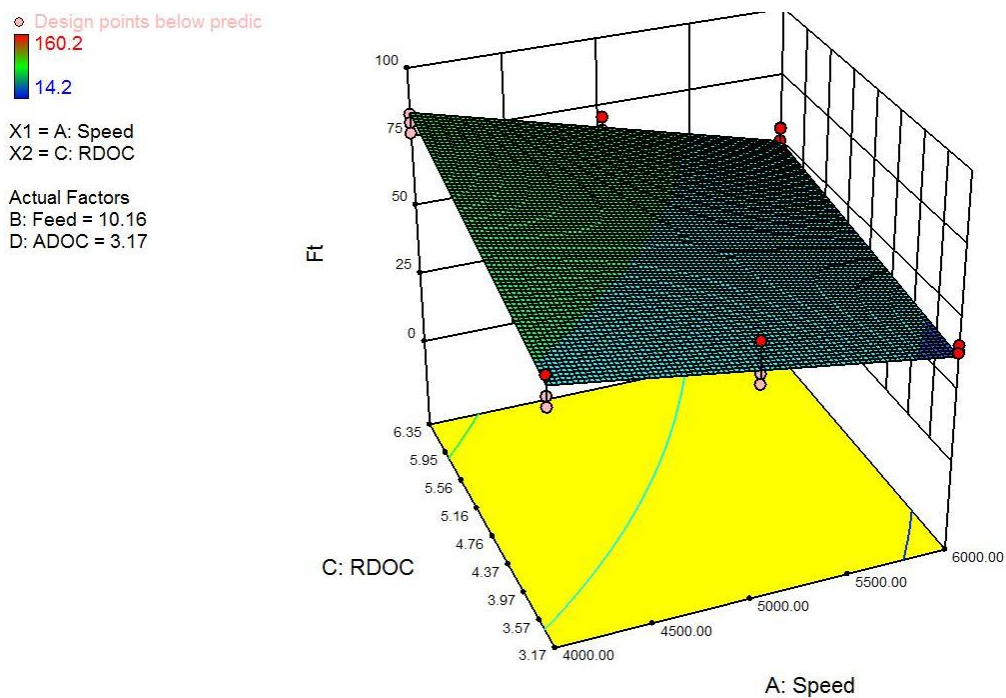


Figure H-335:CB1100 tangential cutting force response surface

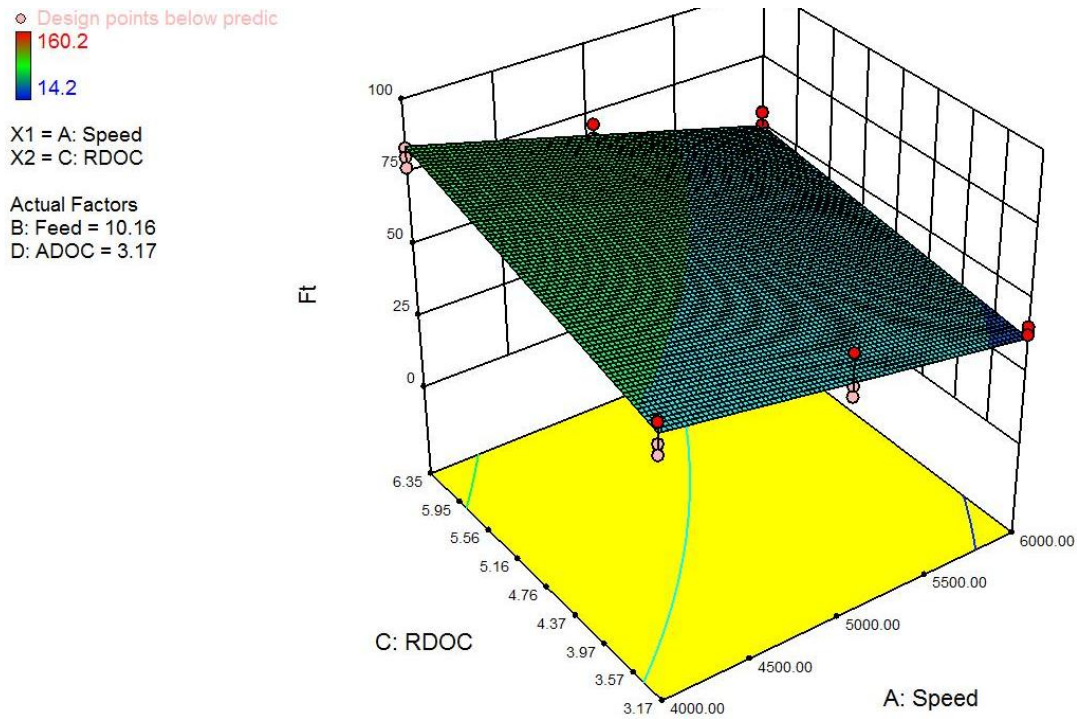


Figure H-336:CB1100 tangential cutting force response surface

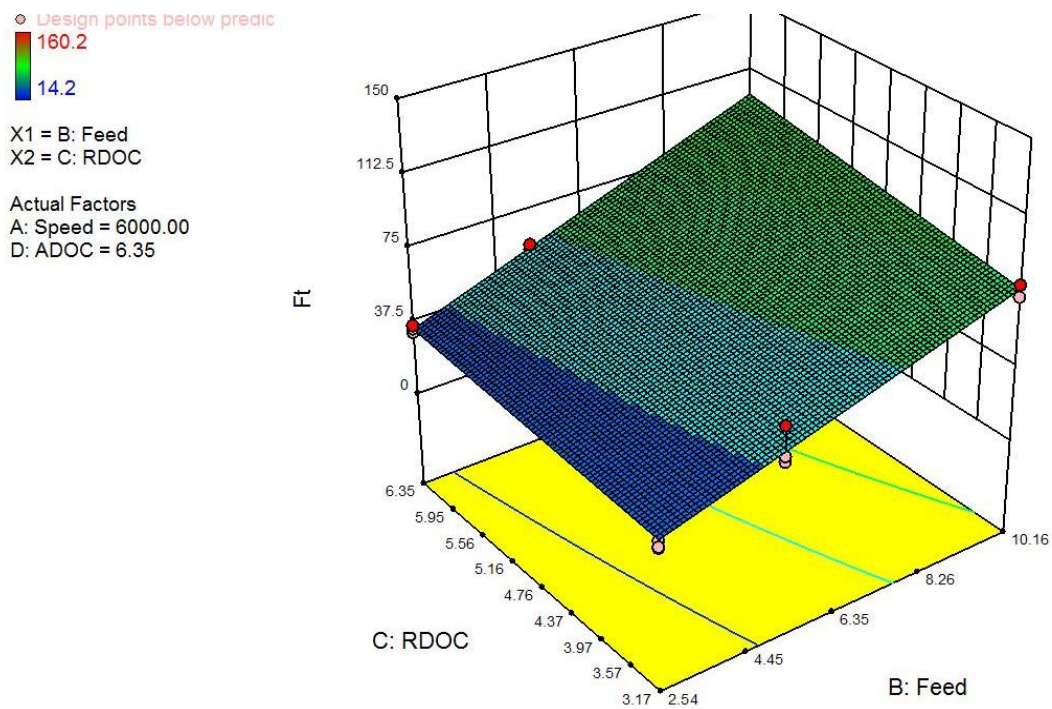


Figure H-337:CB1100 tangential cutting force response surface

● Design points above predic
 ○ Design points below predic
 160.2
 14.2

X1 = B: Feed
 X2 = C: RDOC
 Actual Factors
 A: Speed = 4000.00
 D: ADOC = 3.17

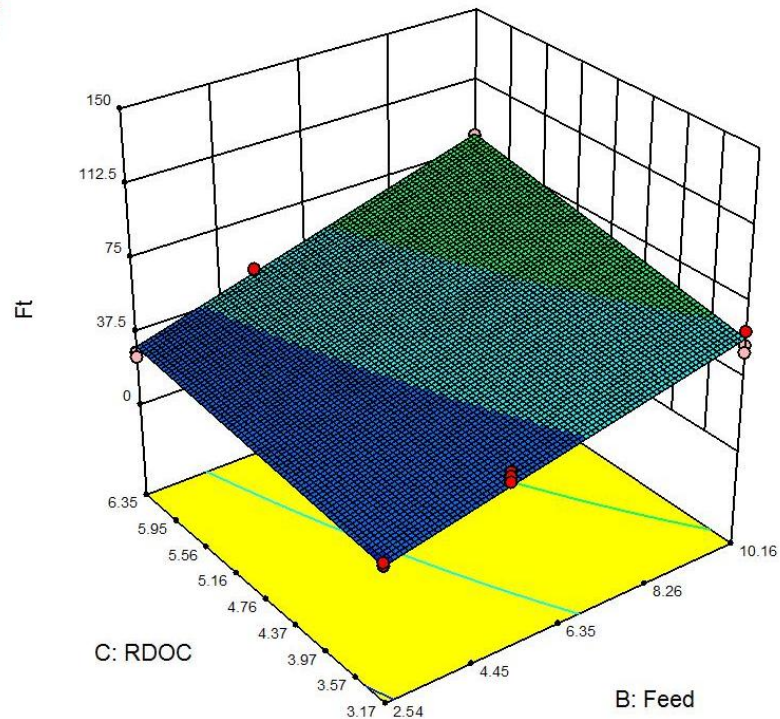


Figure H-338:CB1100 tangential cutting force response surface

● Design points above predic
 ○ Design points below predic
 160.2
 14.2

X1 = B: Feed
 X2 = C: RDOC
 Actual Factors
 A: Speed = 6000.00
 D: ADOC = 3.17

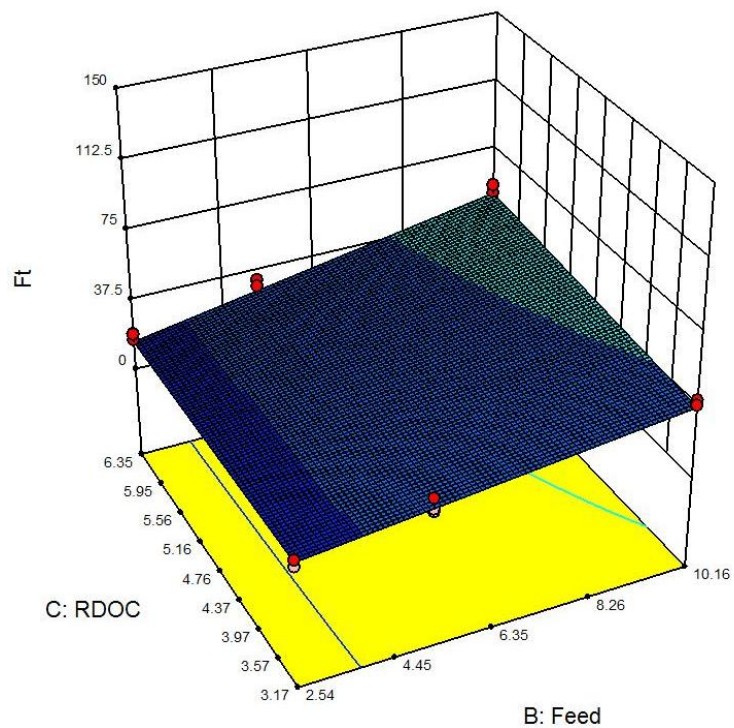


Figure H-339:CB1100 tangential cutting force response surface

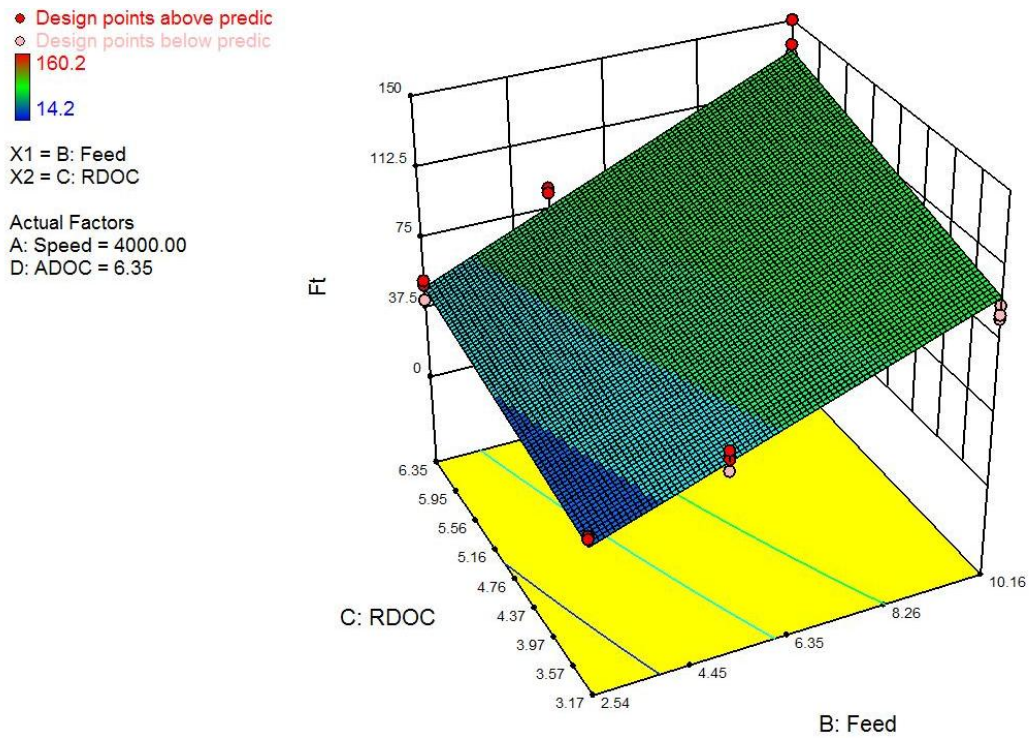


Figure H-340:CB1100 tangential cutting force response surface

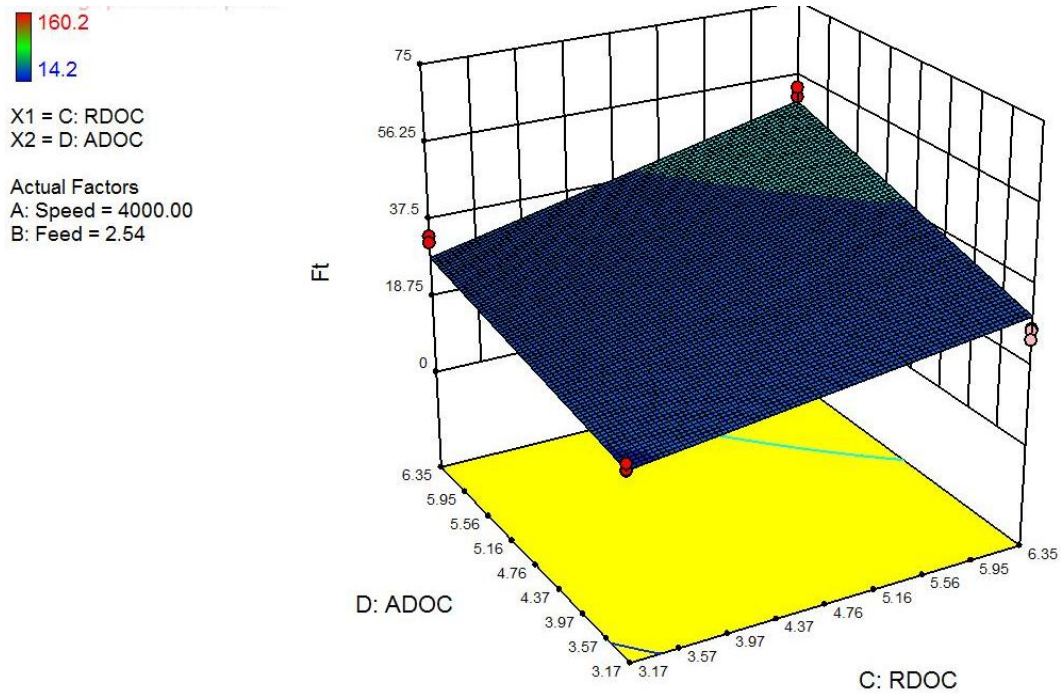


Figure H-341:CB1100 tangential cutting force response surface

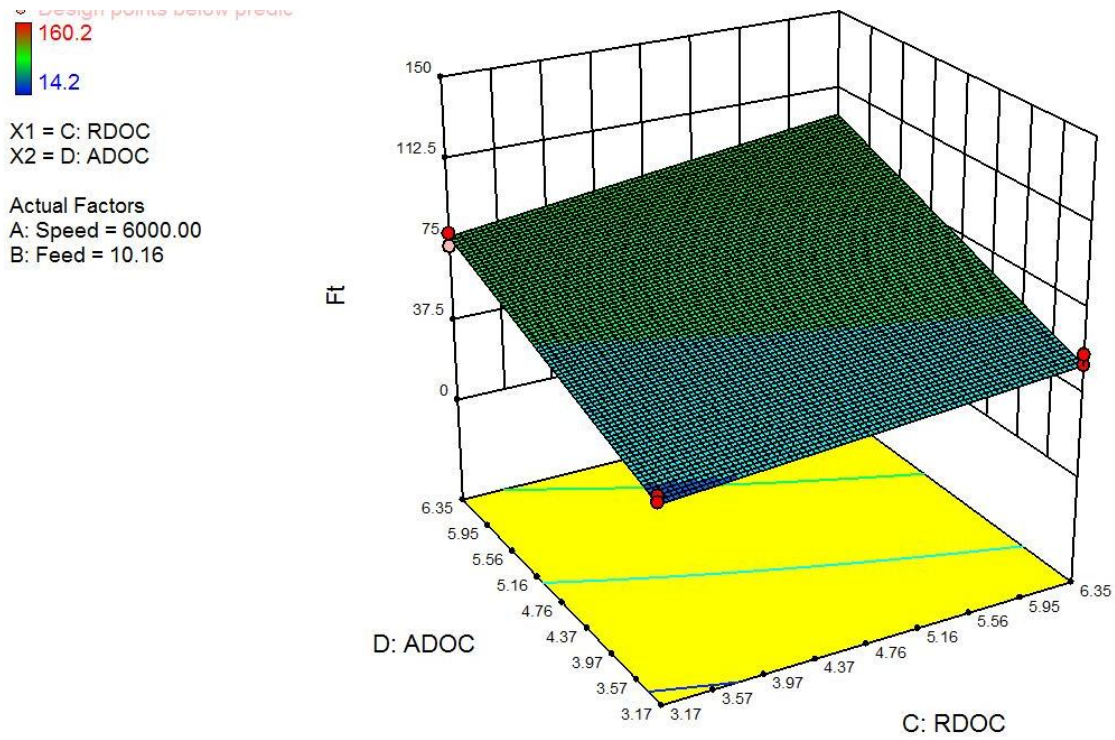


Figure H-342:CB1100 tangential cutting force response surface

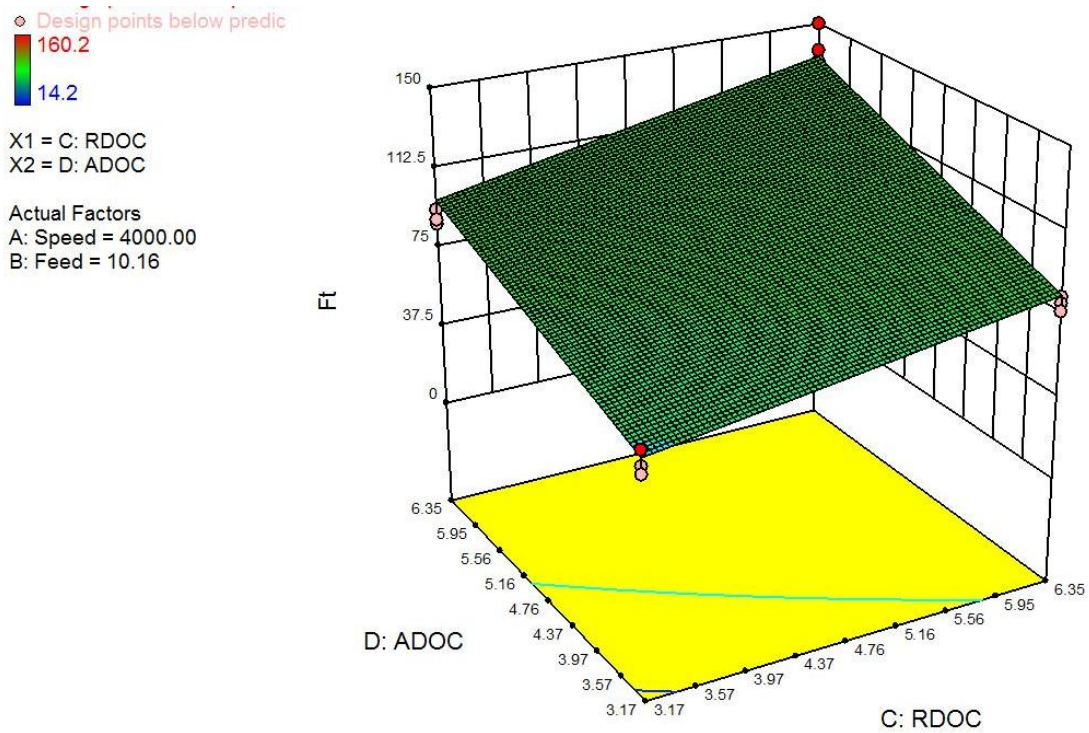


Figure H-343:CB1100 tangential cutting force response surface



X1 = C: RDOC
X2 = D: ADOC

Actual Factors
A: Speed = 6000.00
B: Feed = 2.54

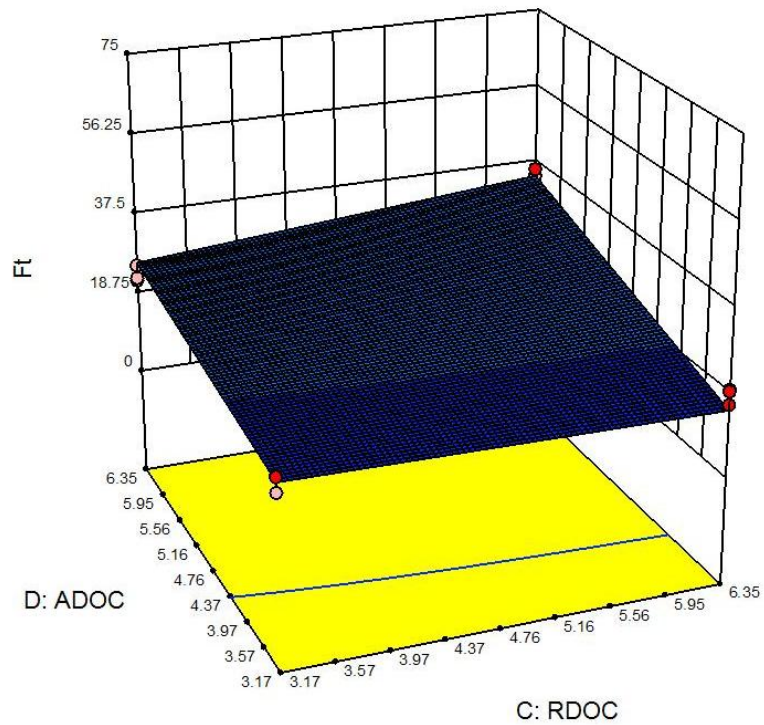


Figure H-344:CB1100 tangential cutting force response surface



X1 = B: Feed
X2 = D: ADOC

Actual Factors
A: Speed = 6000.00
C: RDOC = 6.35

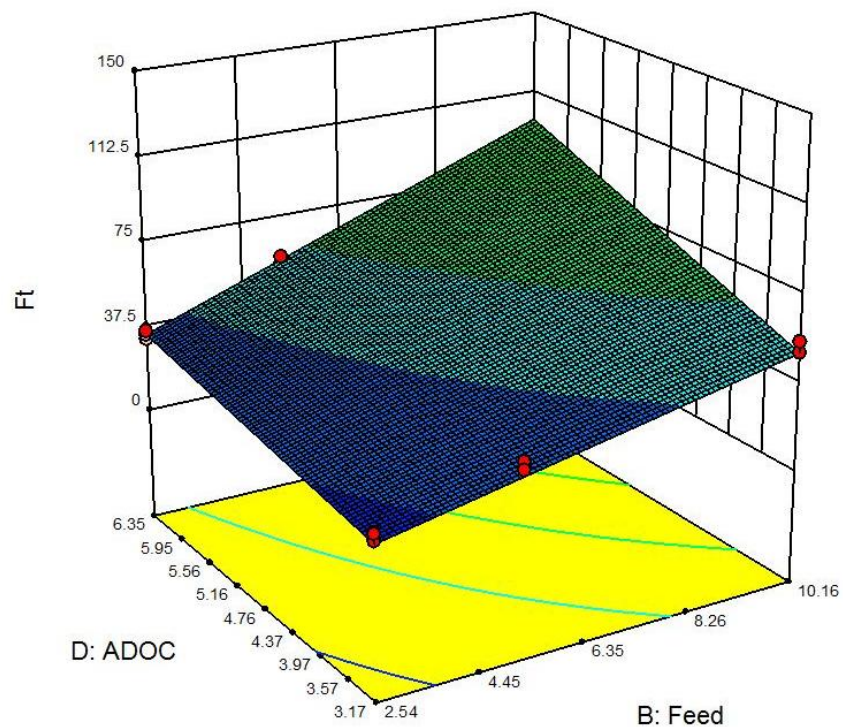


Figure H-345:CB1100 tangential cutting force response surface

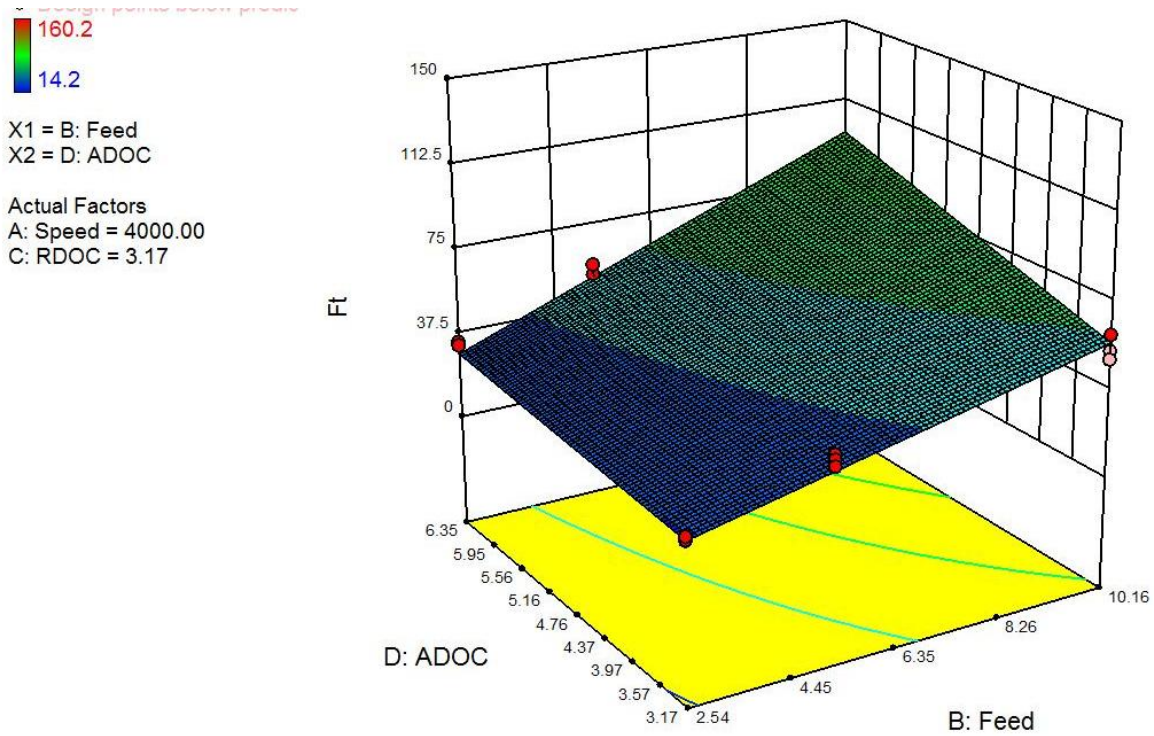


Figure H-346:CB1100 tangential cutting force response surface

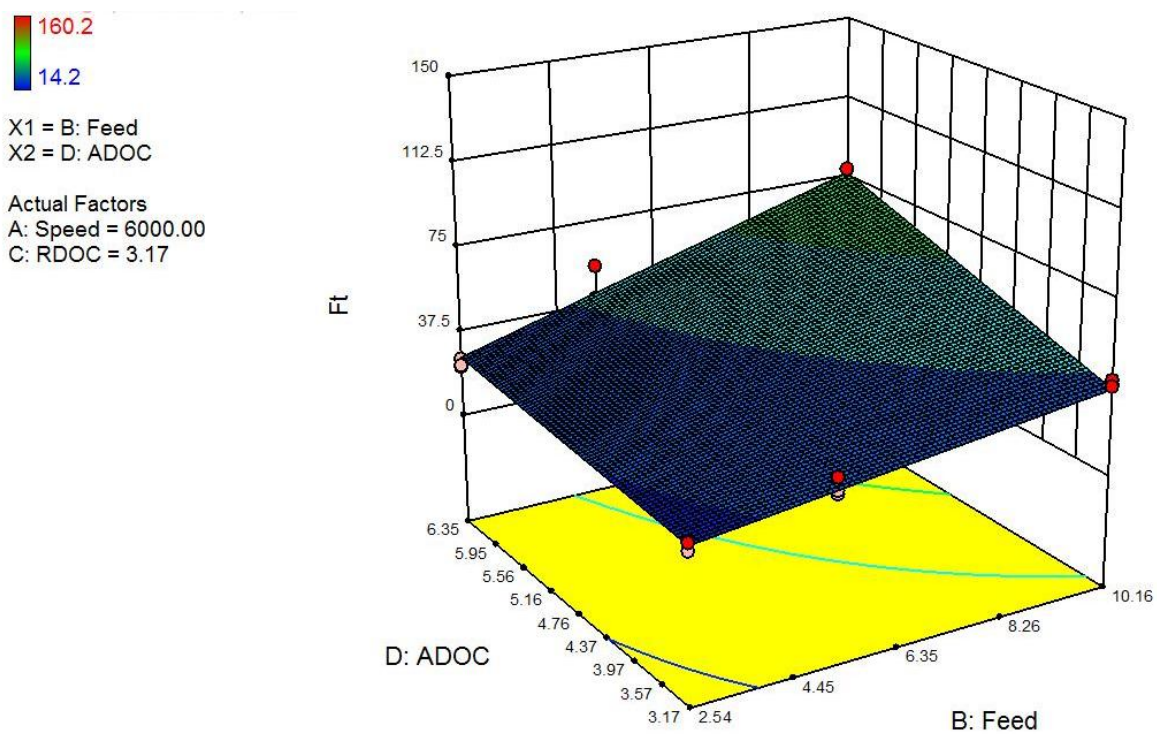


Figure H-347:CB1100 tangential cutting force response surface

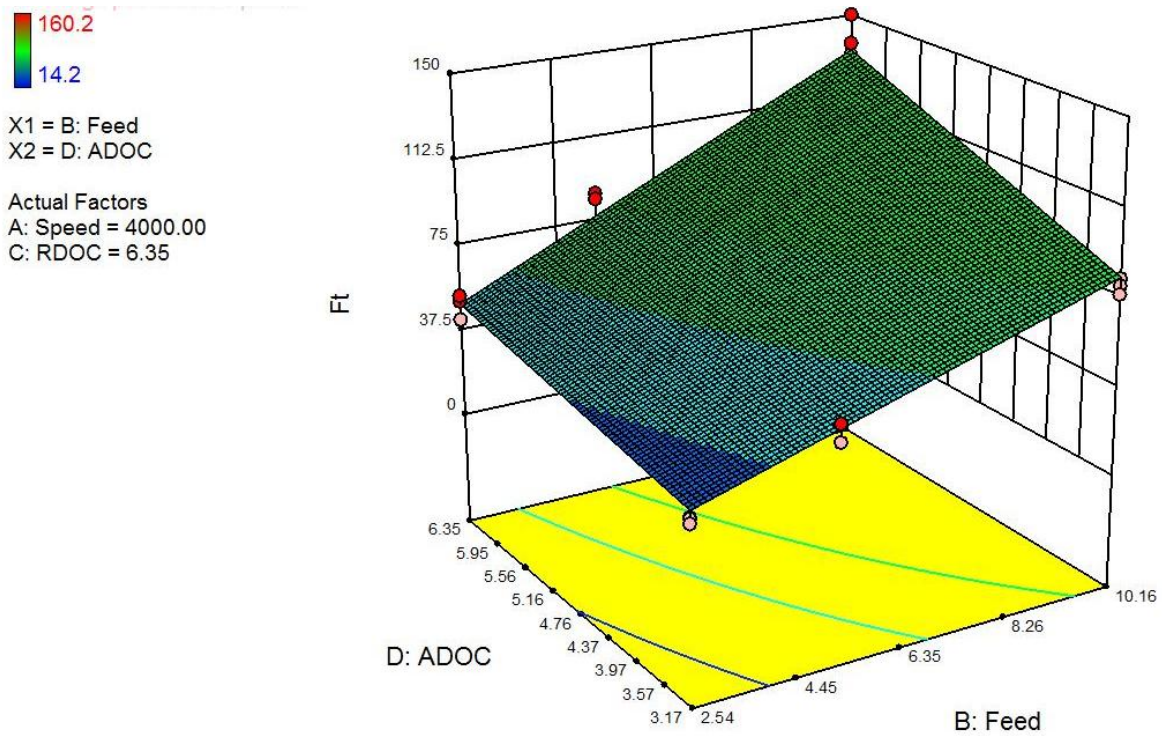


Figure H-348:CB1100 tangential cutting force response surface

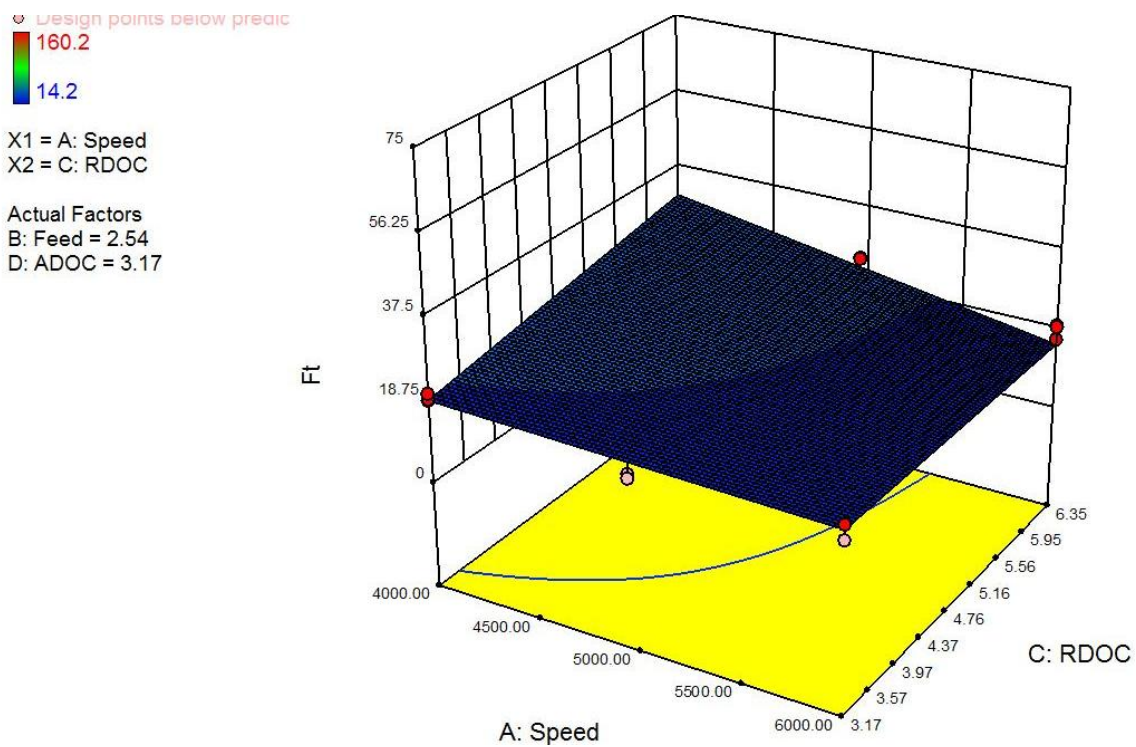


Figure H-349:CB1100 tangential cutting force response surface

▼ Design points above predic
 ○ Design points below predic
 160.2
 14.2

X1 = A: Speed
 X2 = C: RDOC

Actual Factors
 B: Feed = 10.16
 D: ADOC = 6.35

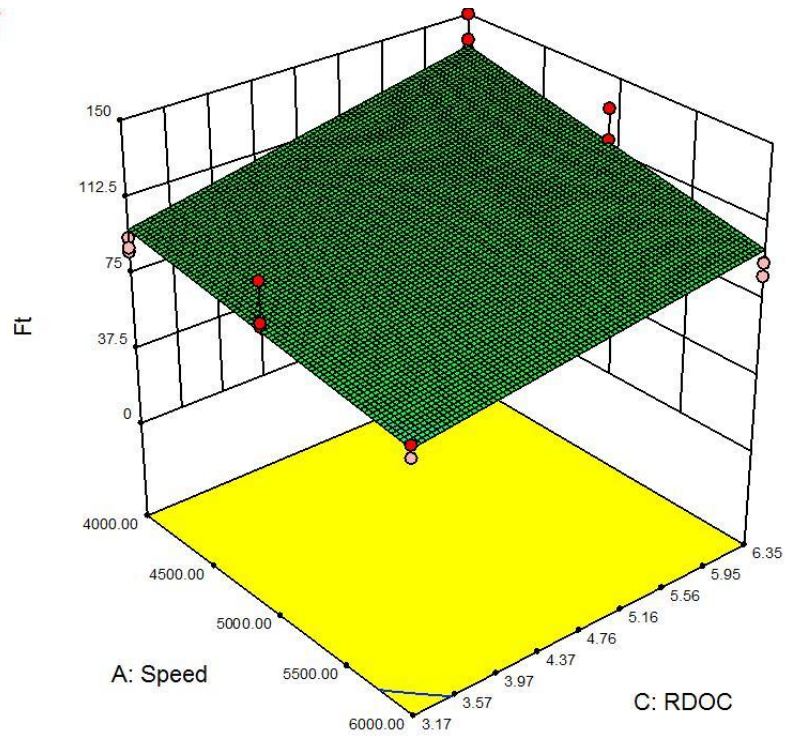


Figure H-350:CB1100 tangential cutting force response surface

○ Design points below predic
 160.2
 14.2

X1 = A: Speed
 X2 = C: RDOC

Actual Factors
 B: Feed = 2.54
 D: ADOC = 6.35

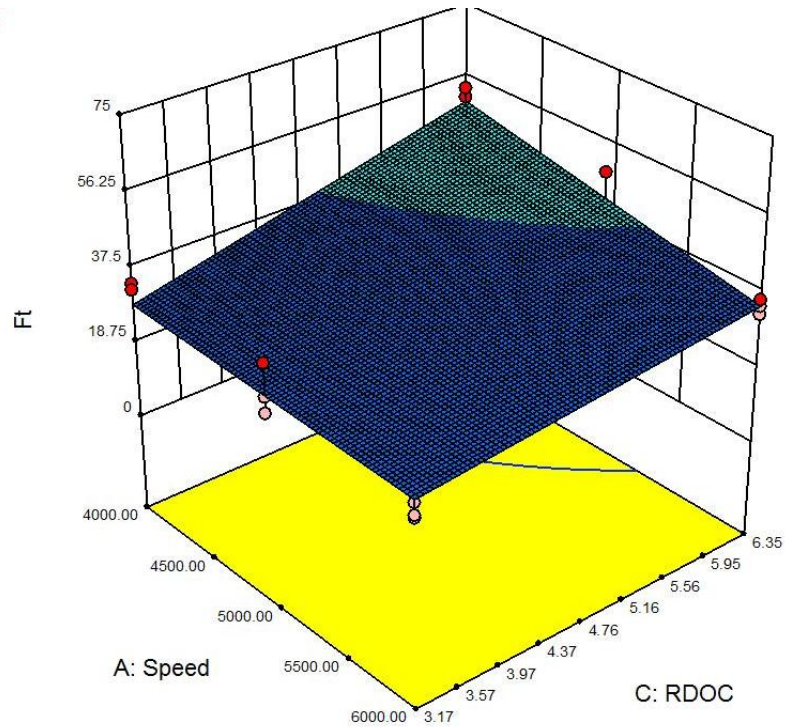


Figure H-351:CB1100 tangential cutting force response surface

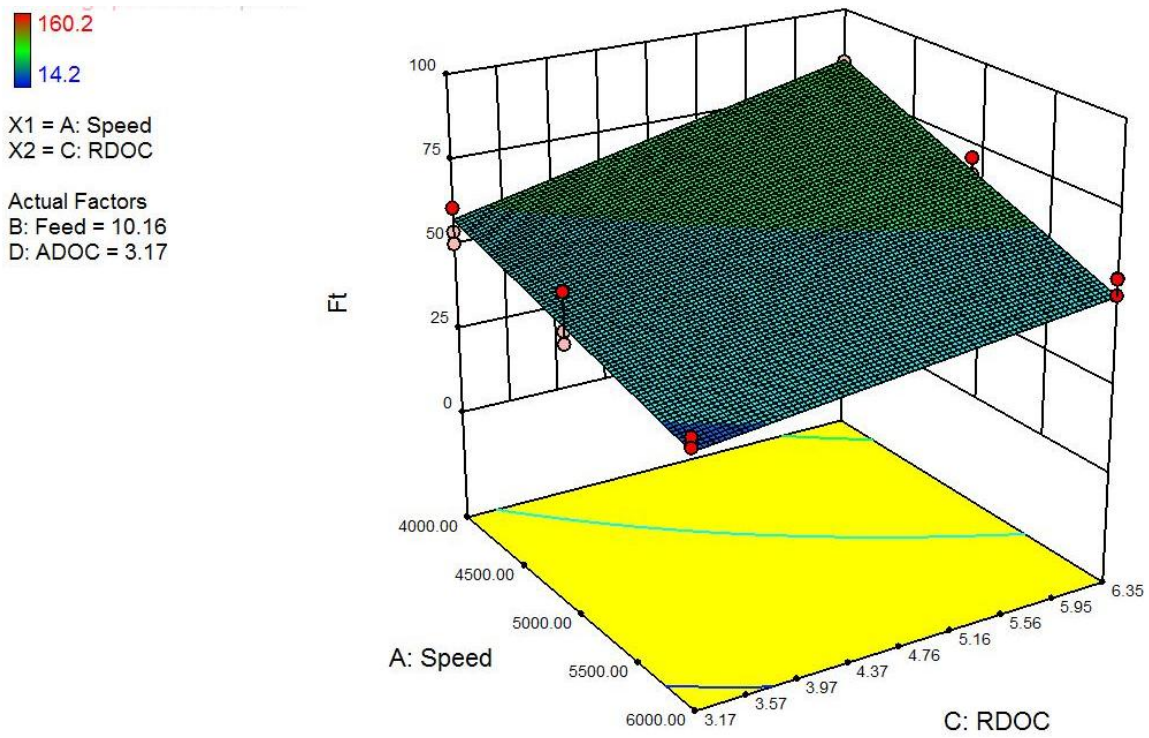


Figure H-352:CB1100 tangential cutting force response surface

2.) AAC

○ Design points below predict



X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 6.35
D: ADOC = 3.17

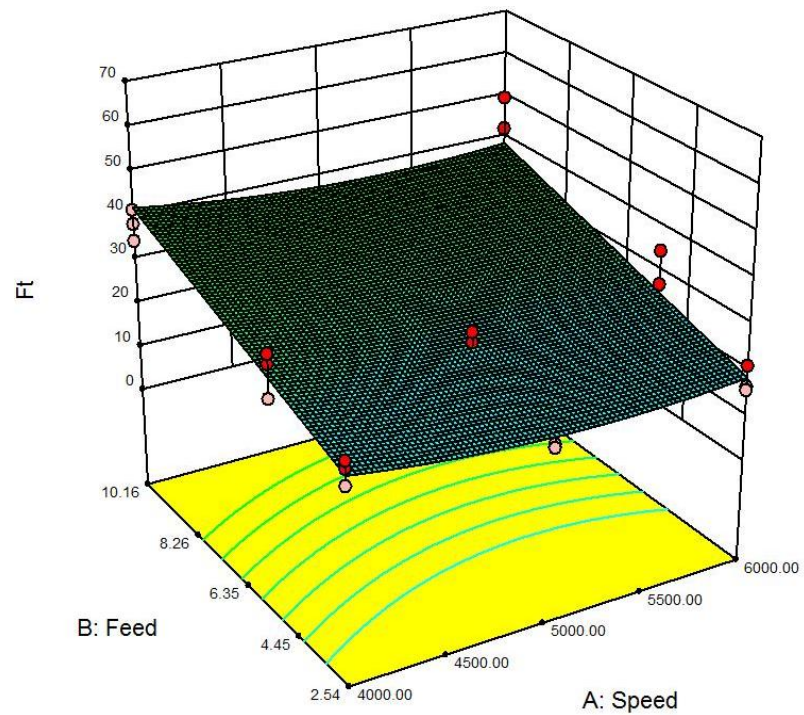


Figure H-353: AAC tangential cutting force response surface

○ Design points below predict



X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 6.35
D: ADOC = 6.35

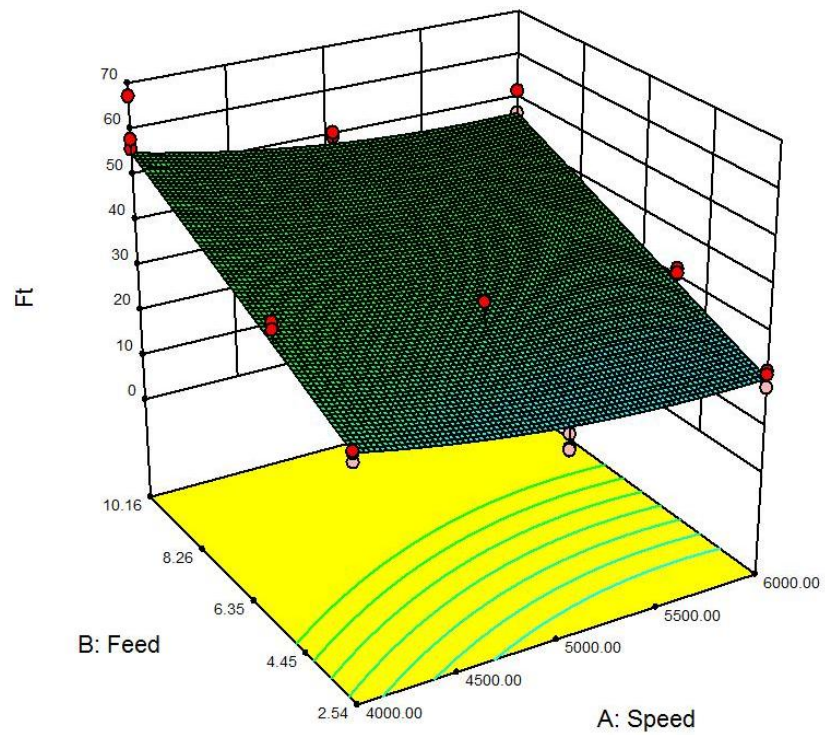


Figure H-354: AAC tangential cutting force response surface

Design points below predict

67.2

9.6

X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 3.17
D: ADOC = 3.17

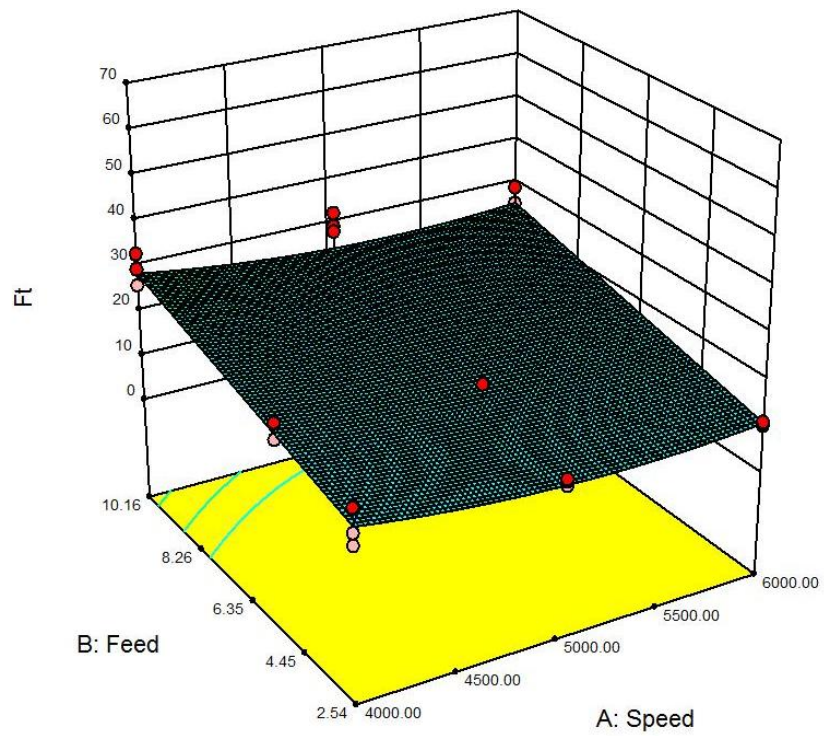


Figure H-355: AAC tangential cutting force response surface

Design points below predict

67.2

9.6

X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 3.17
D: ADOC = 6.35

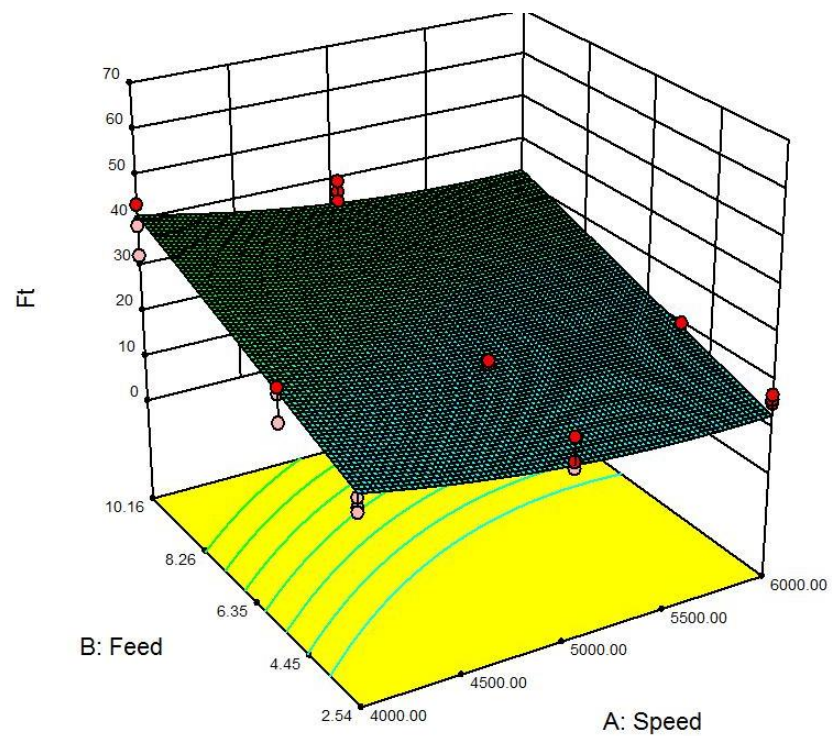


Figure H-356: AAC tangential cutting force response surface

Design points below predict
67.2
9.6

X1 = B: Feed
X2 = C: RDOC

Actual Factors
A: Speed = 6000.00
D: ADOC = 6.35

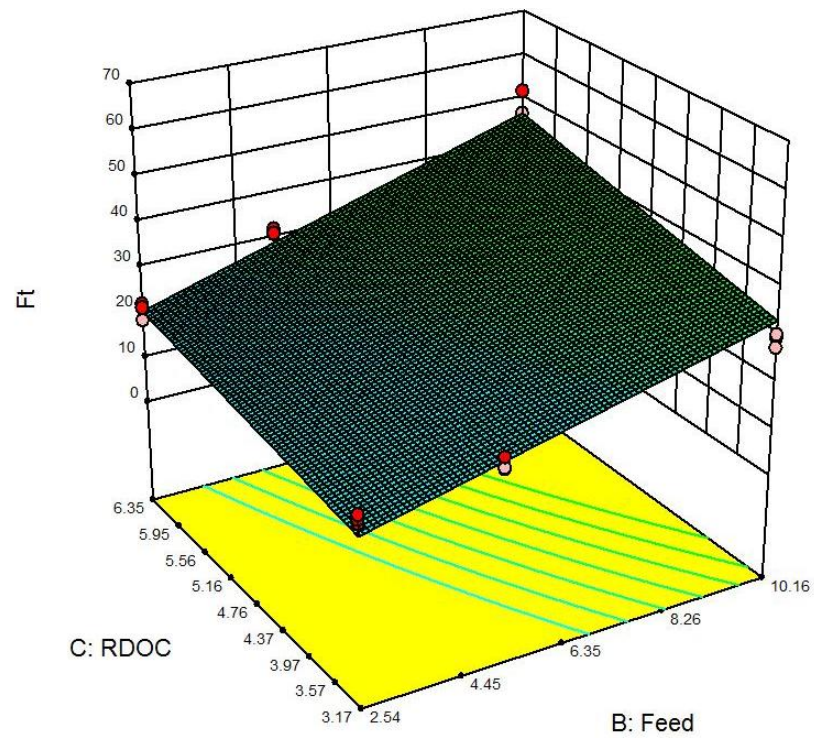


Figure H-357: AAC tangential cutting force response surface

Design points below predict
67.2
9.6

X1 = B: Feed
X2 = C: RDOC

Actual Factors
A: Speed = 4000.00
D: ADOC = 6.35

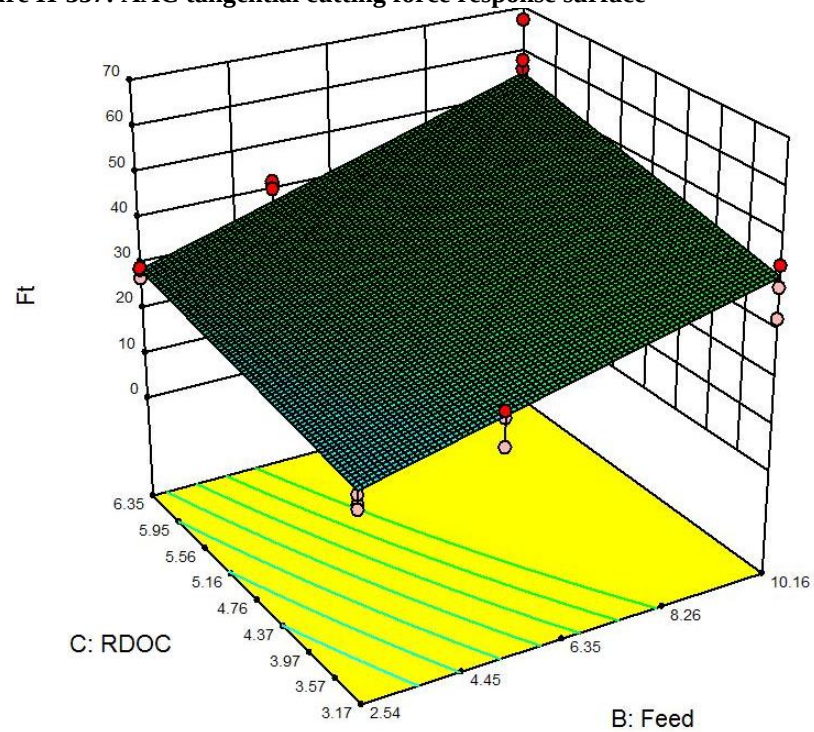


Figure H-358: AAC tangential cutting force response surface

Design points below predict



X1 = B: Feed
X2 = C: RDOC

Actual Factors
A: Speed = 4000.00
D: ADOC = 3.17

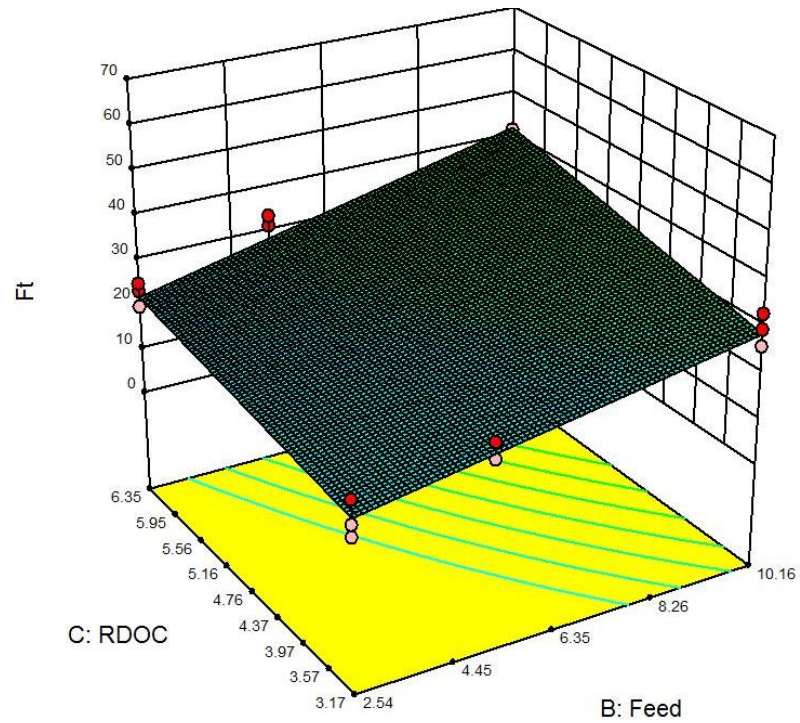


Figure H-359: AAC tangential cutting force response surface

Design points below predict



X1 = B: Feed
X2 = C: RDOC

Actual Factors
A: Speed = 6000.00
D: ADOC = 3.17

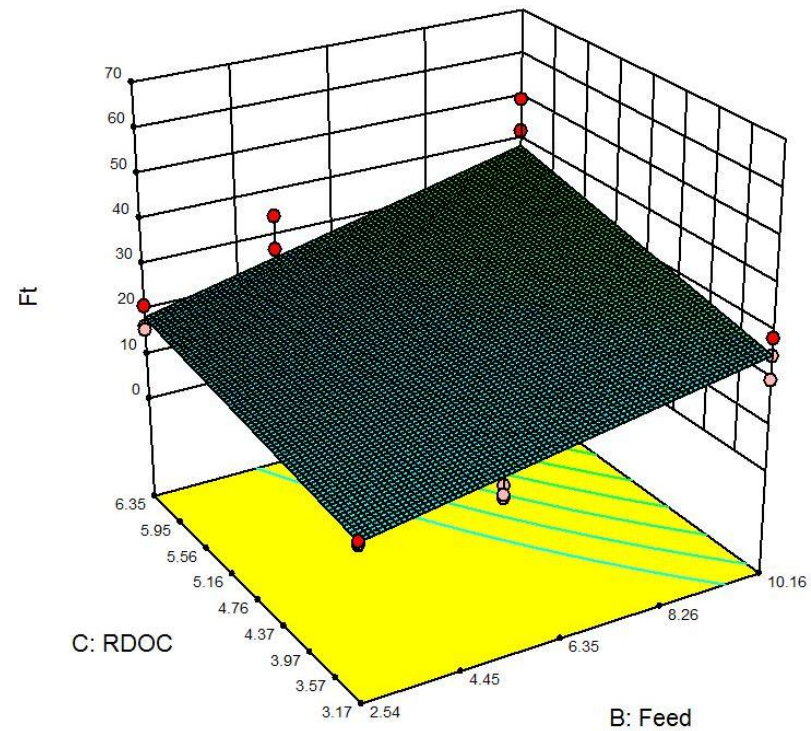


Figure H-360: AAC tangential cutting force response surface

Design points below predict



X1 = B: Feed
X2 = D: ADOC

Actual Factors
A: Speed = 6000.00
C: RDOC = 6.35

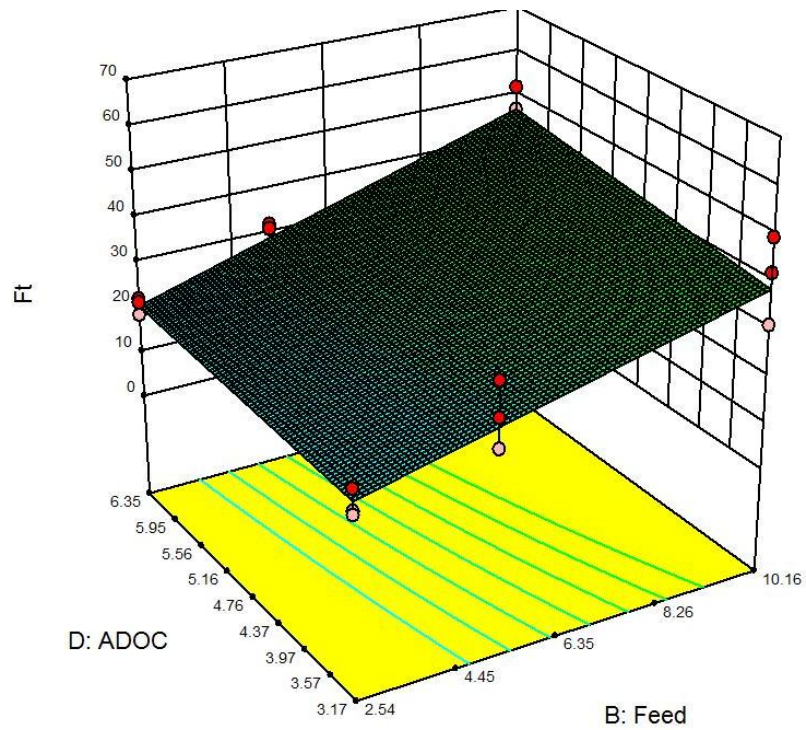


Figure H-361: AAC tangential cutting force response surface

Design points below predict



X1 = B: Feed
X2 = D: ADOC

Actual Factors
A: Speed = 4000.00
C: RDOC = 6.35

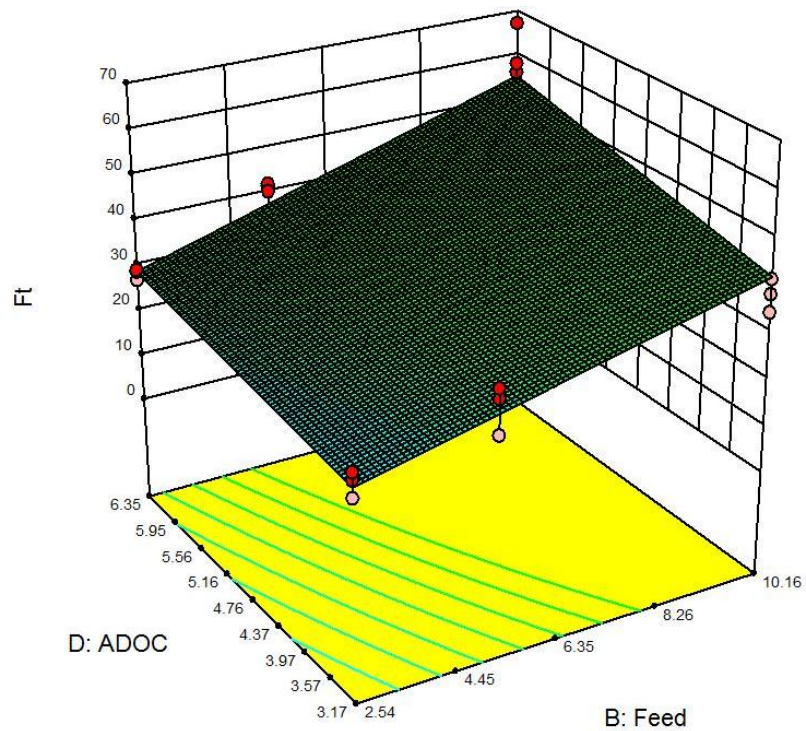


Figure H-362: AAC tangential cutting force response surface

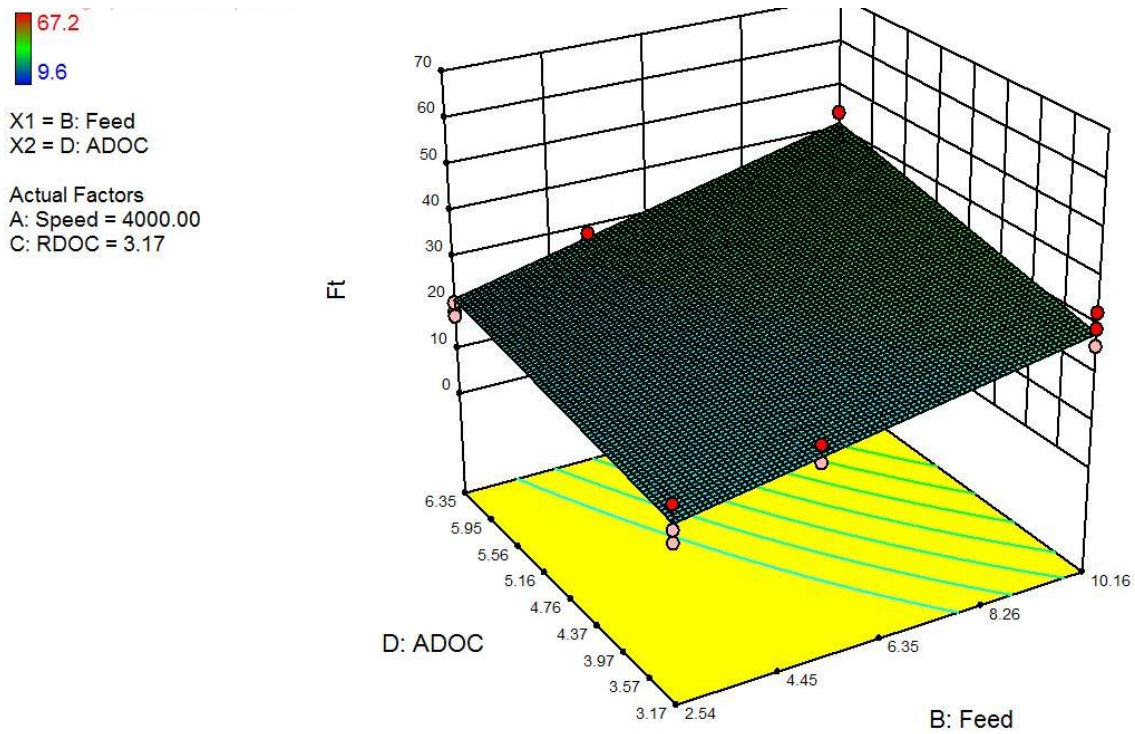


Figure H-363: AAC tangential cutting force response surface

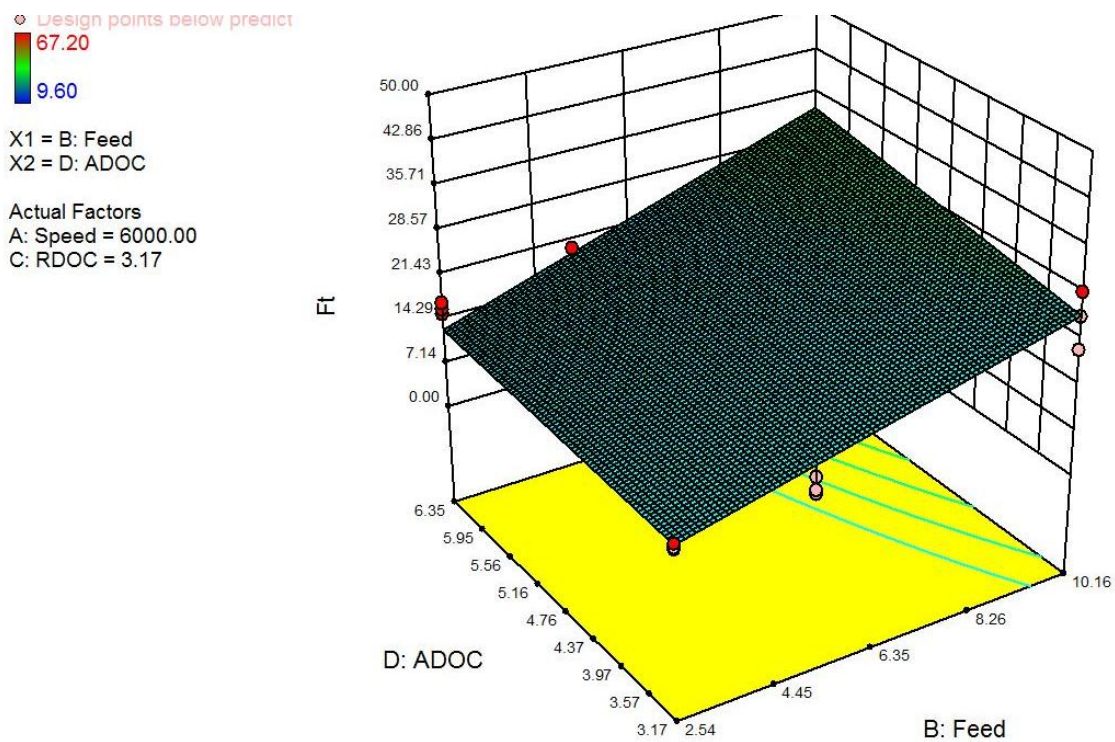


Figure H-364: AAC tangential cutting force response surface

○ Design points below predict
 58.6
 7.6

X1 = A: Speed
 X2 = D: ADOC

Actual Factors
 B: Feed = 10.16
 C: RDOC = 6.35

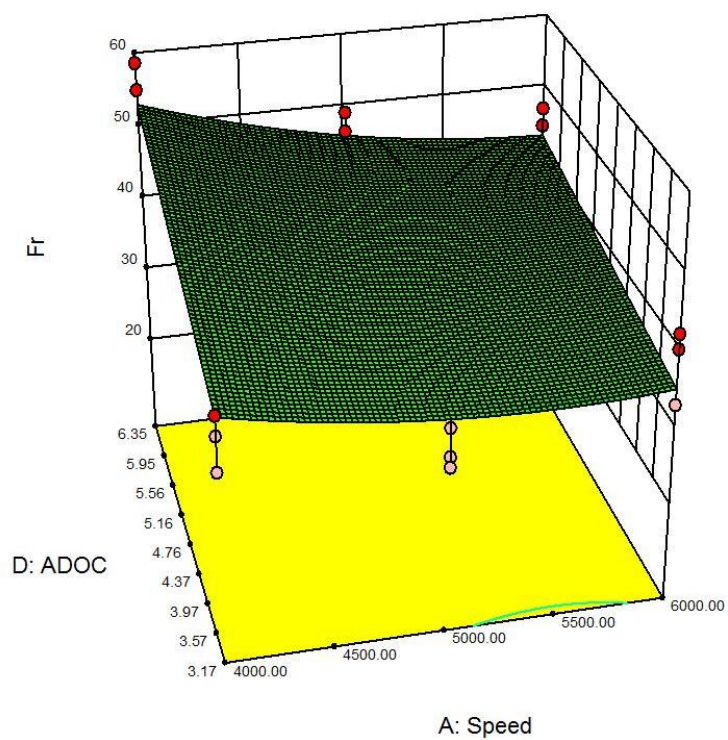


Figure H-365: AAC radial cutting force response surface

○ Design points below predict
 58.6
 7.6

X1 = A: Speed
 X2 = D: ADOC

Actual Factors
 B: Feed = 2.54
 C: RDOC = 6.35

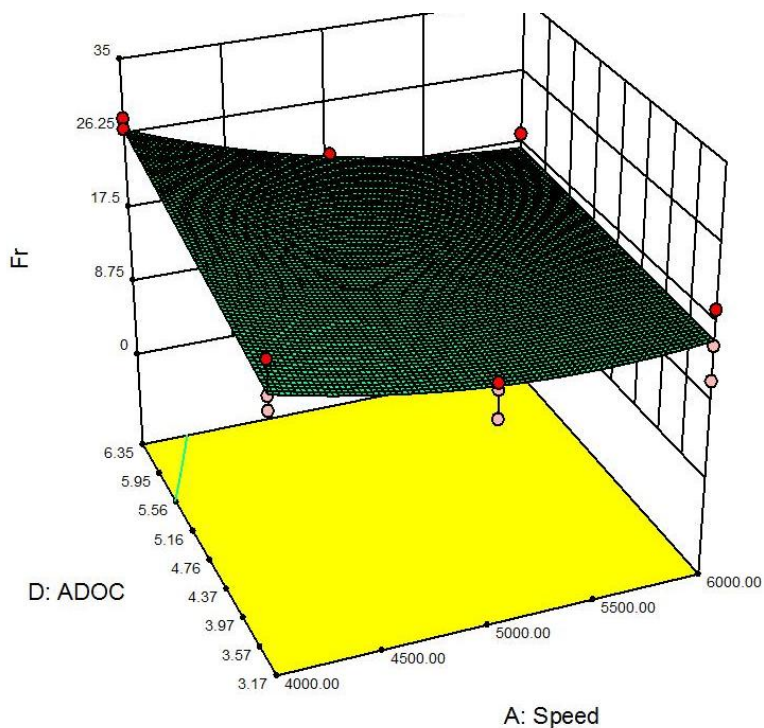


Figure H-366: AAC radial cutting force response surface

Design points above predict
 Design points below predict
 58.6
 7.6
 X1 = A: Speed
 X2 = D: ADOC
 Actual Factors
 B: Feed = 2.54
 C: RDOC = 3.17

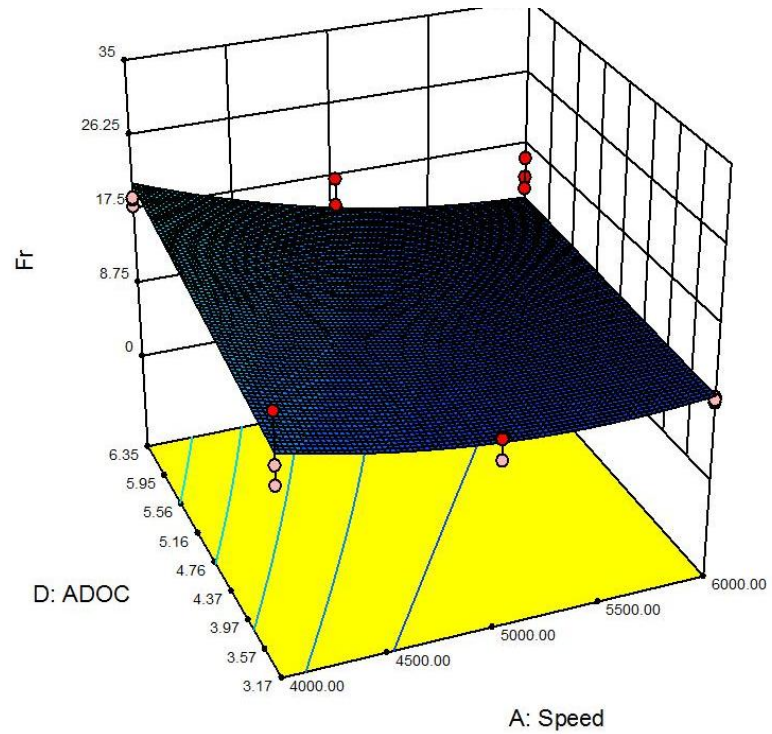


Figure H-367: AAC radial cutting force response surface

Design points above predict
 Design points below predict
 58.6
 7.6
 X1 = A: Speed
 X2 = D: ADOC
 Actual Factors
 B: Feed = 10.16
 C: RDOC = 3.17

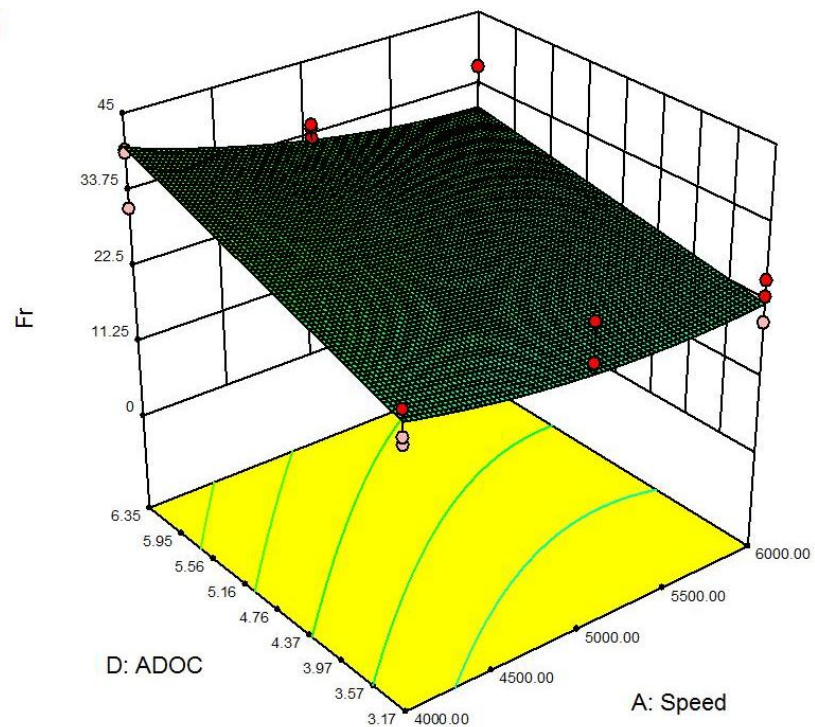


Figure H-368: AAC radial cutting force response surface

◊ Design points below predict
 58.6
 7.6

X1 = B: Feed
 X2 = C: RDOC

Actual Factors
 A: Speed = 6000.00
 D: ADOC = 6.35

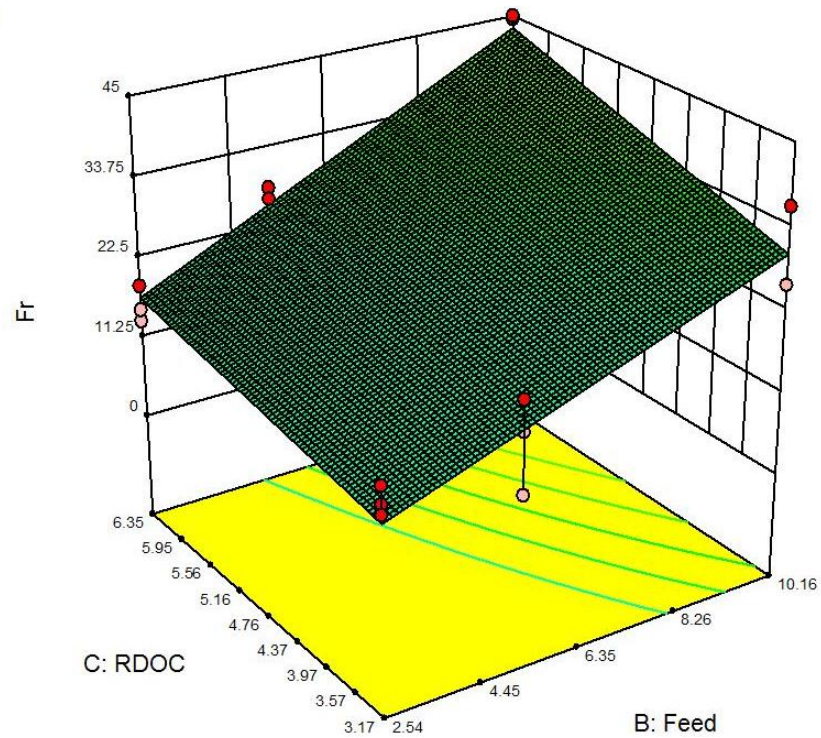


Figure H-369: AAC radial cutting force response surface

◊ Design points above predict
 ◊ Design points below predict
 58.6
 7.6

X1 = B: Feed
 X2 = C: RDOC

Actual Factors
 A: Speed = 4000.00
 D: ADOC = 6.35

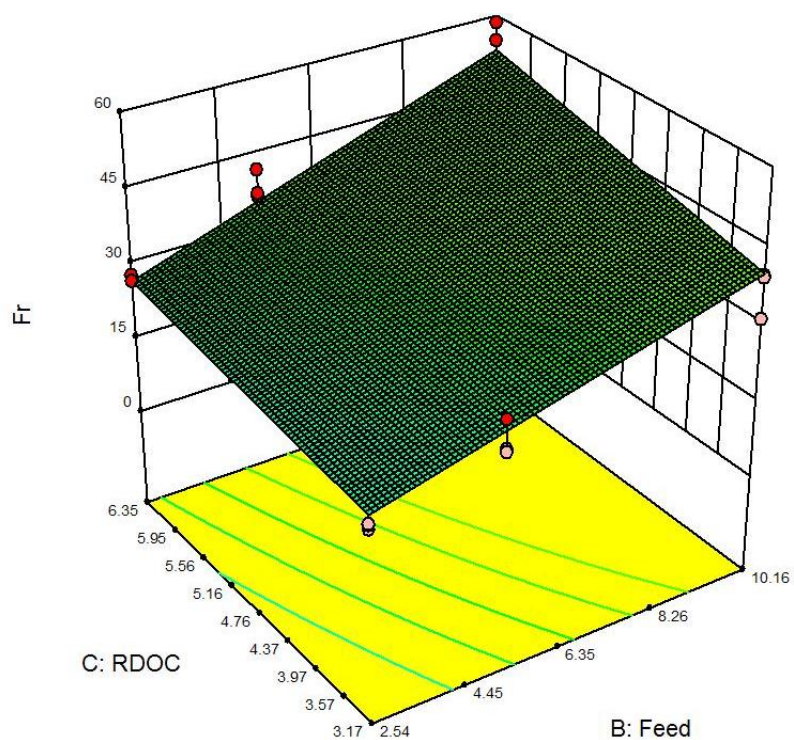


Figure H-370: AAC radial cutting force response surface

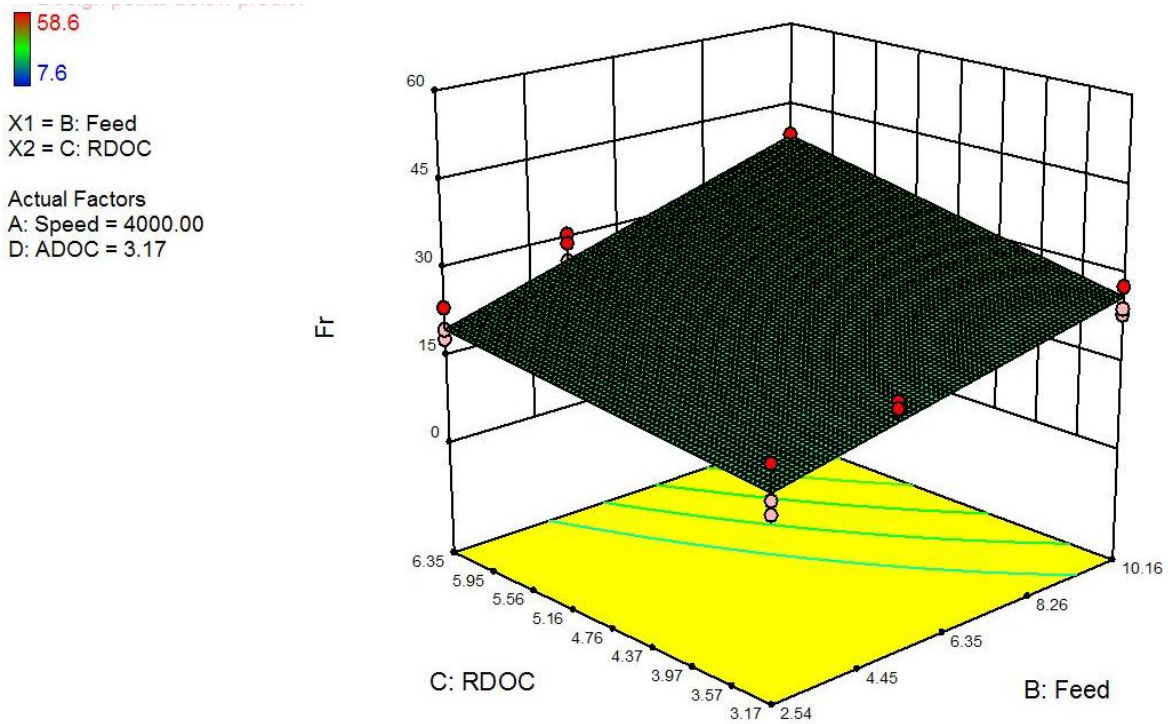


Figure H-371: AAC radial cutting force response surface

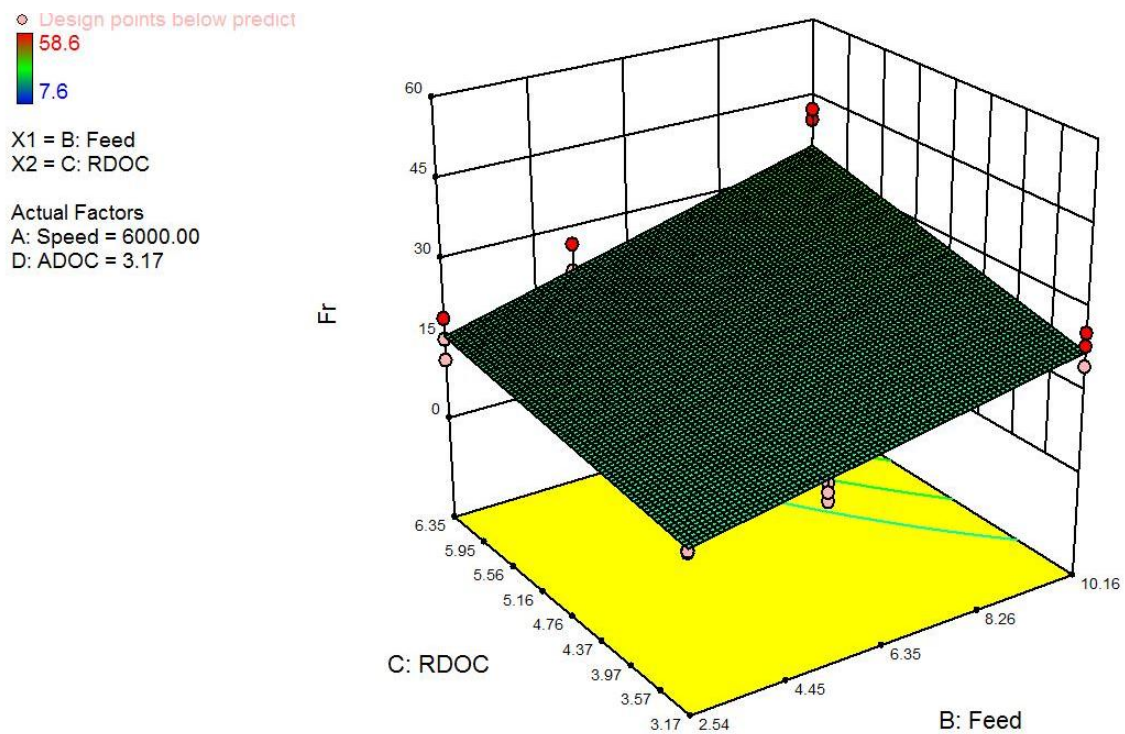


Figure H-372: AAC radial cutting force response surface.

● Design points above predict
 ○ Design points below predict
 58.6
 7.6
 X1 = B: Feed
 X2 = D: ADOC
 Actual Factors
 A: Speed = 6000.00
 C: RDOC = 6.35

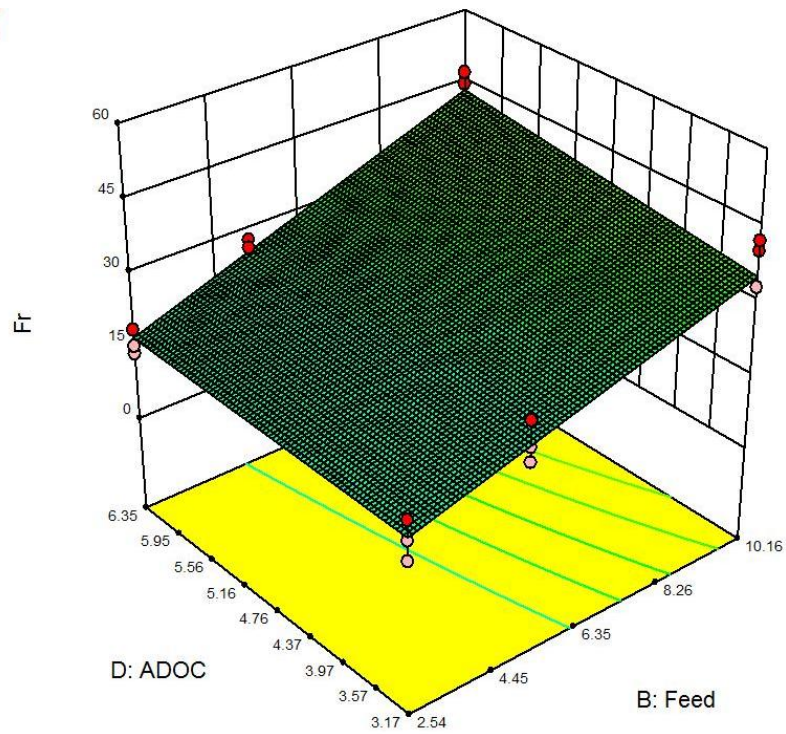


Figure H-373: AAC radial cutting force response surface.

● Design points above predict
 ○ Design points below predict
 58.6
 7.6
 X1 = B: Feed
 X2 = D: ADOC
 Actual Factors
 A: Speed = 4000.00
 C: RDOC = 6.35

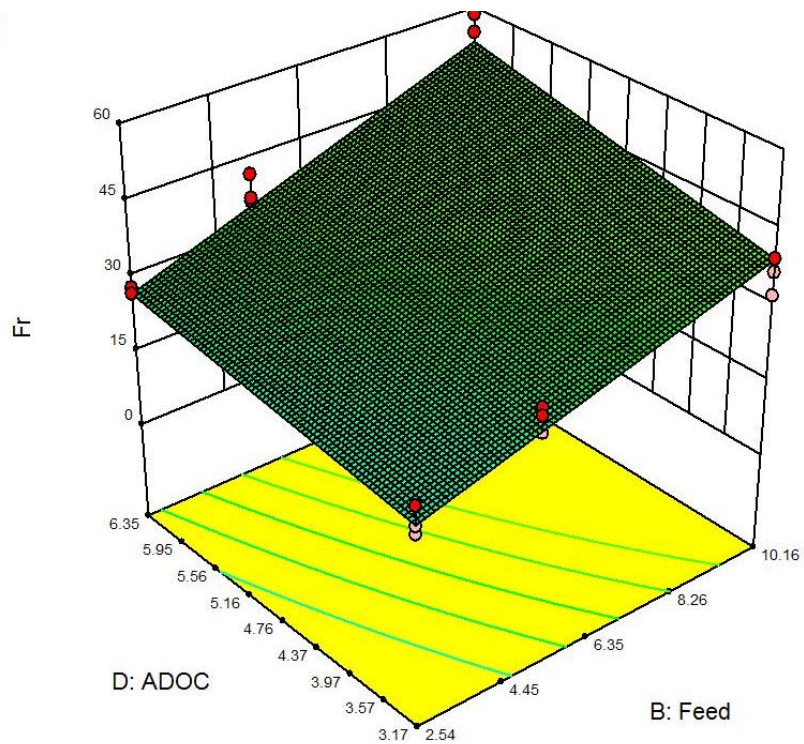


Figure H-374: AAC radial cutting force response surface.

● Design points above predicted
 ○ Design points below predicted
 58.6
 7.6

X1 = B: Feed
 X2 = D: ADOC

Actual Factors
 A: Speed = 4000.00
 C: RDOC = 3.17

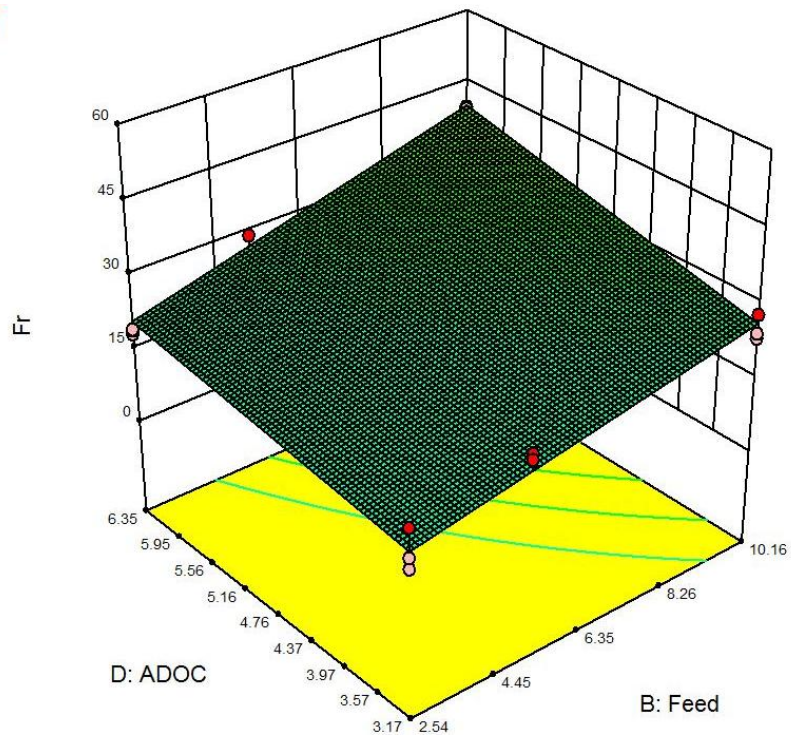


Figure H-375: AAC radial cutting force response surface.

● Design points above predicted
 ○ Design points below predicted
 58.6
 7.6

X1 = B: Feed
 X2 = D: ADOC

Actual Factors
 A: Speed = 6000.00
 C: RDOC = 3.17

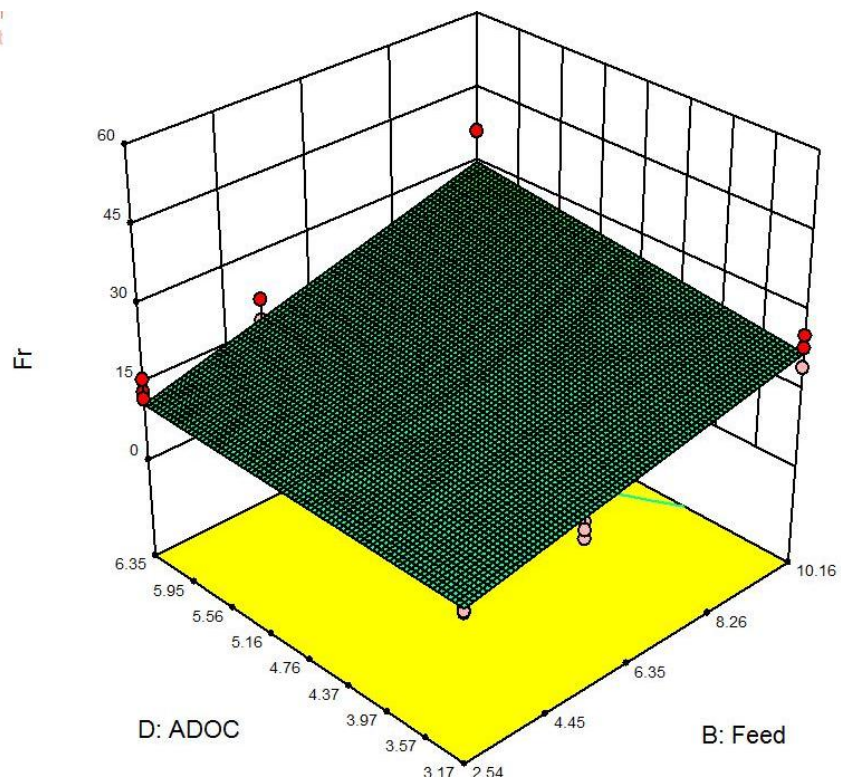


Figure H-376: AAC radial cutting force response surface.

3.) Cfoam

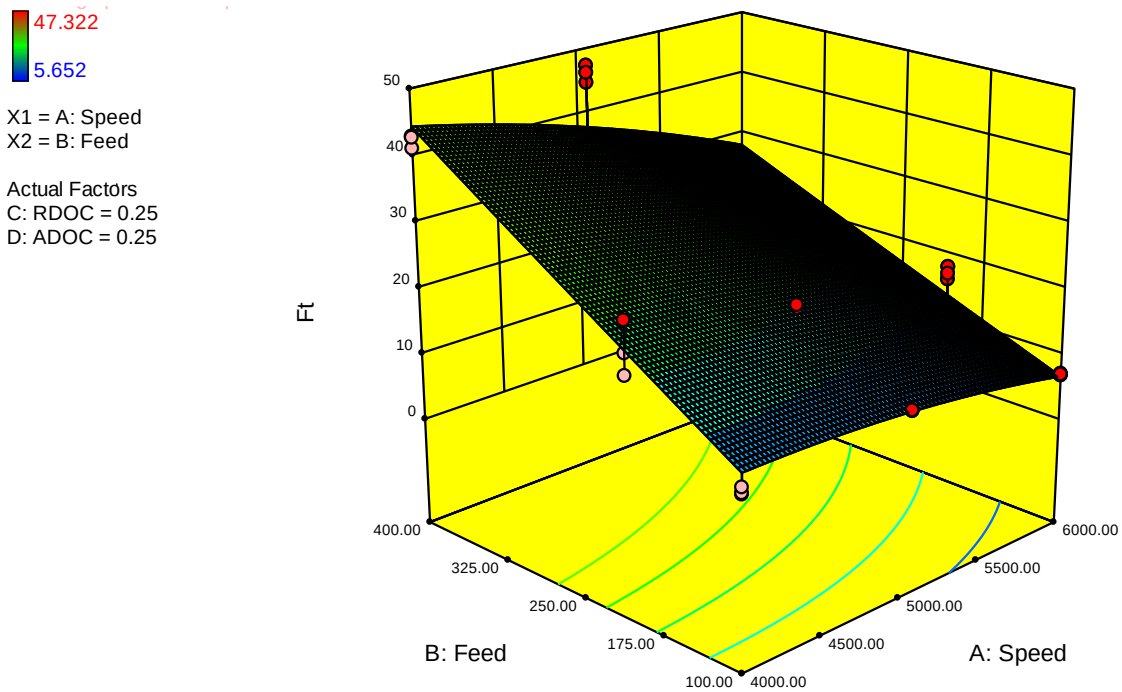


Figure H-377: Cfoam tangential cutting force response surface.

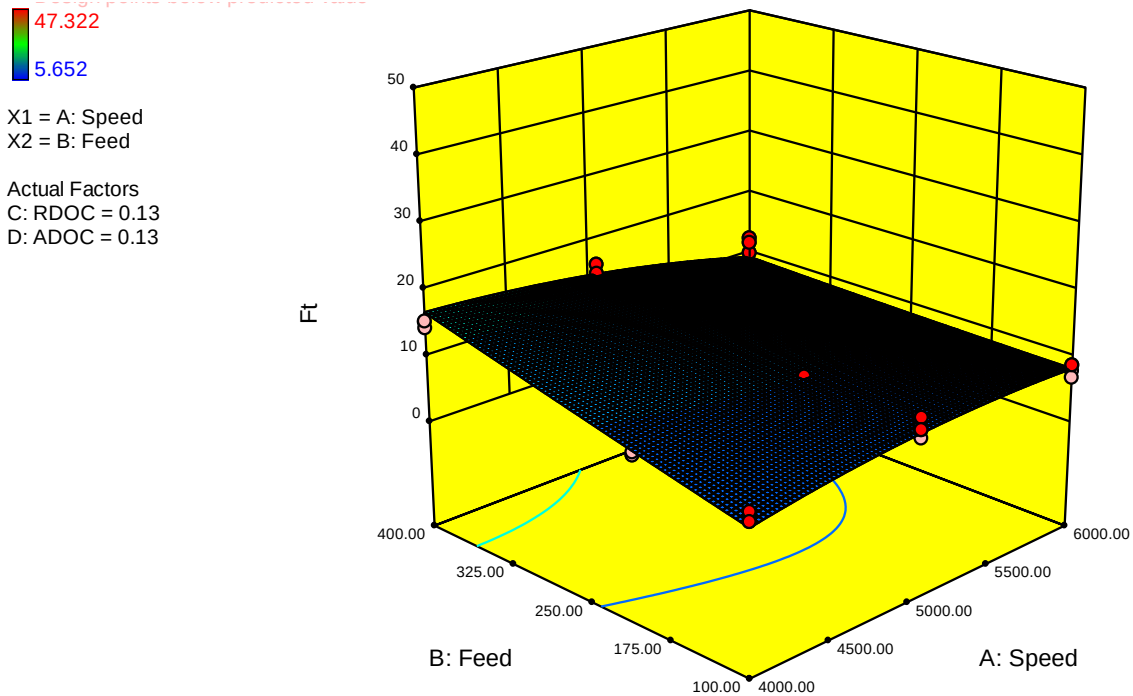


Figure H-378: Cfoam tangential cutting force response surface.

47.322
5.652
 X1 = A: Speed
 X2 = B: Feed
 Actual Factors
 C: RDOC = 0.13
 D: ADOC = 0.25

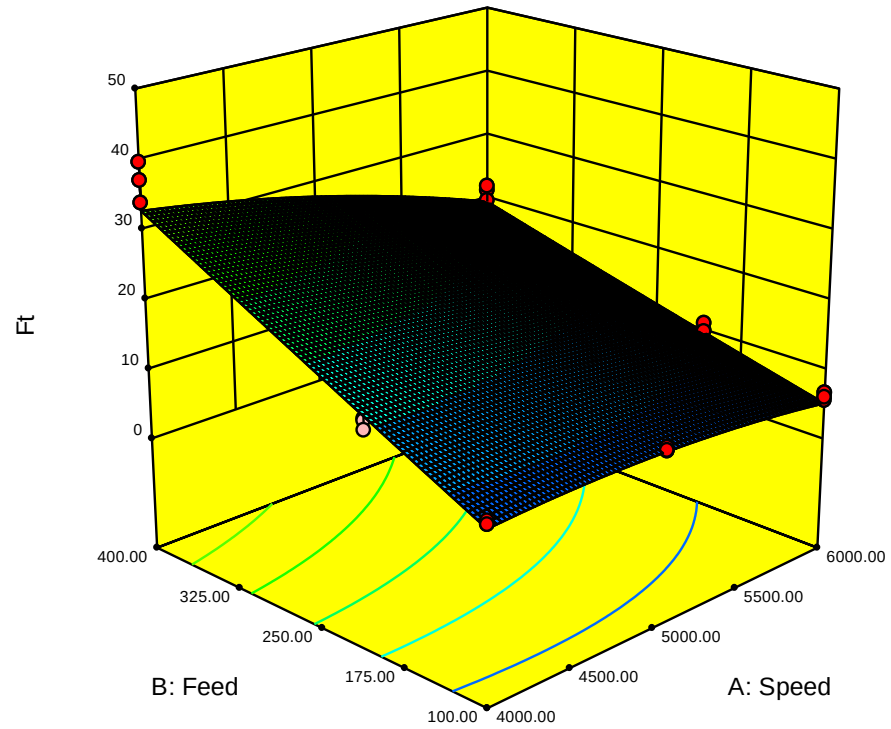


Figure H-379: Cfoam tangential cutting force response surface

47.322
5.652
 X1 = A: Speed
 X2 = B: Feed
 Actual Factors
 C: RDOC = 0.25
 D: ADOC = 0.13

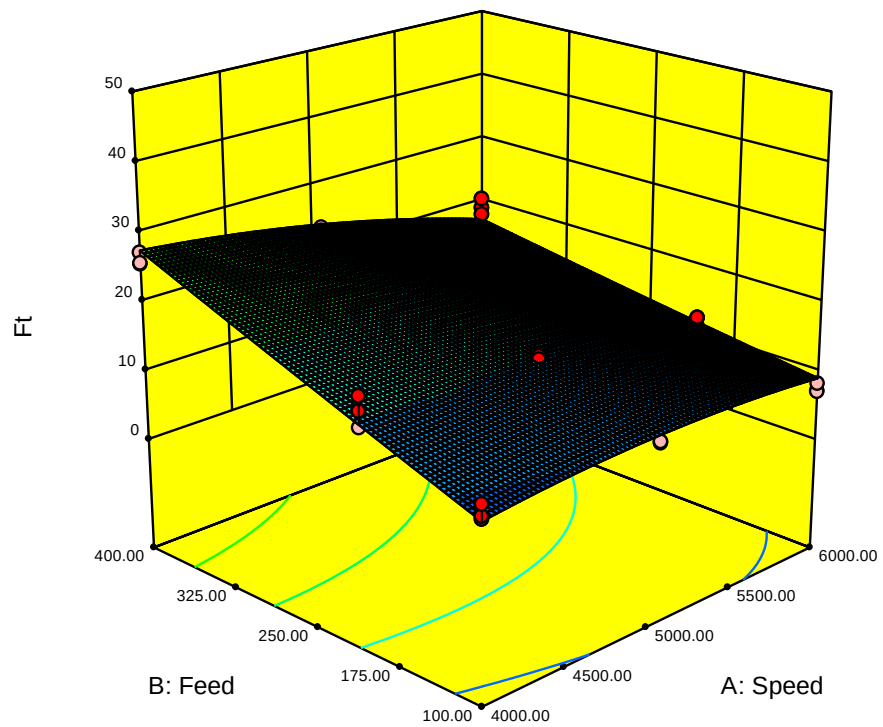


Figure H-380: Cfoam tangential cutting force response surface.

45.244
5.82
 X1 = A: Speed
 X2 = B: Feed
 Actual Factors
 C: RDOC = 0.25
 D: ADOC = 0.25

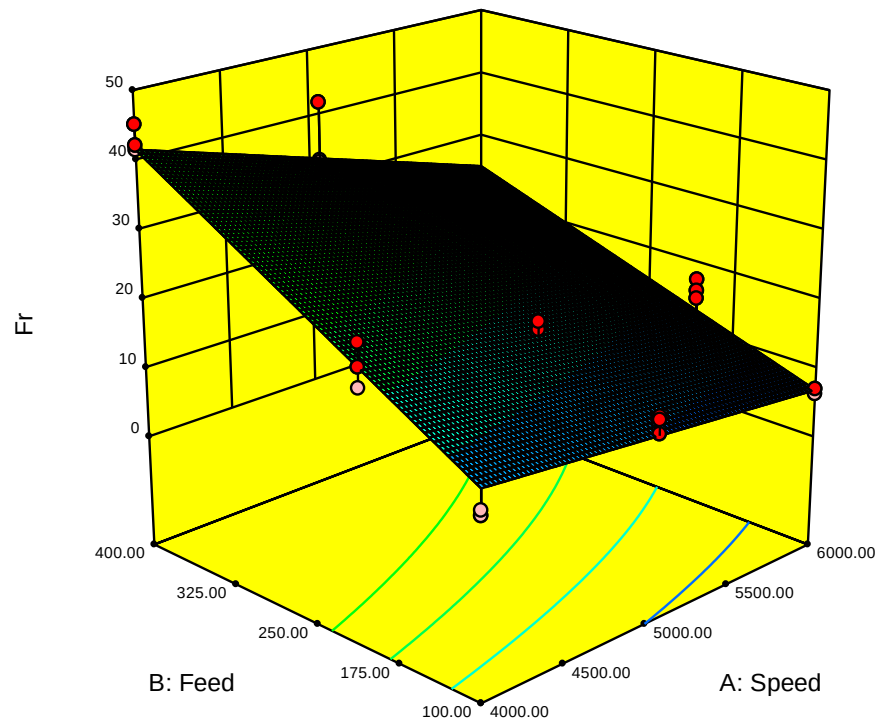


Figure H-381: Cfoam tangential cutting force response surface.

45.244
5.82
 X1 = A: Speed
 X2 = B: Feed
 Actual Factors
 C: RDOC = 0.13
 D: ADOC = 0.25

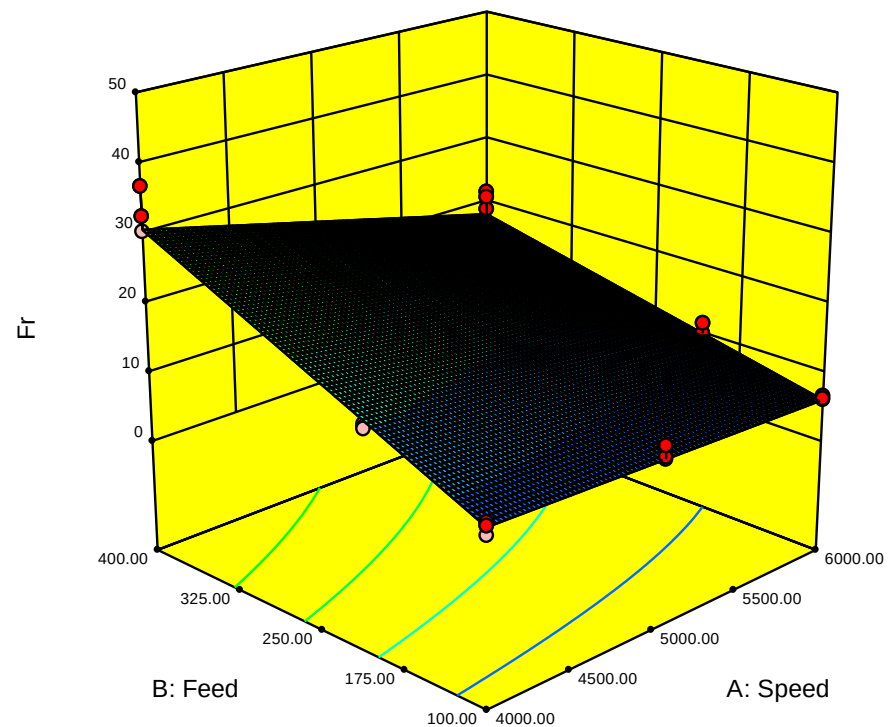
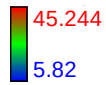


Figure H-382: Cfoam tangential cutting force response surface.



X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 0.13
D: ADOC = 0.13

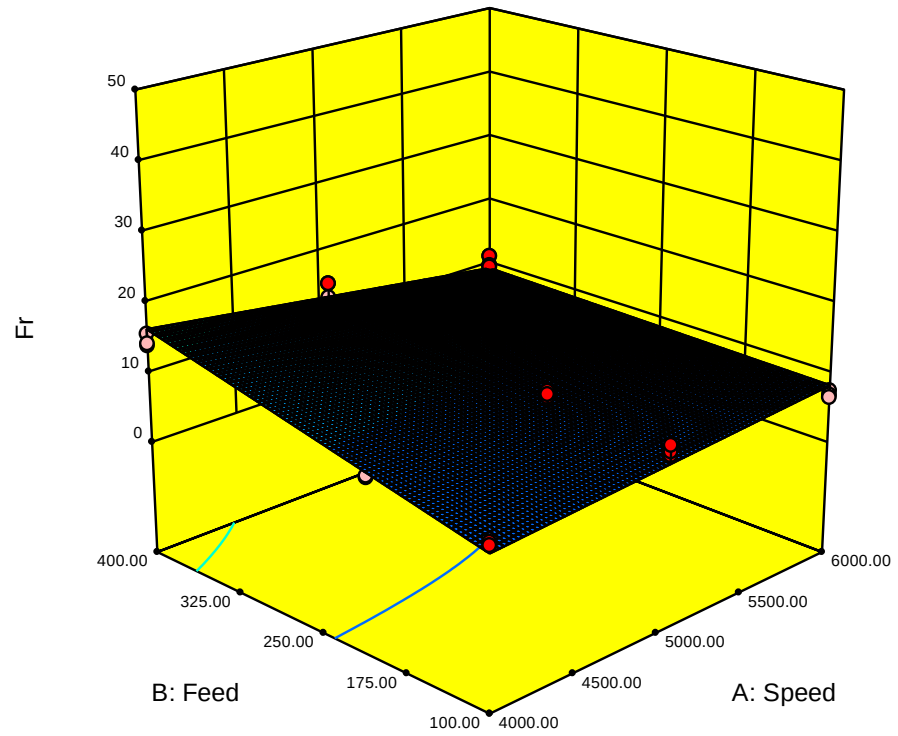
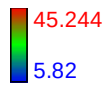


Figure H-383: Cfoam tangential cutting force response surface.



X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 0.13
D: ADOC = 0.25

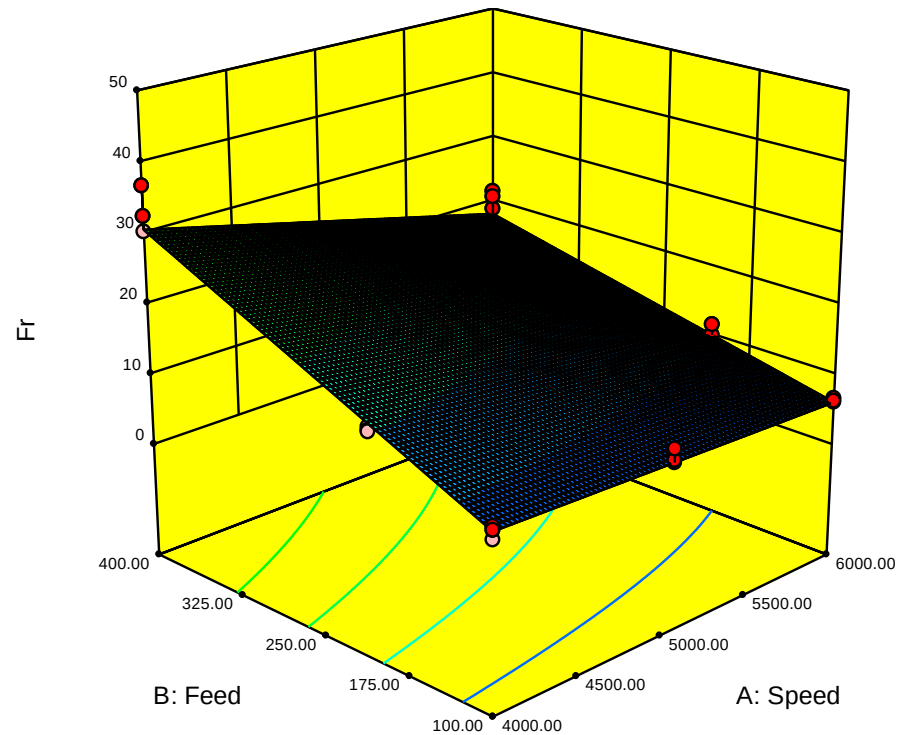


Figure H-384: Cfoam tangential cutting force response surface.



X1 = A: Speed
X2 = B: Feed

Actual Factors
C: RDOC = 0.25
D: ADOC = 0.13

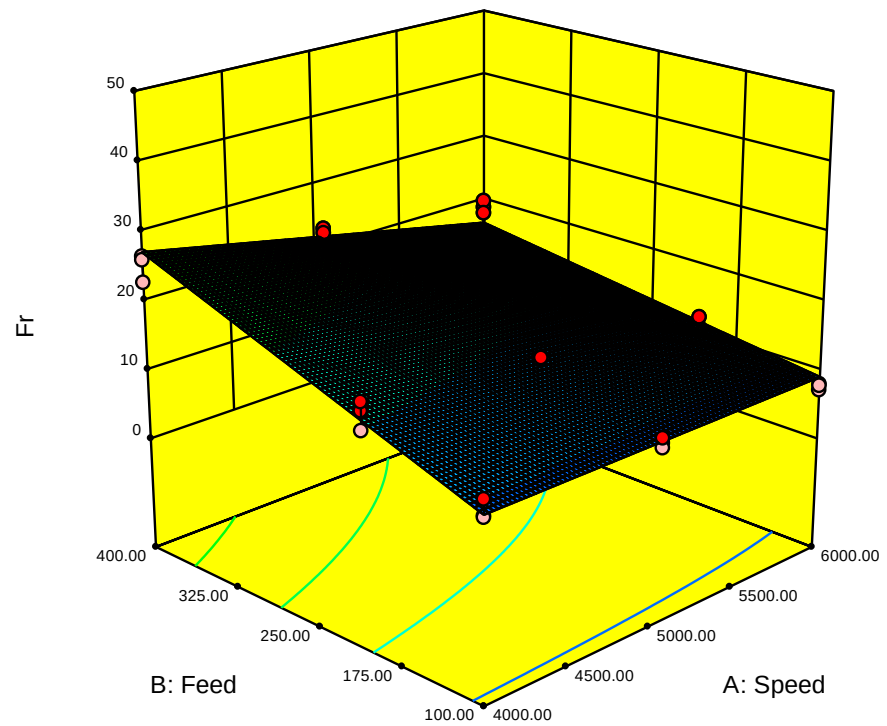


Figure H-385: Cfoam tangential cutting force response surface

Appendix: I. Matlab code for porous cutting force model

1.) Run.m

```
%% Run.m - This file is the main manifest file which calls the
%% needed sub-functions and stores the results in the
%% array kdstorage

clear all
tic

hUi = getappdata(0, 'hUi');
material = getappdata(hUi, 'material');
inputlist = getappdata(hUi, 'inputlist');
numruns = getappdata(hUi, 'numruns');

numconditions = size(inputlist);
numconditions = numconditions(1);

if numruns == 0
    numruns = numconditions;
end

results = zeros(numruns, 3);

for k = 1:numruns;
    disp(strcat('conditions set', num2str(k)))

    inputs = inputlist(k, :);

    kdstorage = Dynamic_coeff2(inputs);
    % kd storage is an Nx2000x4 array (where N is the element
    number)
    % the dimensions are: elementx(datapoint)xV where V is a
    vector with
    % dimensions time, beta=1, Kd = 2, Tc = 3, F = 4;

    RPM = inputs(13);
    N = inputs(10);

    for n = 1:N
        %Transform beta into time [s]
        for i = 1:6000
```

```

            kdstorage(n,i,1) = kdstorage(n,i,1)/
((RPM*(2*pi))/60);

        end

    end

    %Prepare force summation array
    %must be an array of j flutes
    min_final_time = min(kdstorage(:,6000,1));
    elem_force = zeros(2000, N+1);

    %Add time steps in left most column
    for i = 1:2000

        elem_force(i, 1) = (i-1)*(min_final_time/2000);

    end

    for n = 1:N
        %write closest the time's value
        for a = 1:2000
            [~, index] = min(abs(kdstorage(n,:,1) -
elem_force(a,1)));
            elem_force(a, n+1) = kdstorage(n,index,4);
        end
    end

    tot_elem_force = zeros(2000, 2);

    for i = 1:2000
        tot_elem_force(i,1) = elem_force(i,1);
        tot_elem_force(i,2) = sum(elem_force(i, 2:N+1));
    end

    % figure
    % plot(kdstorage(1,:,1))
    % title('Time')
    % xlabel('point')
    % ylabel('time [s]')
    %
    % figure
    % plot( kdstorage(1,:,2))
    % title('Kd')
    % xlabel('point')
    % ylabel('Kd')

```

```

%
% figure
% plot(kdstorage(1,:,1),kdstorage(1,:,3))
% title('chip thickness')
% xlabel('time')
% ylabel('chip thickness[mm]')
%
% figure
% plot(kdstorage(1,:,1),kdstorage(1,:,4))
% title('elemental Force')
% xlabel('time')
% ylabel('Force [n]')
% Create sample images from figure

feed = inputs(14);
adoc = inputs(12);
rdepth = inputs(11);

image      =      strcat('C:\Users\mm724d\Desktop\BP_Output\',
material,'_',    num2str(RPM),    'RPM_',num2str(feed),    'mpmin_',
num2str(adoc),                                     'mmADOC_',
num2str(rdepth), 'mmRDOC_',num2str(k),'.jpeg') ;
figname     =      strcat('C:\Users\mm724d\Desktop\BP_Output\',
material,'_',    num2str(RPM),    'RPM_',num2str(feed),    'mpmin_',
num2str(adoc),                                     'mmADOC_',
num2str(rdepth), 'mmRDOC_',num2str(k),'.fig') ;
F = figure;

halfway = size(tot_elem_force);
halfway = halfway(1)/2;
max1 = max(tot_elem_force(1:halfway, 2));
max2 = max(tot_elem_force(halfway:end, 2));

results(k,:) = [k, max1, max2];

plot(tot_elem_force(:,1),tot_elem_force(:,2))
disp(max1);
title('Total Cutting Force')
xlabel('time')
ylabel('Force [n]')
saveas(F, figname);
saveas(F, image);
delete(F);
tElapsed = toc

```

```

end

%% write output to excel file

xlswrite('c:\Users\mm724d\Desktop\BP_Output\results.xlsx',results,1,'a4');

disp('Done')

```

2.) Dynamic_coeff2.m

```

function [Kd_storage] = Dynamic_coeff2(Inputs)

% Inputs = [pore_min, pore_max, pore_mean, pore_stdev, pore_den,
% ligament_density, cutter_rad, J, helix, N, RDOC, ADOC, RPM, %
% feed];

% This function returns the value of the porous coefficient for
% storage in the kdstorage array.

%transfer inputs
pore_min = Inputs(1,1);
pore_max = Inputs(1,2);
pore_mean = Inputs(1,3);
pore_stdev = Inputs(1,4);
pore_den = Inputs(1,5);
ligament_density = Inputs(1,6);
cutter_rad = Inputs(1,7);
J = Inputs(1,8); %number of flutes
g = 2*pi/J; %flute separation angle
N = Inputs(1,10); %number of elements
D = Inputs(12); %axial depth of cut
helix = Inputs(9); %helix angle
R = cutter_rad; %radius
rdepth = Inputs(1,11); %radial depth
RPM = Inputs(13);
feed = Inputs(14);

Kd_storage=zeros(N,6000,4);
% Kd_storage2=zeros(N,20000,4);
% Kd_storage3=zeros(N,20000,4);
% Kd_storage4=zeros(N,20000,4);

```

```

j=1;
for n = 1:N
    offset = (j-1)*g + ((n-1/2)*D/N)/(tan((pi/2)-helix)*R);
    %angle of element
    for h = 1:300 % for xxx pores in the rotational
direction.....can be increased if pore size is and more time is
required...
        if h == 1
            place = 0;
            [pore_diameter,percent_area,rad_rot] =
Pore_effects(pore_min, pore_max, pore_mean, pore_stdev,
pore_den, ligament_density, cutter_rad);
            step = rad_rot/20;
        else
            [pore_diameter,percent_area,rad_rot] =
Pore_effects(pore_min, pore_max, pore_mean, pore_stdev,
pore_den, ligament_density, cutter_rad);
            step = rad_rot/20;
        end

        for i=1:20 % 20 datapoints accross each pore

            % Depicts passage through a spherical void by %area
            place = (place + step);
            Kd = percent_area*(1-sin(pi*(1/rad_rot)*((i-
1)*step)));
            Kd_storage(n,(20*(h-1))+ i,2) = Kd;
            Kd_storage(n,(20*(h-1))+ i,1) = place;
            Kd_storage(n,(20*(h-1))+ i,3) = chip2(rdepth,
(offset + place), cutter_rad, J, RPM, feed);
            Kd_storage(n,(20*(h-1))+ i,4) =
Coeff_Rad(feed)*Kd_storage(n,(20*(h-1))+
i,3)*Kd_storage(n,(20*(h-1))+ i,2)*D/N;

        end;

    end;
end;

%Plot of Kd over the pore...uncomment for troubleshooting

% figure
% plot(Kd_storage(1,1:4000,1),Kd_storage(1,1:4000,2),'.')
% grid on

```

```

% title('Kd')
% xlabel('Delta Theta [rad]')
% ylabel('Kd')

3.) Pore_effects.m

function [diameter, area, rad_rot] = Pore_effects(chipArea,
pore_min, pore_max, pore_mean, pore_stdev, pore_den,
ligament_density, cutter_rad)

% this function returns the reduced contact area due to the pore

x=[pore_min:.005:pore_max]; %the data in increaments of .005mm
f = gauss_distribution(x, pore_mean, pore_stdev);
fnom = f/sum(f);
t = [x;fnom];
r = rand;
y = sum(r >= cumsum([0,fnom]));
diameter = t(1,y);
area = (((chipArea - (pi*diameter^2))/4)/chipArea)*100; %
percent solid area
if area > 0
    %do nothing
else
    area = 0; %safety check for erroneous area
end

density = (1 - ((pi*diameter^2)/4) *
(pore_den*.01))*ligament_density ;
%density assumes through thickness of area
if density > 0
    %do nothing
else
    density = 0;
end

rad_rot = asin ((diameter/(2*cutter_rad))*2);

%plot section for the selected distribution. this is a back
check to
%make sure the selected distribution matches the given
paramters.

%{

```



```

    %!!!WARNING!!! be sure to reset the comment before running a
    full test

```

```

checkdata = zeros(2000, 3);

```

```

for i=1:2000
    r = rand;
    y = sum(r >= cumsum([0,fnom]));
    diameter = t(1,y);

    area      =      (1      - ((pi*diameter^2)/4) *      (pd*.01)) *100;
    % (mmmm/pore) (pores/mmmm)
    if area > 0
        %do nothing
    else
        area = 0;
    end

    density      =      (1      - ((pi*diameter^2)/4) *
    (pd*.01)) * ligament_density ;
    if density > 0
        %do nothing
    else
        density = 0;
    end

    checkdata(i,1) = diameter;
    checkdata(i,3) = area;
    checkdata(i,2) = density;
end

```

```

figure
plot(x,f,'.')
grid on
title('Bell Curve')
xlabel('Randomly produced numbers')
ylabel('Gauss Distribution')

```

```

figure
hist(checkdata(:,1), 2000)
title('Produced Pore Diameter Distribution')
xlabel('Pore Diameter [mm]')
ylabel('Counts')

```

```

figure

```

```

hist(checkdata(:,2), 2000)
title('Produced Density Distribution')
xlabel('Density [g/mm^3]')
ylabel('Counts')

figure
hist(checkdata(:,3), 2000)
title('Produced Percent Area Distribution')
xlabel('Area [mm^2]')
ylabel('Counts')
%}

```

4.) gauss_distribution.m

```

%Function simply produces a gaussian distribution
%This function is left as a separate file to make incorporating
new
%distributions easier

function f = gauss_distribution(x, mu, s)
p1 = -.5*((x-mu)/s).^2;
p2 = (s*sqrt(2*pi));
f = exp(p1) ./p2;

```

5.) chip2.m

```

function [ Tc ] = chip2( rdoc, phi,cutter_rad,J, RPM, feed )
%this function calculates instantaneous chip thickness
%simplified chip thickness model with no cutter run out
(Martellotti)

ft = (feed*1000)/(RPM*J); %feed per tooth
R = cutter_rad; %cutter radius
D = 2*R;
engagement = acos(1-(rdoc)/R);

if(phi >= (2*pi))
    phi = mod(phi,(2*pi)); %modulus of phi
end

if(phi <= engagement) %is it in the cut?
    Tc = (ft*sin(phi));

```

```
else
    Tc = 0;
```

```
end
```

6.) Coeff_Rad.m

```
function [ Kr ] = Coeff_Rad(feed)
%storage file for the radial cutting coefficient
```

```
hUi = getappdata(0, 'hUi');
material = getappdata(gcf, 'material');
```

```
if strcmpi(material(1:3), 'aac')
Kr = %input value
```

```
end
if strcmpi(material(1:6), 'CB1100')
Kr = %input value
end
```

```
if strcmpi(material(1:5), 'Cfoam')
Kr = %input value
end
```

```
end
```

7.) Coeff_Tan.m

```
function [ Kt ] = Coeff_Tan(feed)
%storage file for the radial cutting coefficient
```

```
hUi = getappdata(0, 'hUi');
material = getappdata(gcf, 'material');
```

```
if strcmpi(material(1:3), 'aac')
Kt = %input value
```

```
end
if strcmpi(material(1:6), 'CB1100')
Kt = %input value
end
```

```
if strcmpi(material(1:5), 'Cfoam')
Kt = %input value
```

end

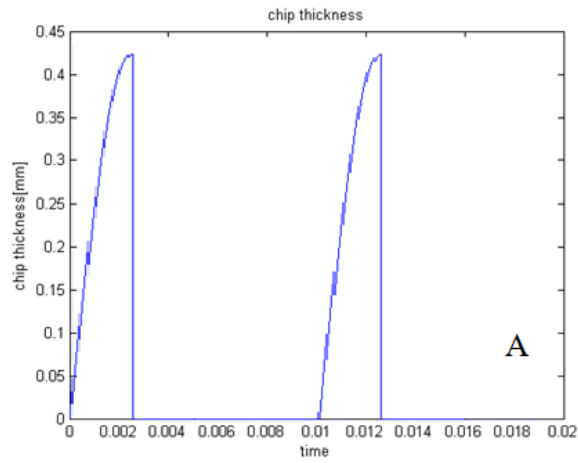
end

Appendix: J. Element size effect

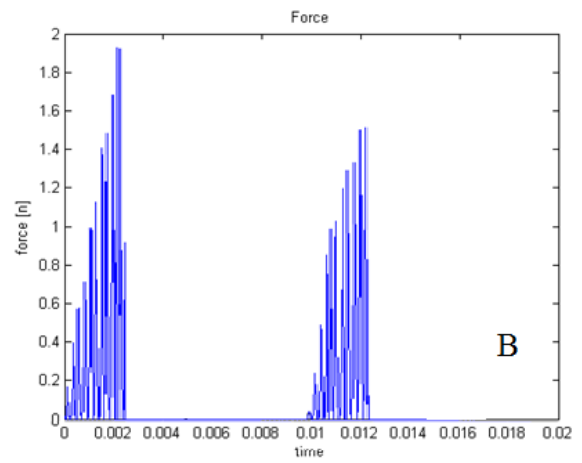
As discussed in previous sections the first and most important input selected is the number of elements. The limitations and implications of the number of elements selected have been detailed. Below is an example of the effect of a high element count/pore size ratio. The figures below are taken from a simulation using the same inputs as those shown in Table 7-1. Except, the element count has increased to 100.

The theoretical chip thickness and elemental cutting force for the high element count case are shown in Figure J-386. From the elemental cutting force plot the decrease in randomness and number of distinct peaks is clearly visible. The closer conformity to the theoretical chip thickness is also evident above.

From several effects of the increased element count to pore radius ratio can be seen. The most obvious is the smooth nature of the high element count plot. The decrease in the scatter in the maximum peak force from profile to profile is also shown. Finally, the increase in the magnitude of the peak force has clearly increased over the low element count plots. As discussed, the effect of the increased element count to pore radius ratio is to erroneously decrease the effective pore size and increase pore density.



a.) Theoretical chip thickness



b.) Elemental cutting force

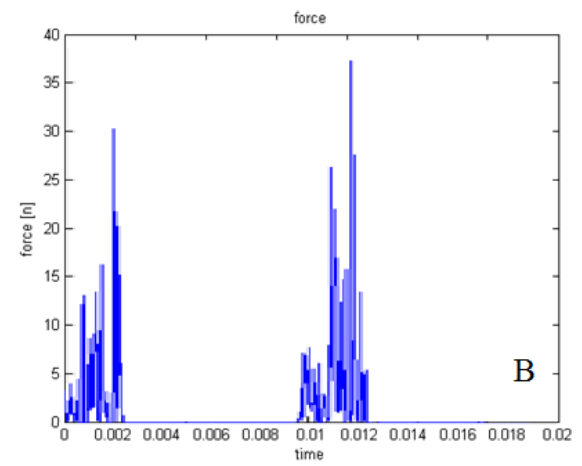
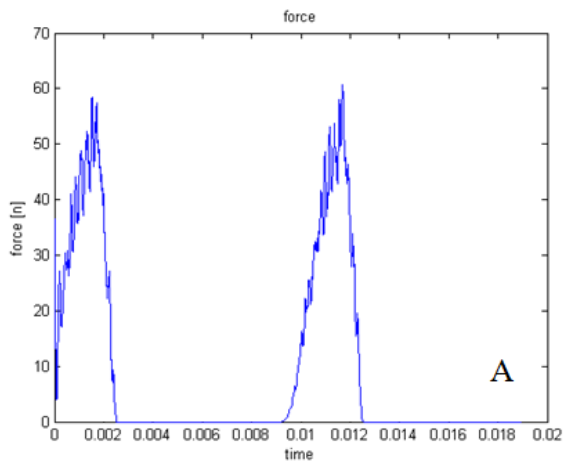


Figure J-386: Element size effect

Appendix: K. Determination of the cutter runout parameters

In the event of runout the instantaneous uncut chip thickness $h_i(z)$ must be calculated in terms of the actual rotation radius of each cutting edge element and the ideal feed per tooth. The actual rotation radius of a cutting edge element in terms of axial position z can be obtained through Equation 7.4. κ is the relative rotation of the element due to the helix angle as a function of the axial position z , Equation 7.5. R and β represent the nominal radius and helix angle of the cutter. ρ and λ are the runout parameters. The instantaneous uncut chip thickness associated with element Q can be calculated using Equation 7.6. Combining Equations 7.6 and 7.4 yields the instantaneous chip thickness as a function of cutter geometry and runout parameters, Equation 7.7. In this formulation the i^{th} tooth removes the material left over by the previous tooth.

$$R_i(z) = R + \rho \cos \left[\lambda - \kappa(z) - \frac{2(i-1)\pi}{N} \right] \quad (7.1)$$

$$\kappa(z) = \frac{z \tan \beta}{R} \quad (7.2)$$

$$h_i(z) = m_i f_z \sin(\theta(z)) + R_i(z) - R_{i-m}(z) \quad (7.3)$$

$$h_i(z) = m_i f_z \sin(\theta(z)) + [-2m_i \rho \sin \left(\frac{m_i \pi}{N} \right) \sin \left(\lambda - \kappa(z) - \frac{(2i - m_i - 2)\pi}{N} \right)] \quad (7.4)$$

By substituting Equation 7.7 into Equation 7.2 the total X, Y, and Z component forces on the i^{th} cutting edge at a cutter rotation of $\varphi_i = \varphi + \frac{2(i-1)\pi}{N}$ can be expressed as Equation 7.8, where $E_{ij}(\varphi_i)$, are defined as in Equation 7.9. Constants A_1 , B_1 , C_1 , and D_1 are given in 7.10.

Assuming the following,

$$\alpha = -\theta_{i,u} - \phi_i - \frac{(2i-3)\pi}{N}$$

Equation 7.12 can be formed where, V_{k1} and V_{k2} are given by Equations 7.13 and 7.14

From 7.13, 7.14 and utilizing the found cutting force coefficients the runout parameters can be determined. Using the component with the largest magnitude at a cutter rotation angles of $\varphi_i = \varphi + \frac{2(i-1)\pi}{N}$ ($i = 1, 2, \dots, N$), Equation 7.15 is obtained. Therefore, based on least squares g_1 and g_2 can be found from equation 7.17: Finally, the runout parameters, ρ and λ , can now be obtained using Equation 7.19

$\begin{bmatrix} \bar{F}_{i,x}(\varphi_i) \\ \bar{F}_{i,y}(\varphi_i) \\ \bar{F}_{i,z}(\varphi_i) \end{bmatrix} = \frac{f_z R}{\tan \beta} \begin{bmatrix} A_1(\varphi_i) & -B_1(\varphi_i) & 0 \\ B_1(\varphi_i) & A_1(\varphi_i) & 0 \\ 0 & 0 & -C_1(\varphi_i) \end{bmatrix} \begin{bmatrix} K_t(\varphi) \\ K_r(\varphi) \\ K_z(\varphi) \end{bmatrix} + \begin{bmatrix} E_{11}(\varphi_i) & E_{12}(\varphi_i) \\ E_{21}(\varphi_i) & E_{22}(\varphi_i) \\ E_{31}(\varphi_i) & E_{32}(\varphi_i) \end{bmatrix} \begin{bmatrix} a_{runout} \\ b_{runout} \end{bmatrix}$	(7.5)
$\begin{aligned} E_{11}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [K_t(\varphi_i) A_1(\varphi_i) - K_r(\varphi_i) B_1(\varphi_i)] \\ E_{12}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [-K_t(\varphi_i) A_1(\varphi_i) + K_r(\varphi_i) B_1(\varphi_i)] \\ E_{21}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [K_t(\varphi_i) A_1(\varphi_i) + K_r(\varphi_i) B_1(\varphi_i)] \\ E_{22}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [-K_t(\varphi_i) A_1(\varphi_i) - K_r(\varphi_i) B_1(\varphi_i)] \\ E_{31}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [K_z(\varphi_i) C_1(\varphi_i)] \\ E_{32}(\varphi_i) &= \frac{2R}{\tan \beta} \sin\left(\frac{\pi}{N}\right) [K_z(\varphi_i) E_1(\varphi_i)] \end{aligned}$	(7.6)
$\begin{aligned} A_1(\varphi_i) &= \frac{1}{4} \cos 2\theta \Big _{\theta_{i,1}}^{\theta_{i,u}} \\ B_1(\varphi_i) &= \frac{1}{4} (2\theta - \sin 2\theta) \Big _{\theta_{i,1}}^{\theta_{i,u}} \\ C_1(\varphi_i) &= \cos \theta \Big _{\theta_{i,1}}^{\theta_{i,u}} \\ D_1(\varphi_i) &= \frac{1}{4} (2\theta + \sin 2\theta) \Big _{\theta_{i,1}}^{\theta_{i,u}} \\ E_1(\varphi_i) &= \sin \theta \Big _{\theta_{i,1}}^{\theta_{i,u}} \end{aligned}$	(7.7)
$\begin{aligned} \gamma &= \lambda - \theta_{i,u} - \phi_i - \frac{(2i-3)\pi}{N} \\ \text{if } \theta_{i,u} &\leq \pi, \phi_i = 0. \text{ Else if } \theta_{i,u} > \pi, \\ \phi_i &= \varphi - \varphi_0 - \sin^{-1}\left(\frac{R_r - R}{R}\right) - \frac{\pi}{2} - \frac{2(i-1)\pi}{N} \end{aligned}$	(7.8)

$\begin{bmatrix} V_{11}(\varphi_i) & V_{12}(\varphi_i) \\ V_{21}(\varphi_i) & V_{22}(\varphi_i) \\ V_{31}(\varphi_i) & V_{32}(\varphi_i) \end{bmatrix} \begin{bmatrix} \rho \cos \lambda \\ \rho \sin \lambda \end{bmatrix} = \begin{bmatrix} F_x(\varphi_i) - \overline{F_x(\varphi_i)} \\ F_y(\varphi_i) - \overline{F_y(\varphi_i)} \\ F_z(\varphi_i) - \overline{F_z(\varphi_i)} \end{bmatrix}$	(7.9)
$V_{k1}(\varphi_i) = \cos \alpha \sum_{i=1}^N E_{k1}(\varphi_i) + \sin \alpha \sum_{i=1}^N E_{k2}(\varphi_i)$	(7.10)
$V_{k2}(\varphi_i) = \cos \alpha \sum_{i=1}^N E_{k2}(\varphi_i) - \sin \alpha \sum_{i=1}^N E_{k1}(\varphi_i)$	(7.11)
$T \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = TF$	(7.12)
$T = \begin{bmatrix} V_{21}(\varphi_i) & V_{22}(\varphi_i) \\ \vdots & \vdots \\ V_{21}(\varphi_i) & V_{22}(\varphi_i) \\ \vdots & \vdots \\ V_{21}(\varphi_i) & V_{22}(\varphi_i) \end{bmatrix}$ $TF = \begin{bmatrix} F_{YM}(\varphi_1) - \overline{F_Y(\varphi)} \\ \vdots \\ F_{YM}(\varphi_i) - \overline{F_Y(\varphi)} \\ \vdots \\ F_{YM}(\varphi_N) - \overline{F_Y(\varphi)} \end{bmatrix}$ $\begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = \begin{bmatrix} \rho \cos \lambda \\ \rho \sin \lambda \end{bmatrix}$	(7.13)
$\begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = [T^T T]^{-1} [T^T TF]$	(7.14)
$\rho = \frac{g_1}{\cos \lambda} = \frac{g_2}{\sin \lambda}$	(7.15)
$\lambda = \tan^{-1} \frac{g_2}{g_1}$	(7.16)

Appendix: L. Regression surface plots of simulated and measured radial cutting forces

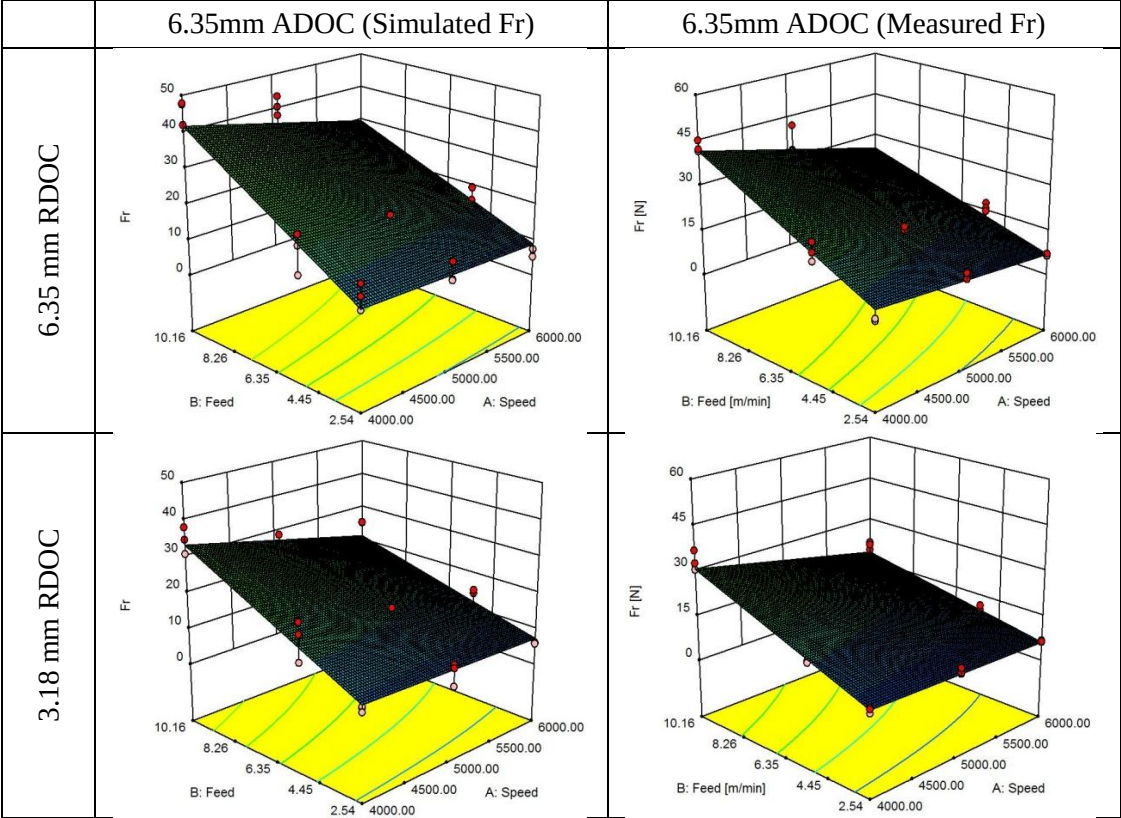
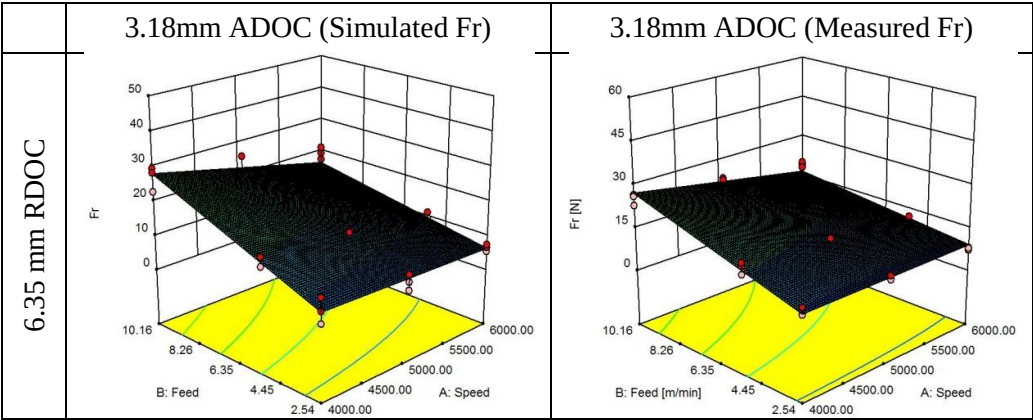
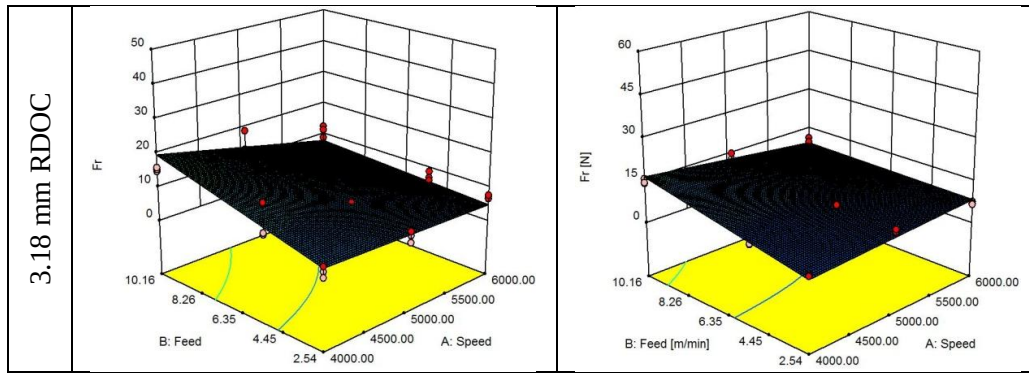


Figure L-387: Surface plots of simulated and measured radial cutting force in Cfoam, 6.35mm ADOC.





FigureA-388: Surface plots of simulated and measured radial cutting force in Cfoam, 3.18 mm ADOC.

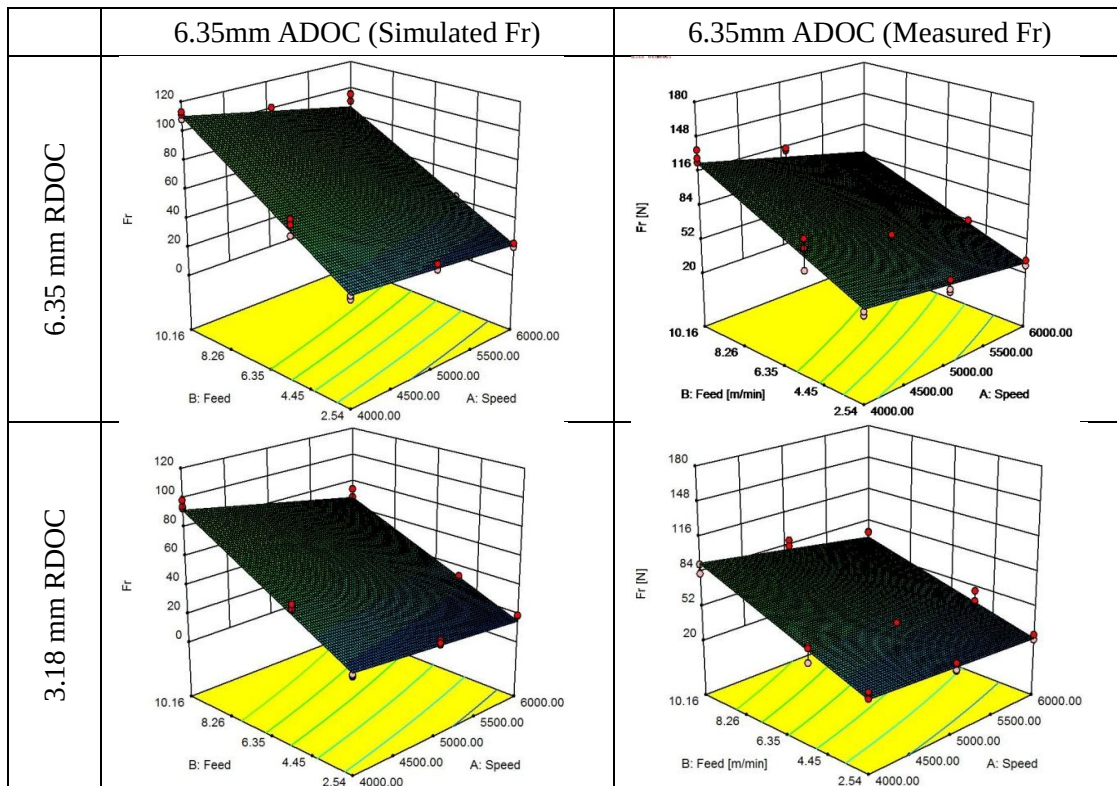


Figure L-389: Surface plots of simulated and measured radial cutting force in CB1100, 6.35mm ADOC.

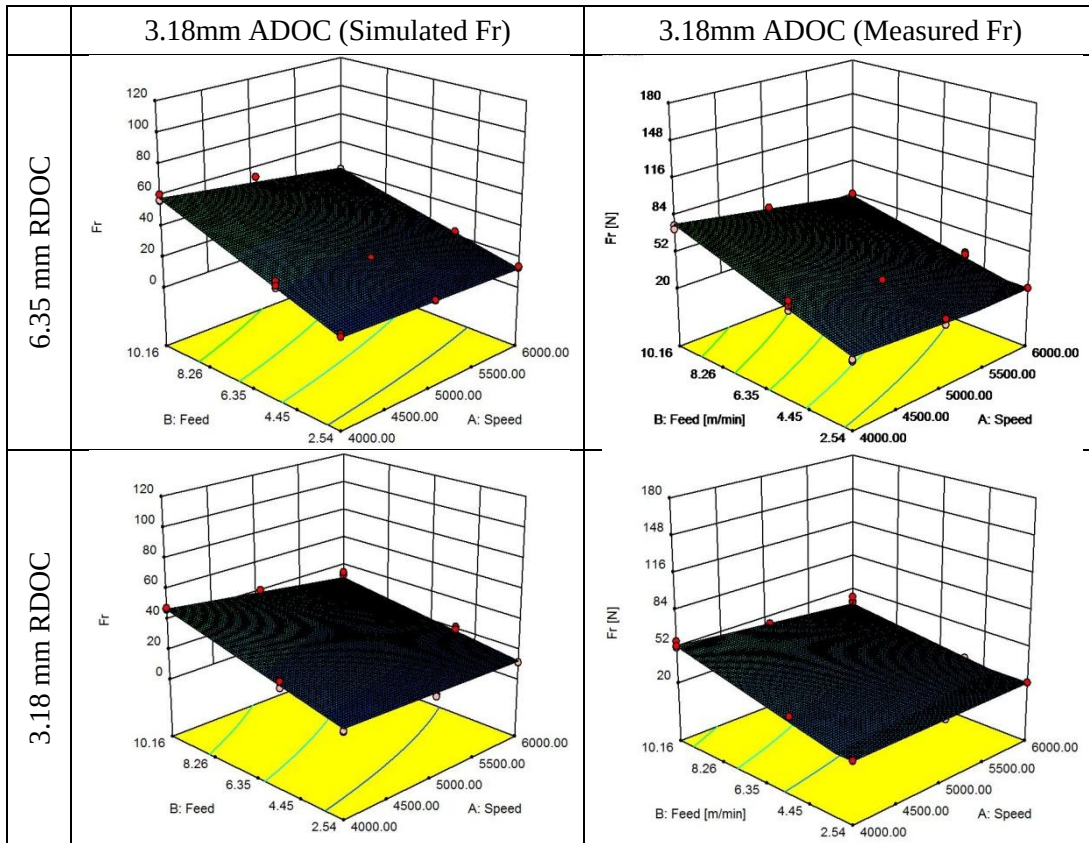
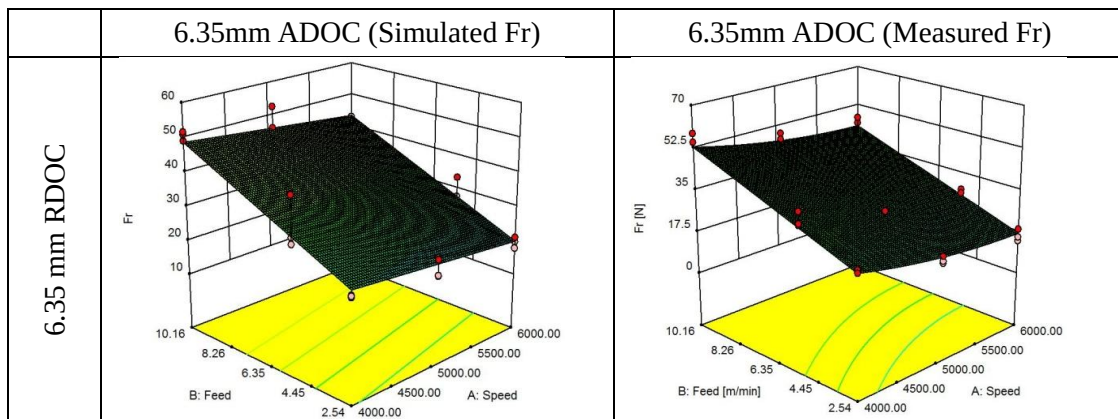


Figure L-390: Surface plots of simulated and measured radial cutting force in CB1100, 3.18mm ADOC.

AAC



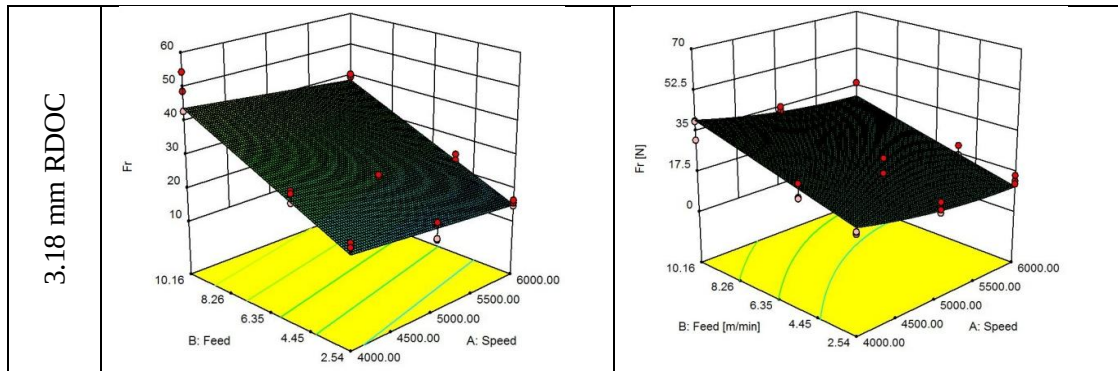


Figure L-391: Surface plots of simulated and measured radial cutting force in AAC, 6.35mm ADOC.

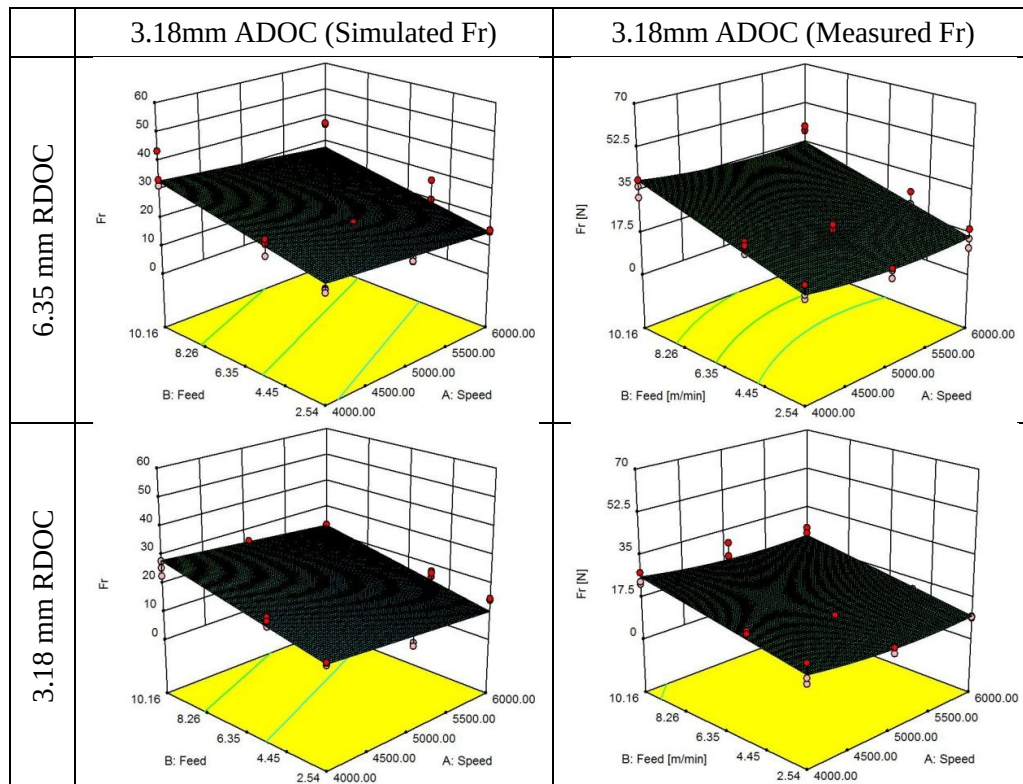


Figure L-392: Surface plots of simulated and measured radial cutting force in AAC, 3.18mm ADOC.

Appendix: M. Cfoam four-point bend specimen roughness tables

Table M-4: Cfoam four point bend specimen roughness.

Sample:	6k100-1						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	35.7176	43.1564	161.1475	197.5742	210.8368	0.1854	2.4135
	27.7358	35.5369	134.1961	170.9064	201.0882	-0.2291	3.056
	29.6106	38.1599	156.8617	187.2636	211.1902	0.1884	3.11
averages:	31.02133	38.95107	150.7351	185.2481	207.7051	0.048233	2.859833
Sample:	6k100-3						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	24.9736	31.5473	123.3733	156.3289	164.1776	0.1613	2.7645
	29.2087	35.6928	123.1182	189.7934	189.7934	-0.5519	3.0832
	27.0662	35.1611	122.2692	168.5969	206.8833	-0.3273	3.5843
averages:	27.08283	34.13373	122.9202	171.5731	186.9514	-0.2393	3.144
Sample:	6k100-6						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	30.2288	37.3294	136.1886	187.9371	187.9371	-0.0006	2.642
	30.5435	39.9798	144.2661	169.8588	215.8889	-0.0707	3.0135
	30.0002	40.5806	144.2366	197.1166	207.5643	-0.1755	3.2059
averages:	30.2575	39.2966	141.5638	184.9708	203.7968	-0.08227	2.9538
Sample:	6k100-9						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	32.3122	41.6938	165.6721	211.175	213.8518	0.0054	3.1642
	28.94	37.1286	134.2365	169.4546	187.2672	0.2592	2.8726
averages:	30.6261	39.4112	149.9543	190.3148	200.5595	0.1323	3.0184
Sample:	6k100-12						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	27.599	35.8775	118.9324	185.8291	217.1163	-0.5842	3.8666
	35.5405	43.6098	146.5071	199.6365	227.3044	-0.1021	2.5367
	23.816	30.8617	116.8025	172.5529	186.7003	0.4391	3.5374
averages:	28.98517	36.783	127.414	186.0062	210.3737	-0.0824	3.313567

Sample:	6k100-15						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	25.8785	32.3897	129.262	147.7287	180.0607	0.0493	3.0214
	26.3729	32.3422	118.4475	150.38	162.5003	-0.1072	2.5792
	31.4183	38.9011	140.2665	189.3844	221.9795	-0.2718	2.8672
averages:	27.8899	34.54433	129.3253	162.4977	188.1802	-0.1099	2.8226
Sample:	4k400-1						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	33.8369	43.1794	151.4125	233.8347	233.8347	-0.0268	2.9353
	33.0024	40.5663	145.8737	187.2597	210.3229	-0.4449	2.7033
	36.7448	43.6564	161.1197	186.373	200.6626	-0.3354	2.2456
averages:	34.52803	42.46737	152.802	202.4891	214.9401	-0.26903	2.628067
Sample:	4k400-2						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	30.3871	37.9809	129.4899	165.7725	186.4779	-0.3043	2.8244
	34.9012	41.8227	142.5376	182.2617	182.2617	0.0062	2.182
	34.947	43.5938	168.3551	216.6114	216.6114	0.2403	2.693
averages:	33.41177	41.13247	146.7942	188.2152	195.117	-0.01927	2.566467
Sample:	4k400-5						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	37.3314	46.5054	171.708	219.3665	228.1295	-0.0835	2.7098
	33.1367	40.483	148.6217	181.5122	209.9917	0.1609	2.8151
	31.9904	39.3262	130.3963	146.0718	181.5906	-0.2551	2.5113
averages:	34.15283	42.10487	150.242	182.3168	206.5706	-0.05923	2.678733
Sample:	4k400-8						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	28.5634	34.4911	130.6979	170.0449	177.3134	-0.0491	2.4669
	34.7419	42.5724	155.991	203.9533	211.3446	0.1521	2.5356

averages:	31.65265	38.53175	143.3445	186.9991	194.329	0.0515	2.50125
Sample:	4k400-11						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	29.6487	38.5292	140.7353	219.5165	219.5165	-0.3101	3.4589
	31.3816	39.4044	140.6214	185.0413	193.3997	0.0057	2.7089
	35.4427	42.6238	153.3949	191.4247	202.0276	0.4778	2.4261
averages:	32.15767	40.1858	144.9172	198.6608	204.9813	0.0578	2.864633
Sample:	4k400-14						
	Ra μm	Rq μm	Rz μm	Rmax μm	Rt μm	R Sk	R Ku
	28.5848	34.0345	122.2385	154.1592	154.1592	0.2129	2.2475
	31.3252	39.5168	147.4519	169.1588	200.3647	-0.3007	2.8585
	21.3338	26.9951	104.9365	141.0413	141.0413	0.5235	3.0274
averages:	27.08127	33.51547	124.8756	154.7864	165.1884	0.145233	2.711133

Appendix: N. Material SEM and optical images

1.) AAC

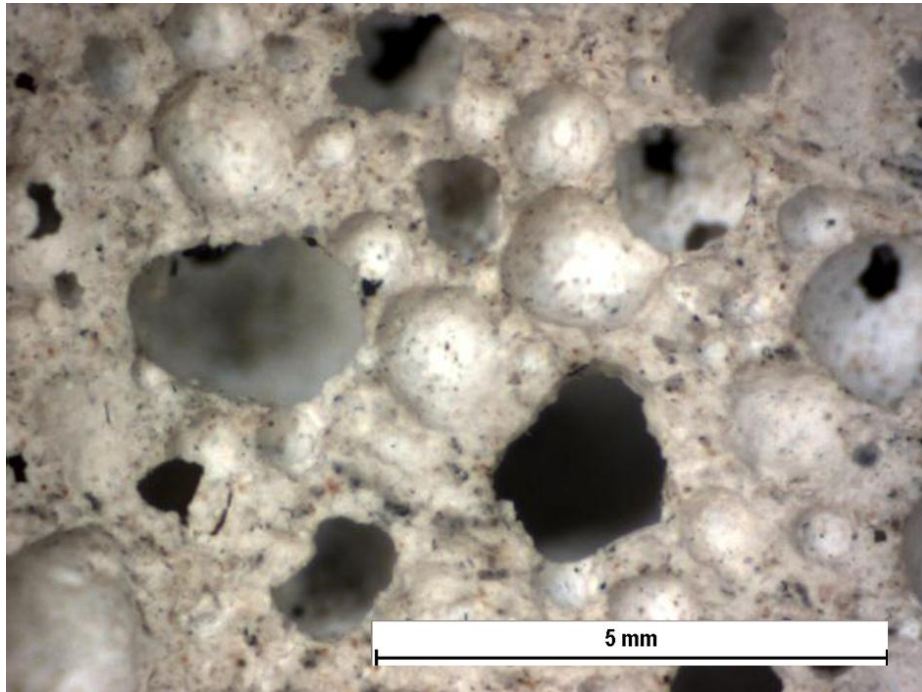


Figure N-393: Photo image of AAC surface

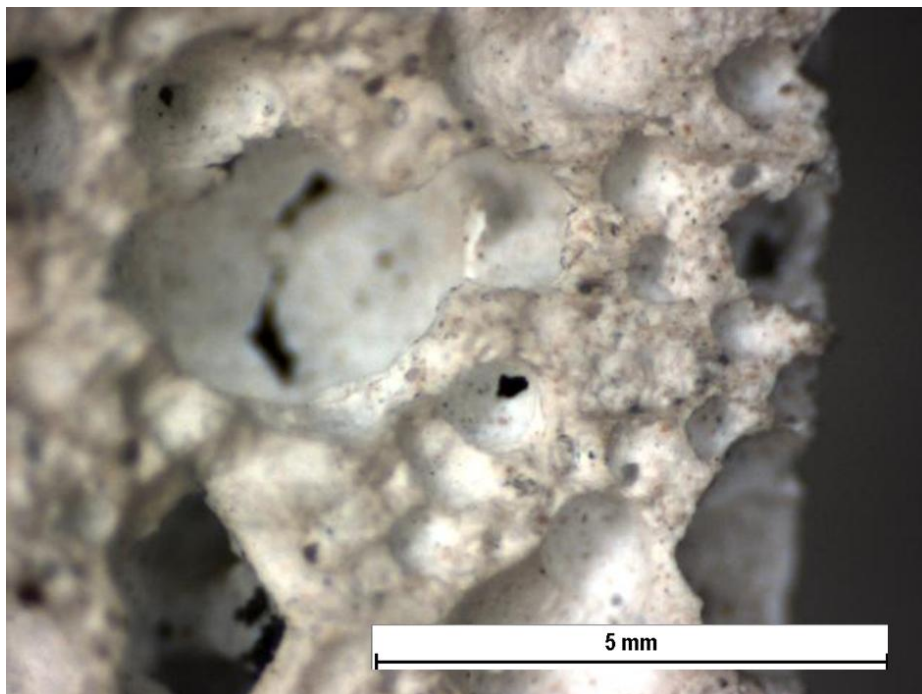


Figure N-394: Photo image of AAC surface

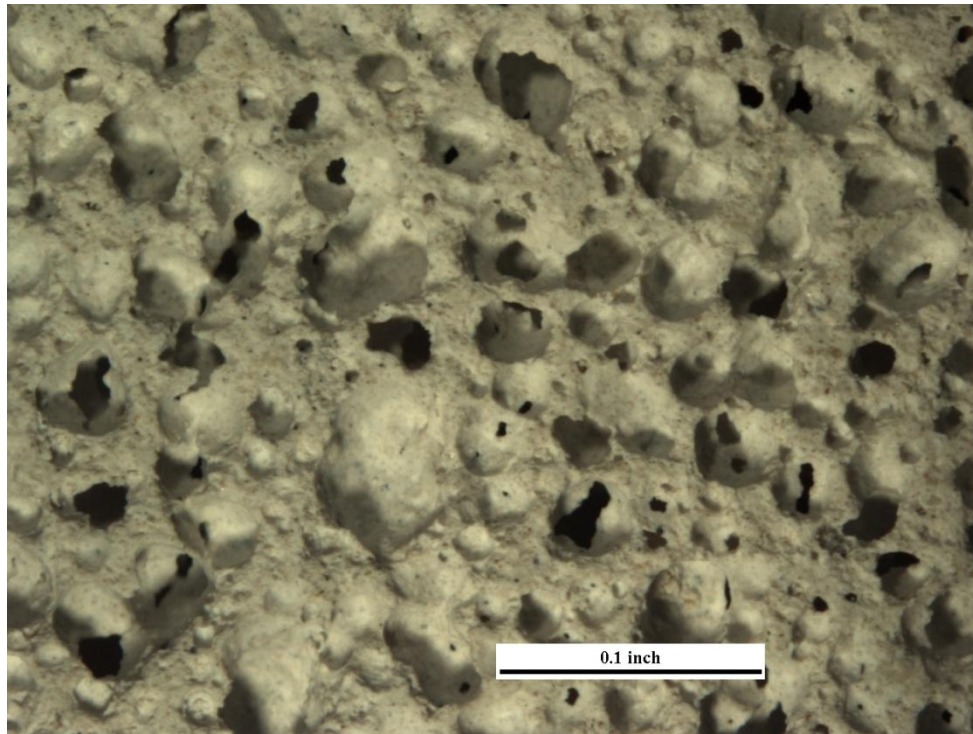


Figure N-395: Photo image of AAC surface

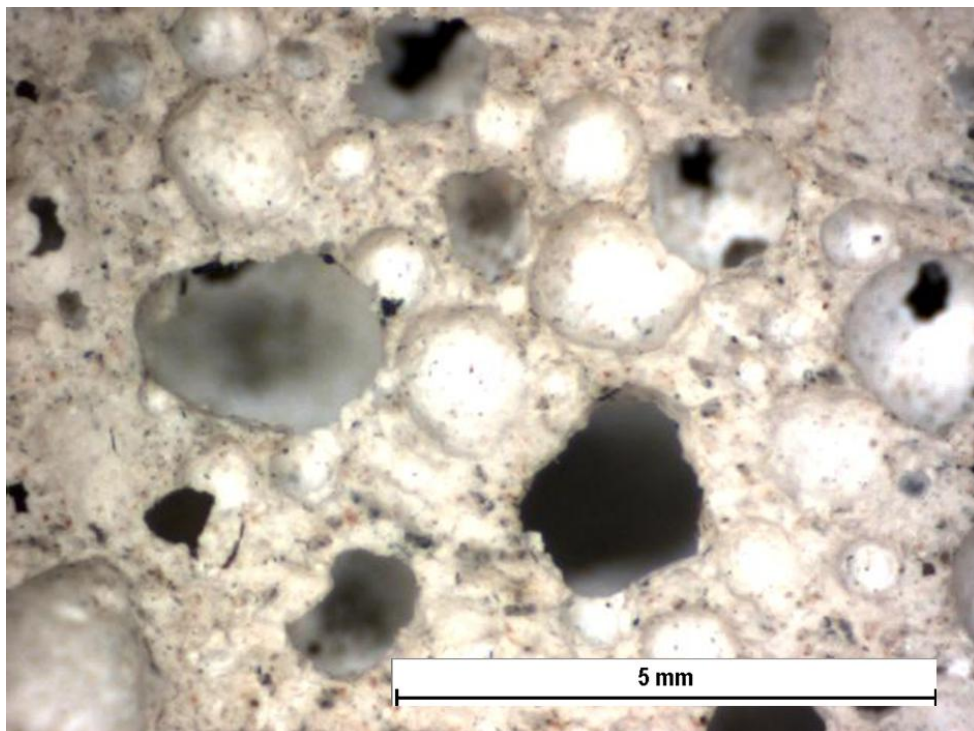


Figure N-396: Photo image of AAC surface

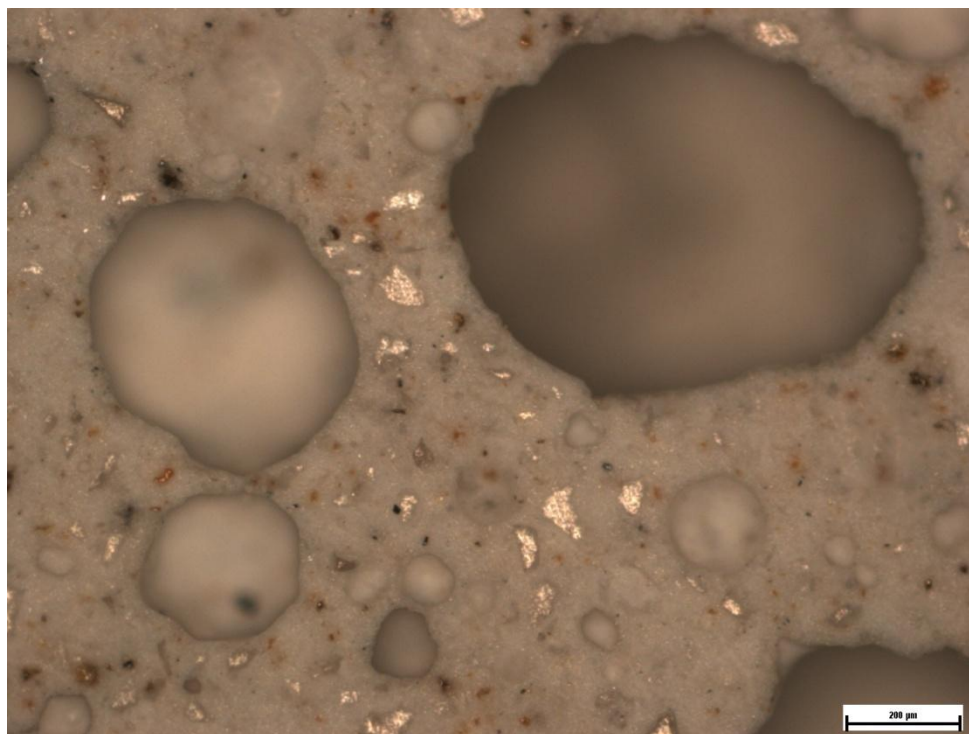


Figure N-397: Photo image of polished AAC surfaced

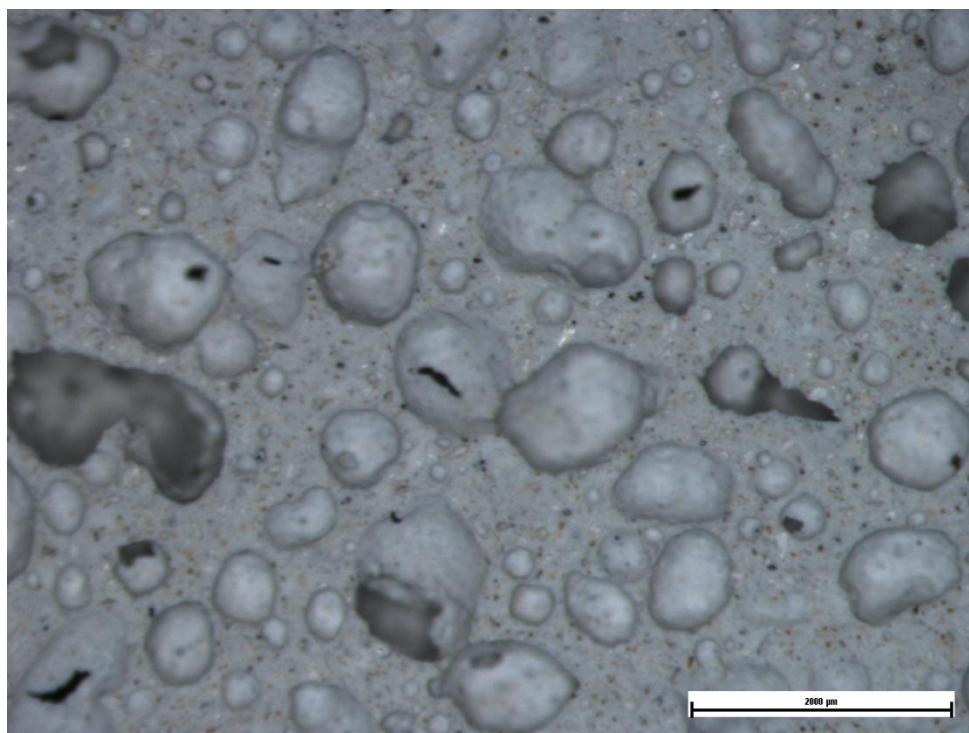


Figure N-398: Photo image of polished AAC surfaced

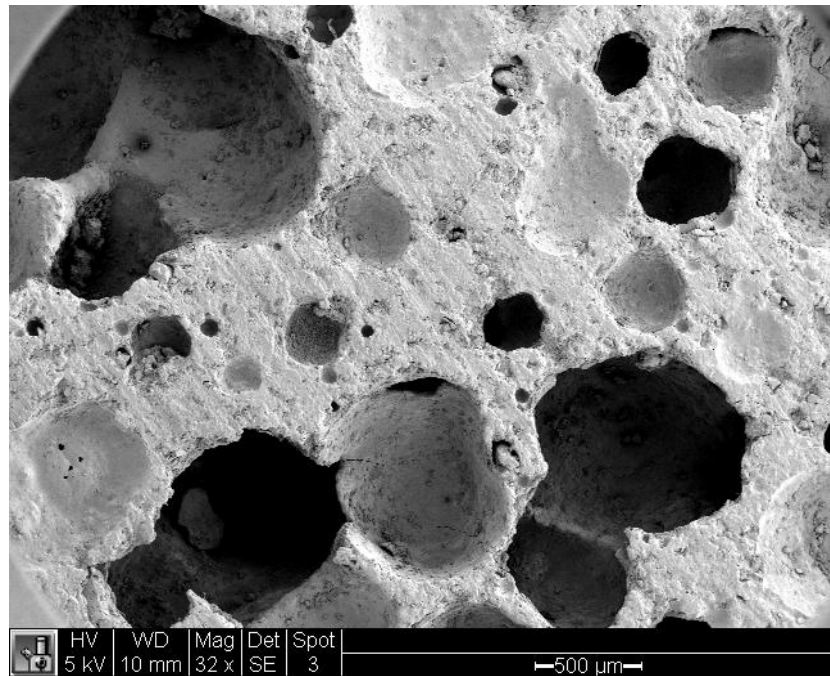


Figure N-399: SEM image of polished AAC surface

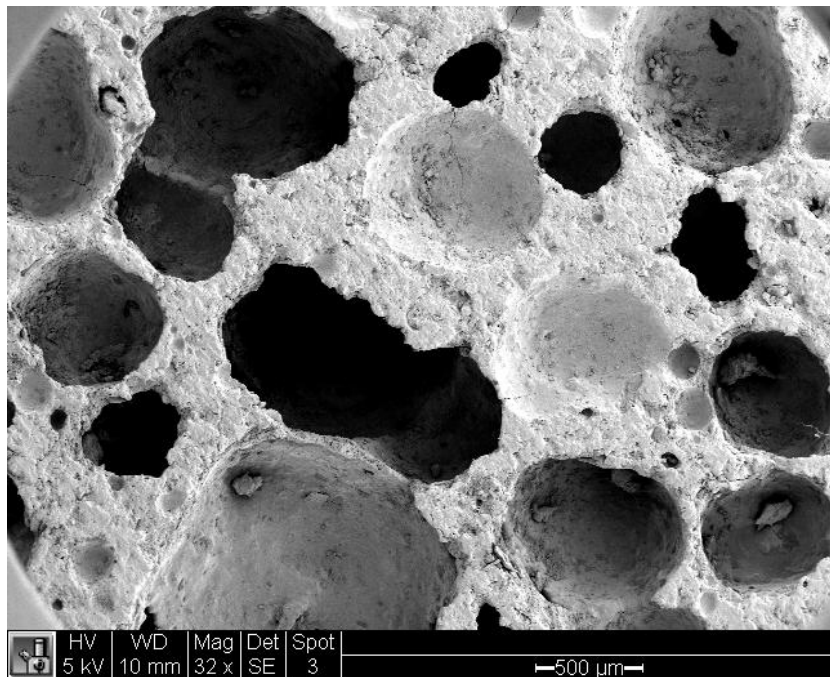


Figure N-400: SEM image of polished AAC surface

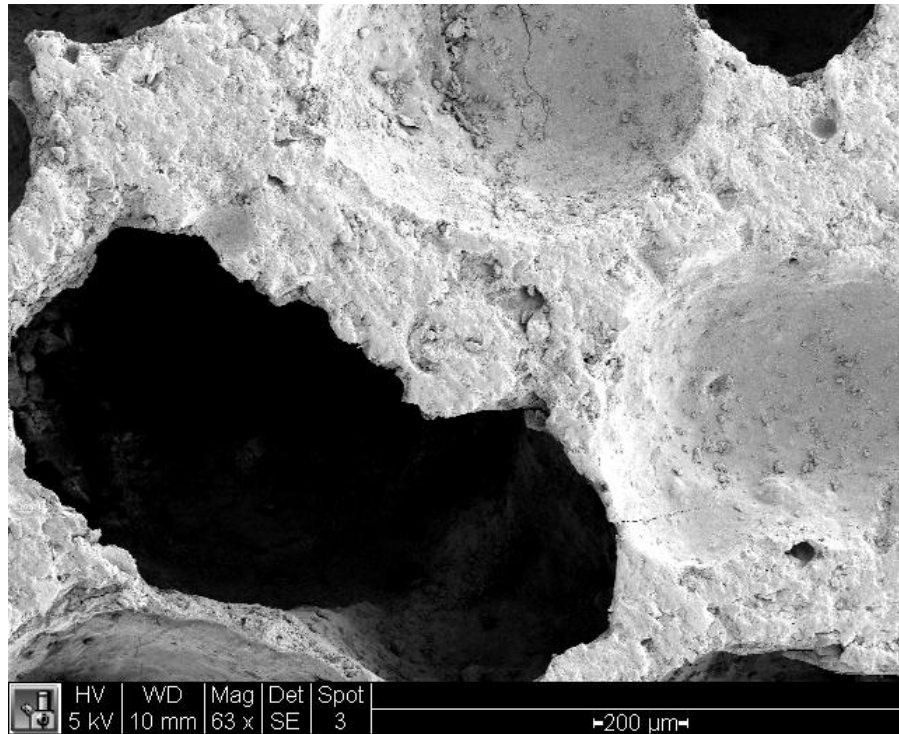


Figure N-401: SEM image of polished AAC surface

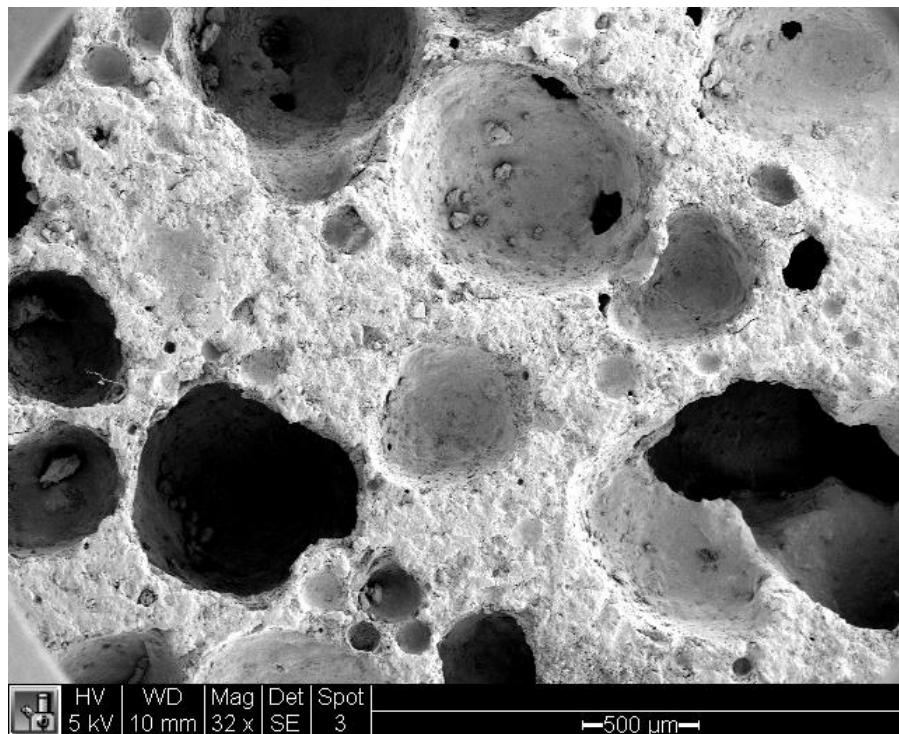


Figure N-402: SEM image of polished AAC surface

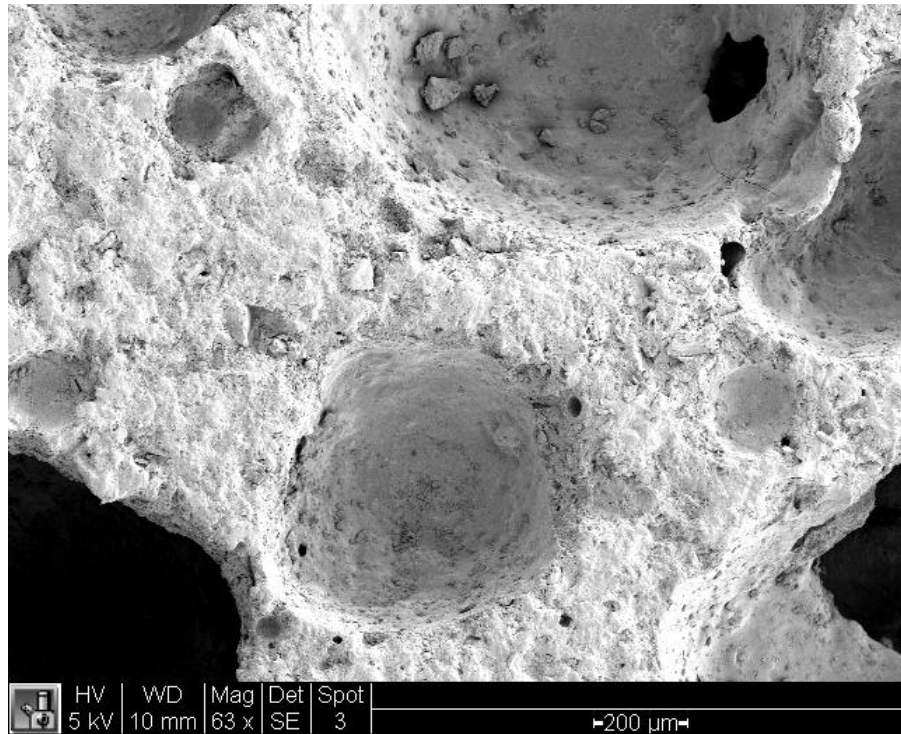


Figure N-403: SEM image of polished AAC surface

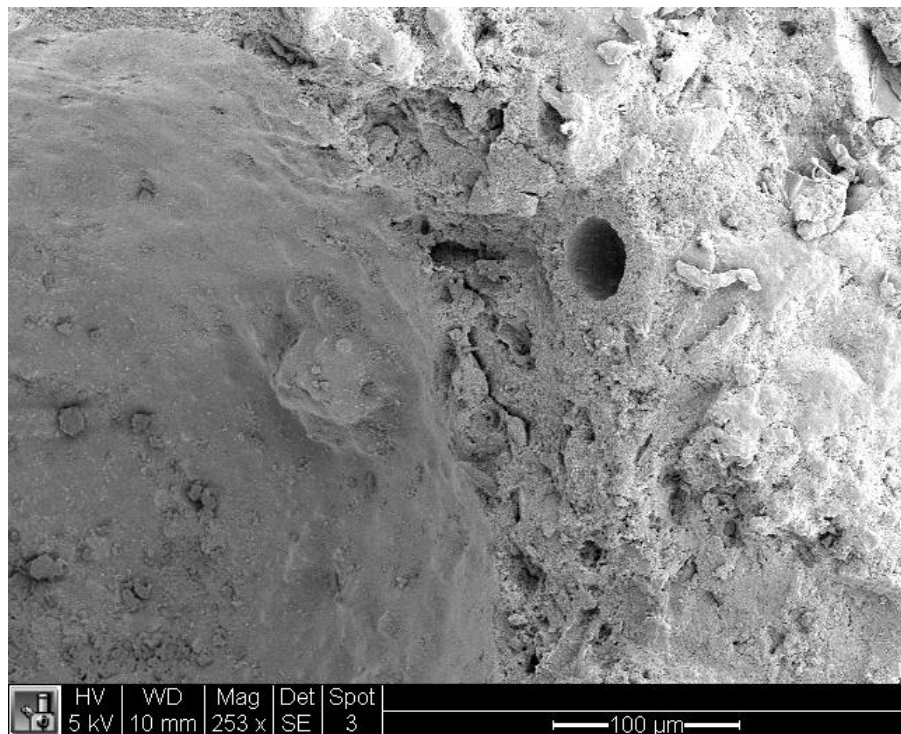


Figure N-404: SEM image of polished AAC surface

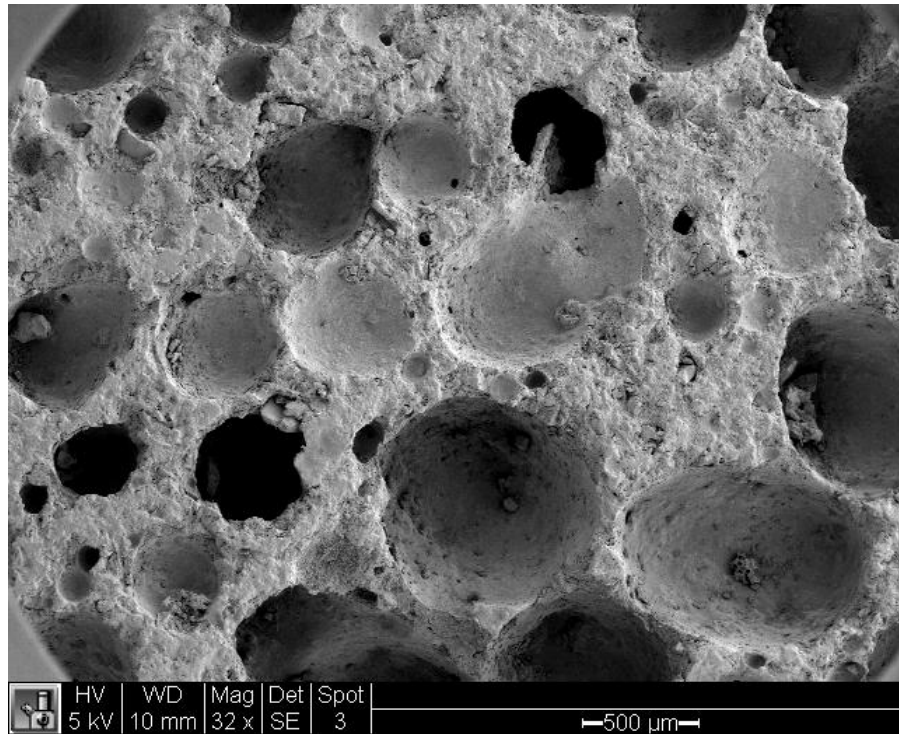


Figure N-405: SEM image of polished AAC surface

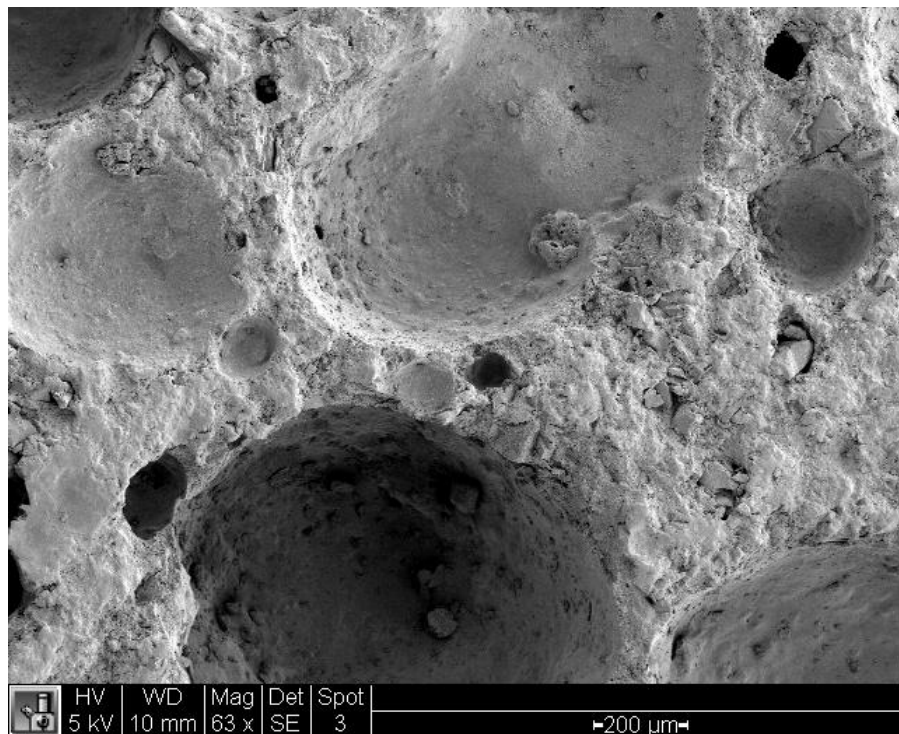


Figure N-406: SEM image of polished AAC surface

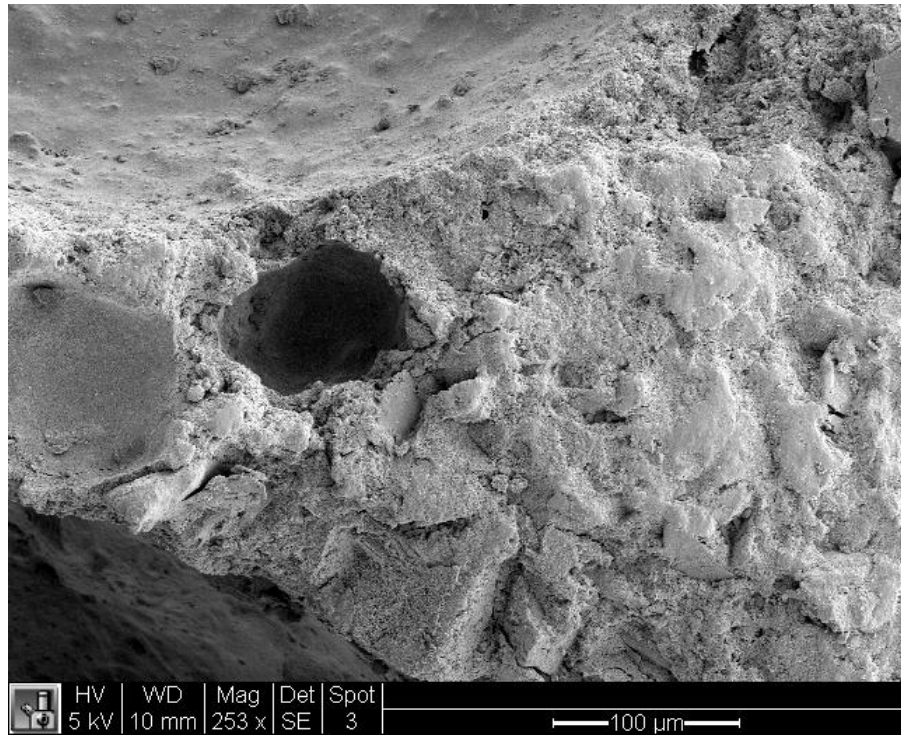


Figure N-407: SEM image of polished AAC surface

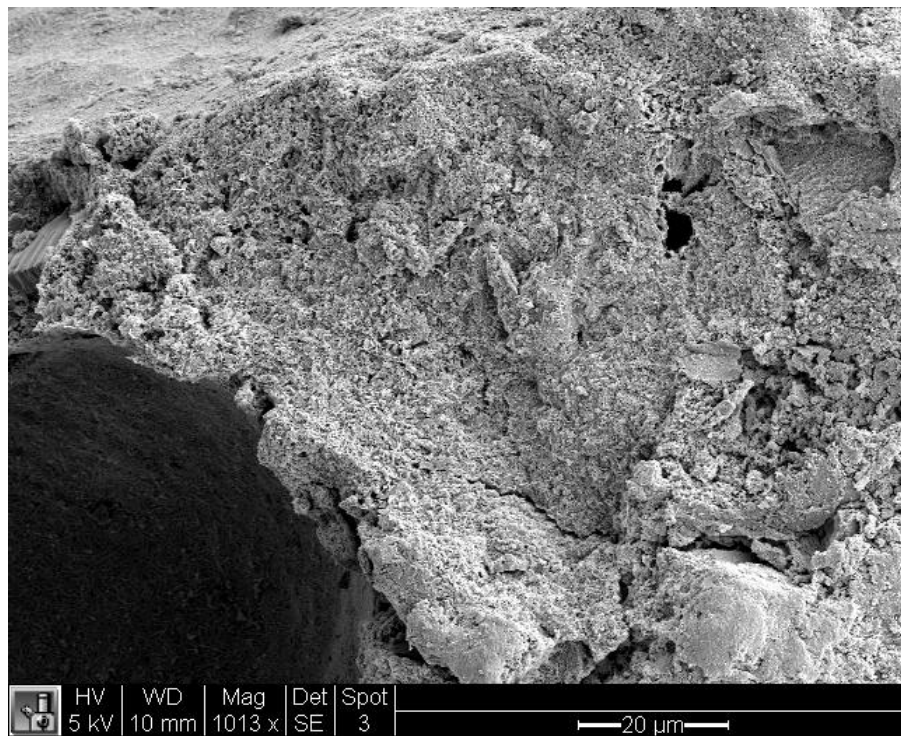


Figure N-408: SEM image of polished AAC surface

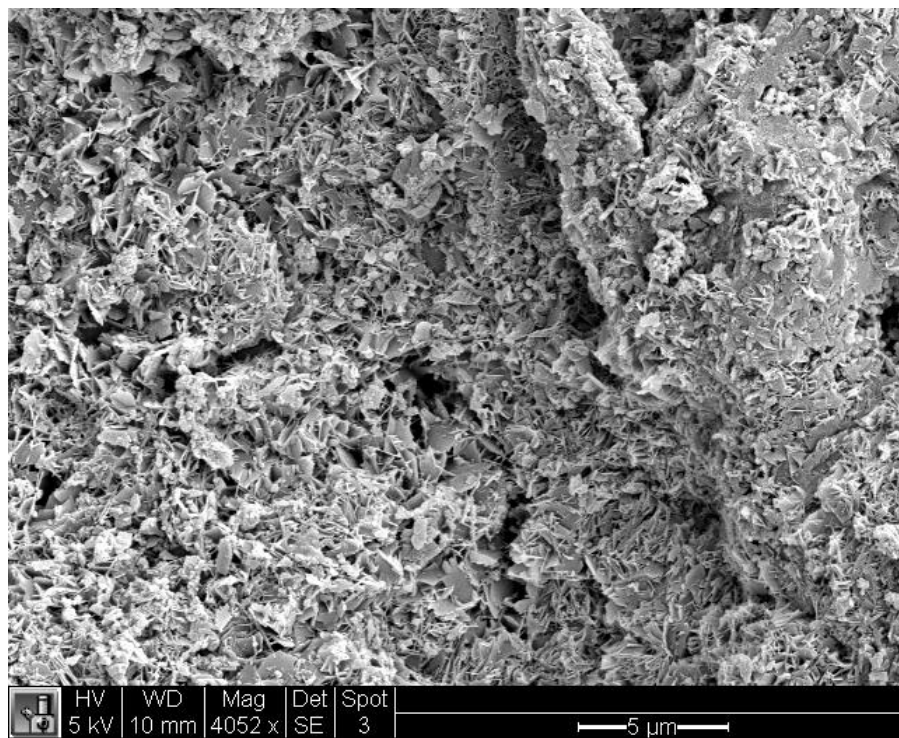


Figure N-409: SEM image of polished AAC surface

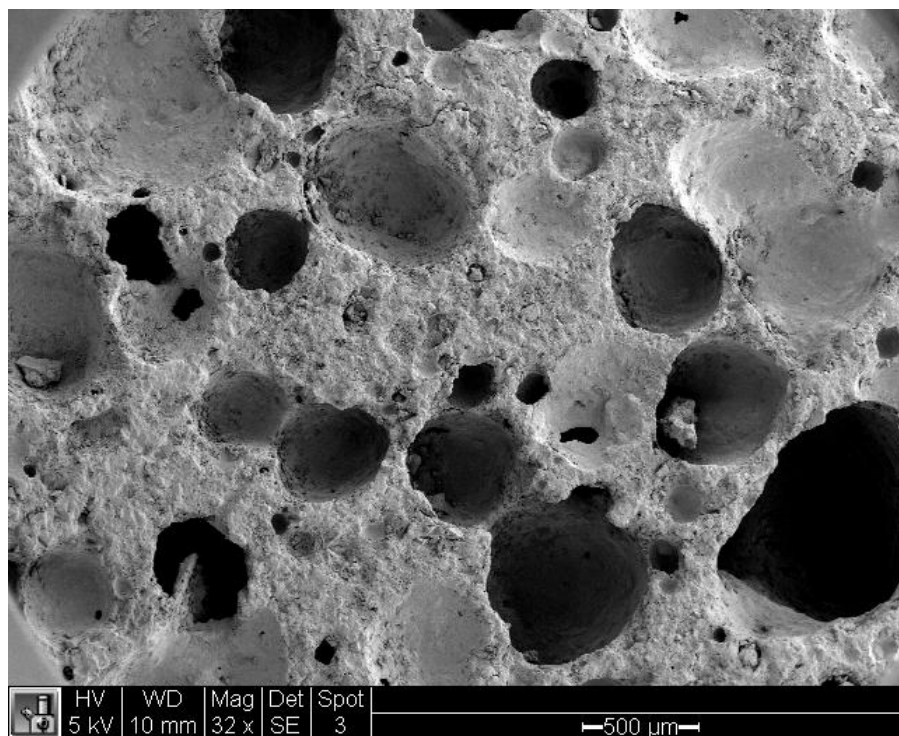


Figure N-410: SEM image of polished AAC surface

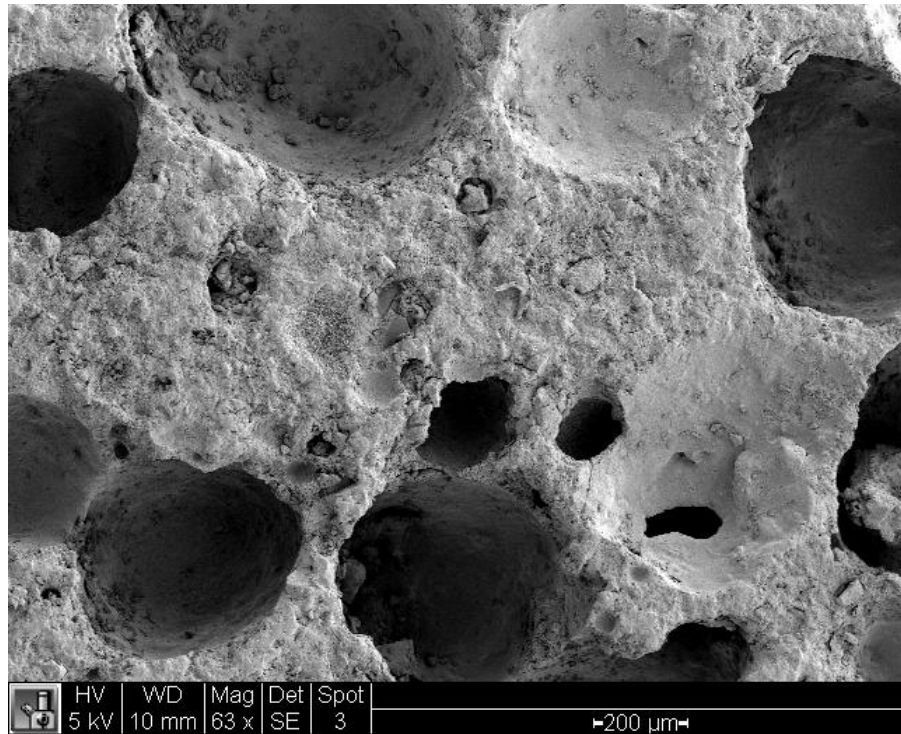


Figure N-411: SEM image of polished AAC surface

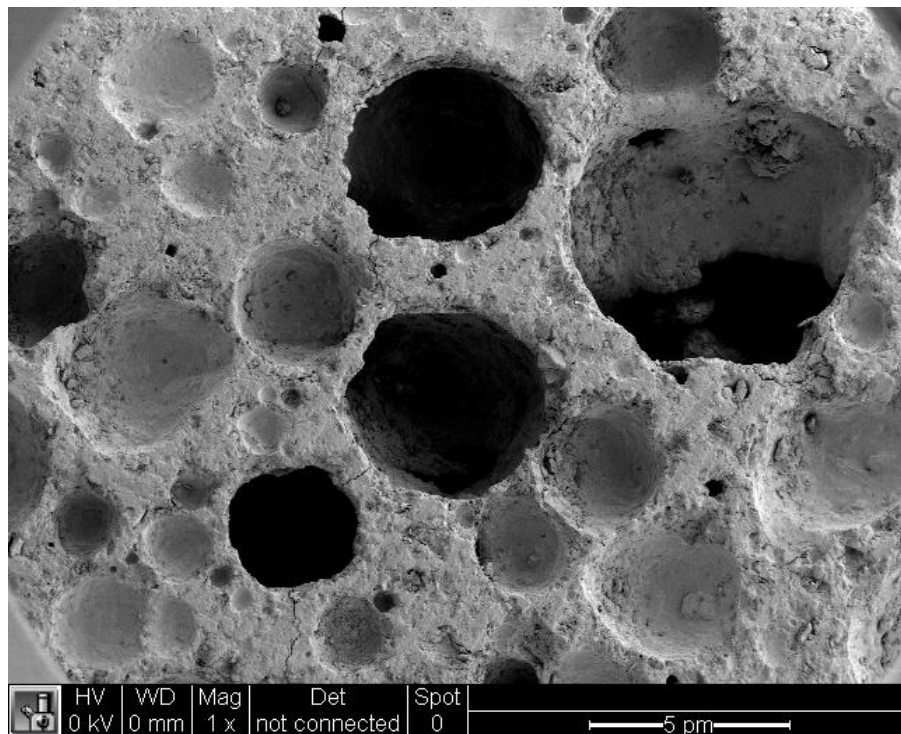


Figure N-412: SEM image of polished AAC surface

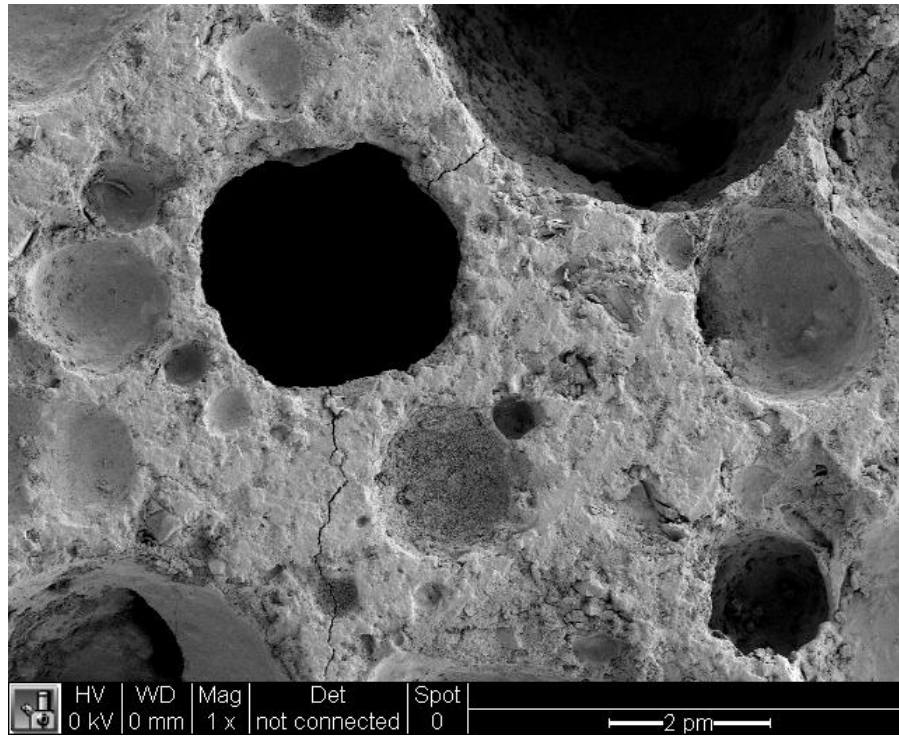


Figure N-413: SEM image of polished AAC surface

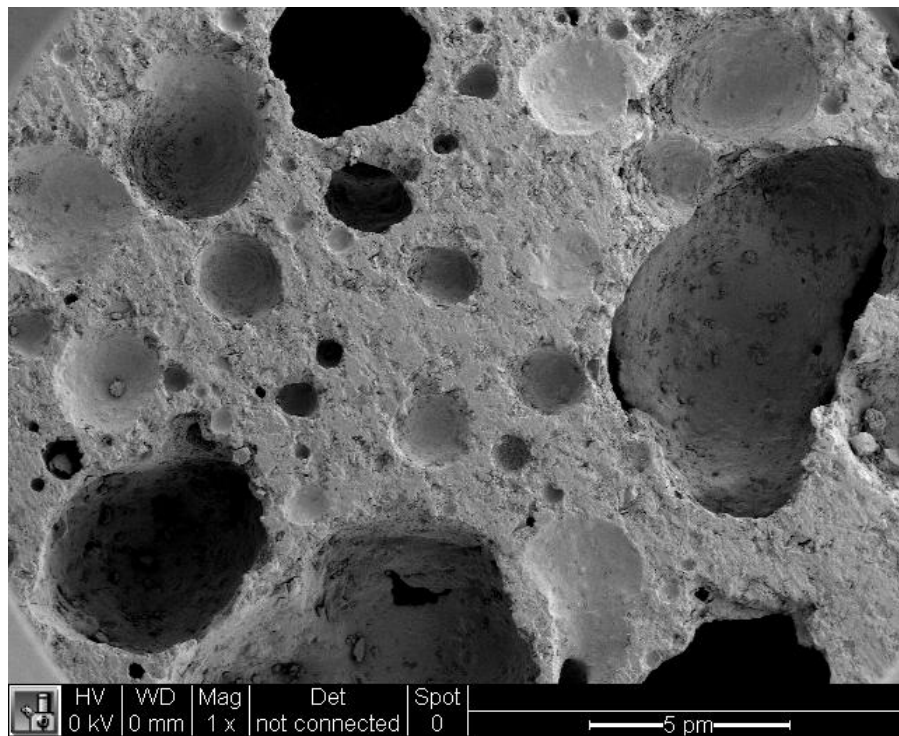


Figure N-414: SEM image of polished AAC surface

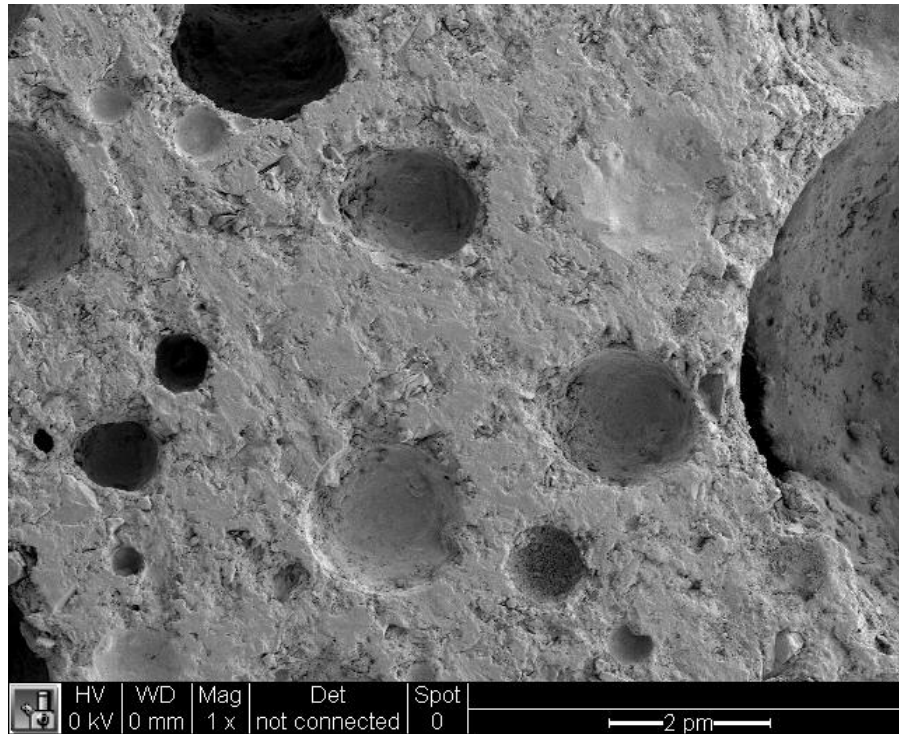


Figure N-415: SEM image of polished AAC surface

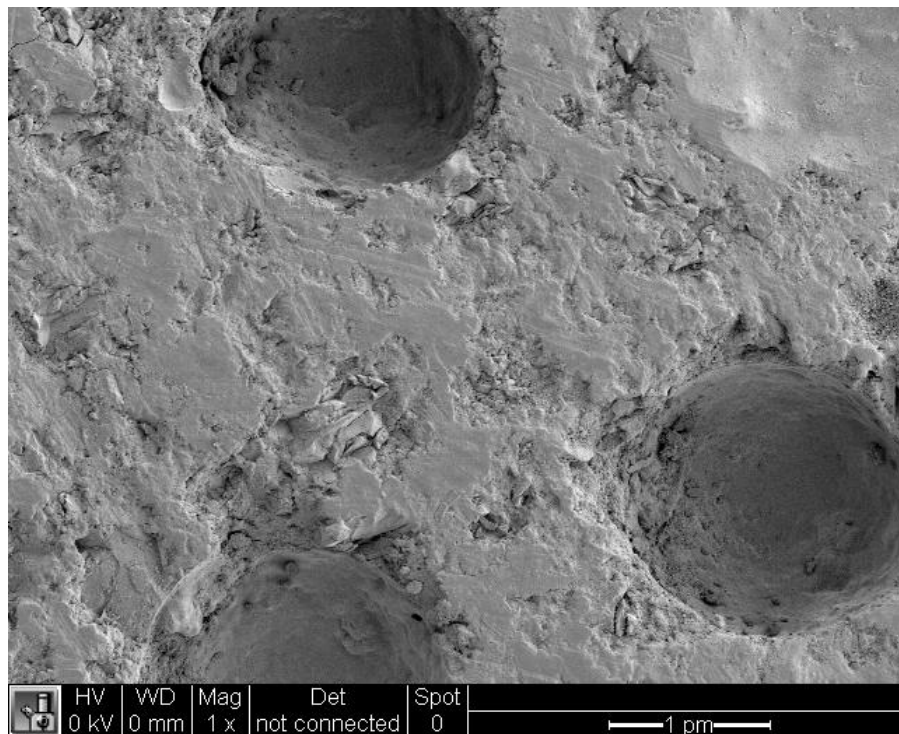


Figure N-416: SEM image of polished AAC surface

2.) CB1100

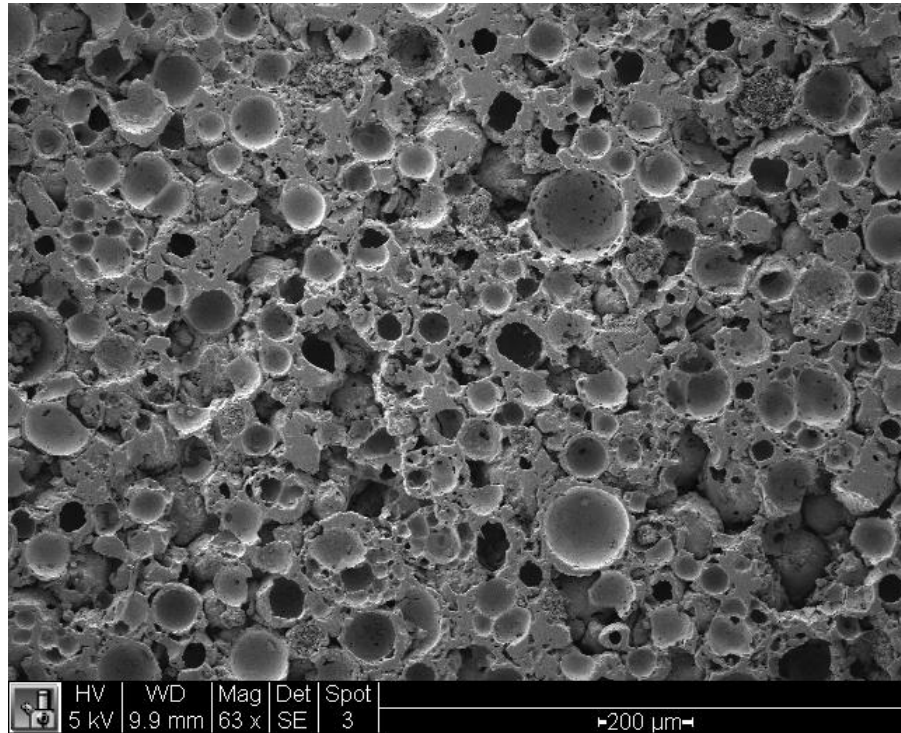


Figure N-417: SEM image of polished CB1100 surface.

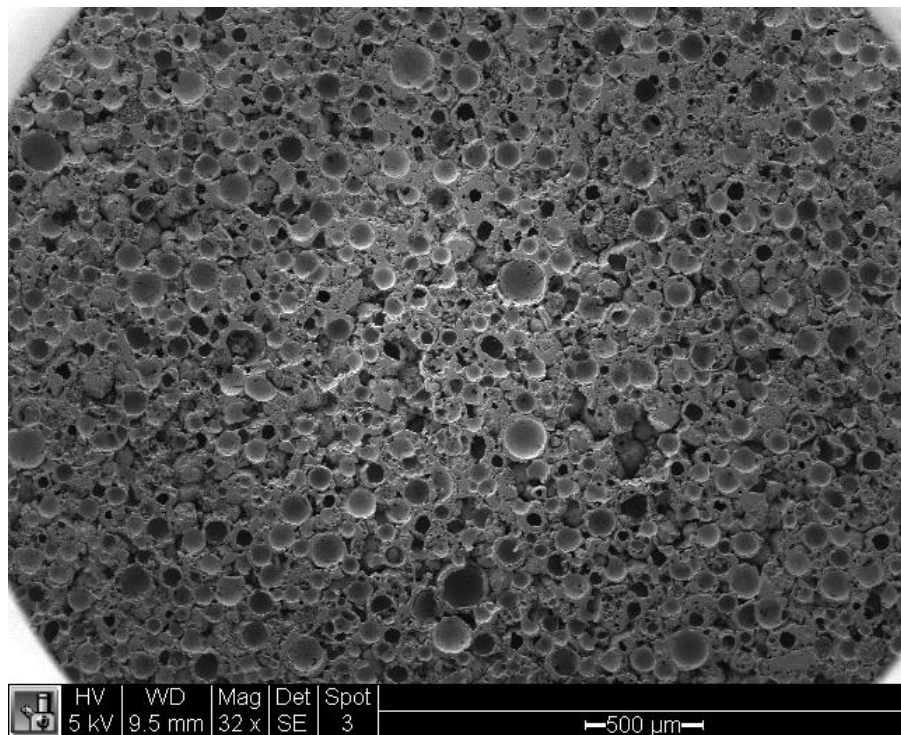


Figure N-418: SEM image of polished CB1100 surface.

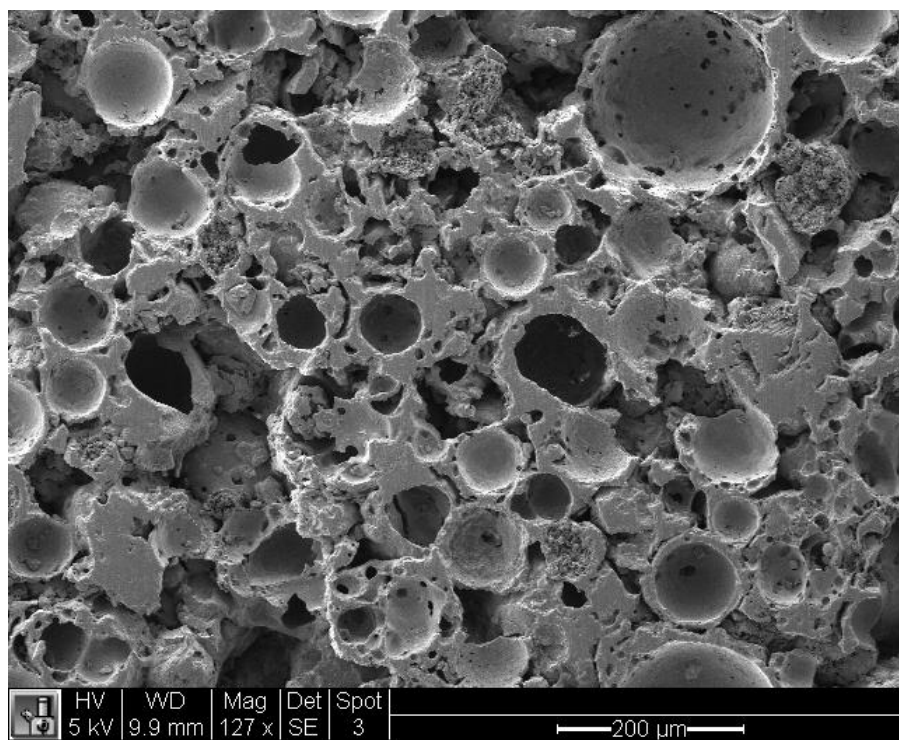


Figure N-419: SEM image of polished CB1100 surface.

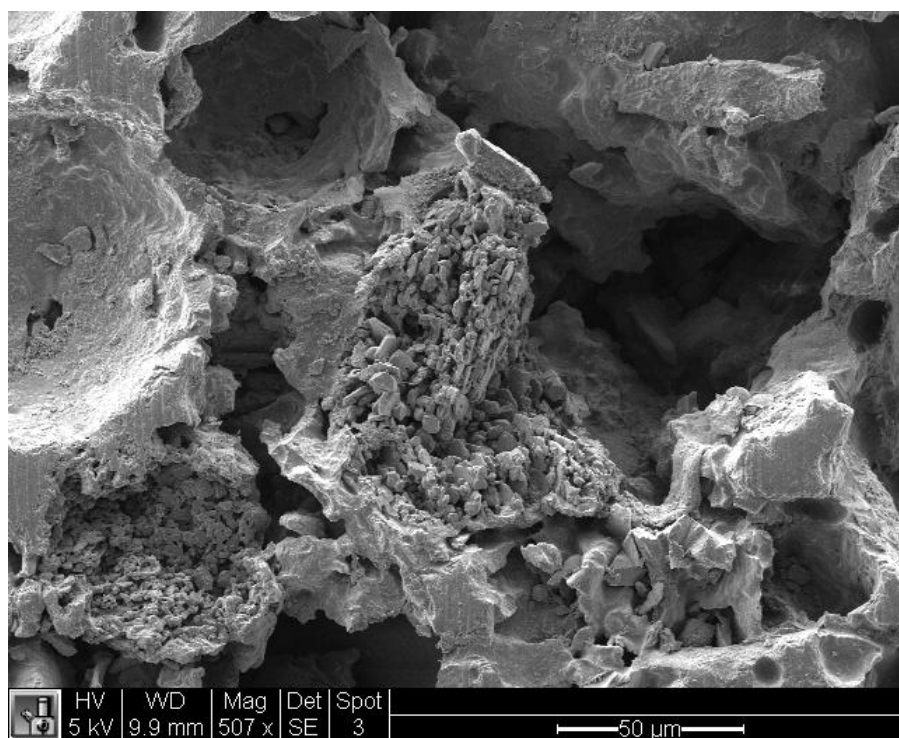


Figure N-420: SEM image of polished CB1100 surface.

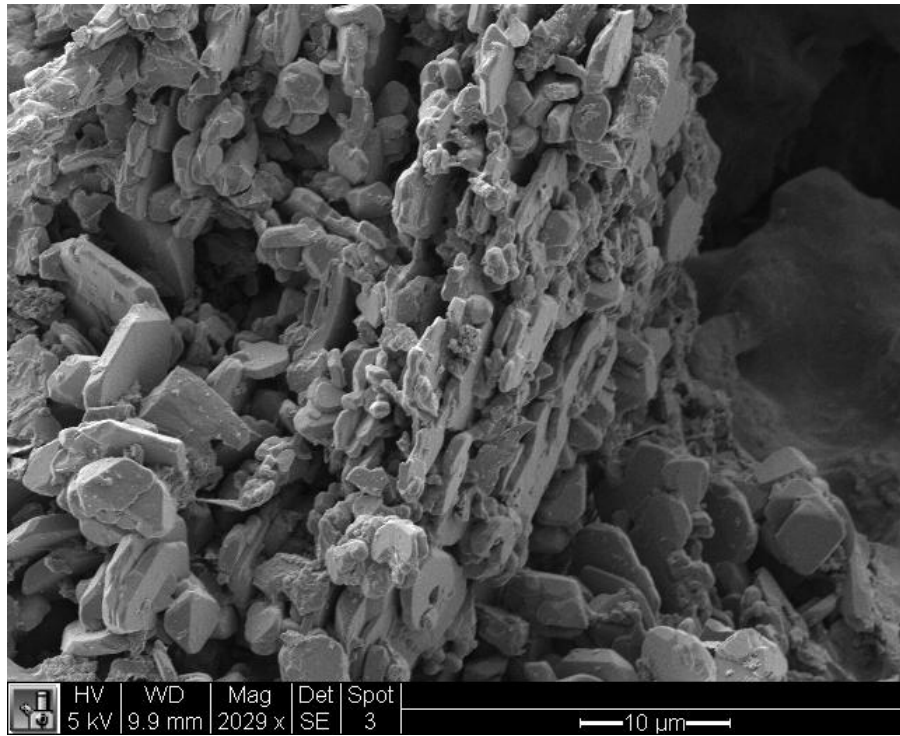


Figure N-421: SEM image of polished CB1100 surface.

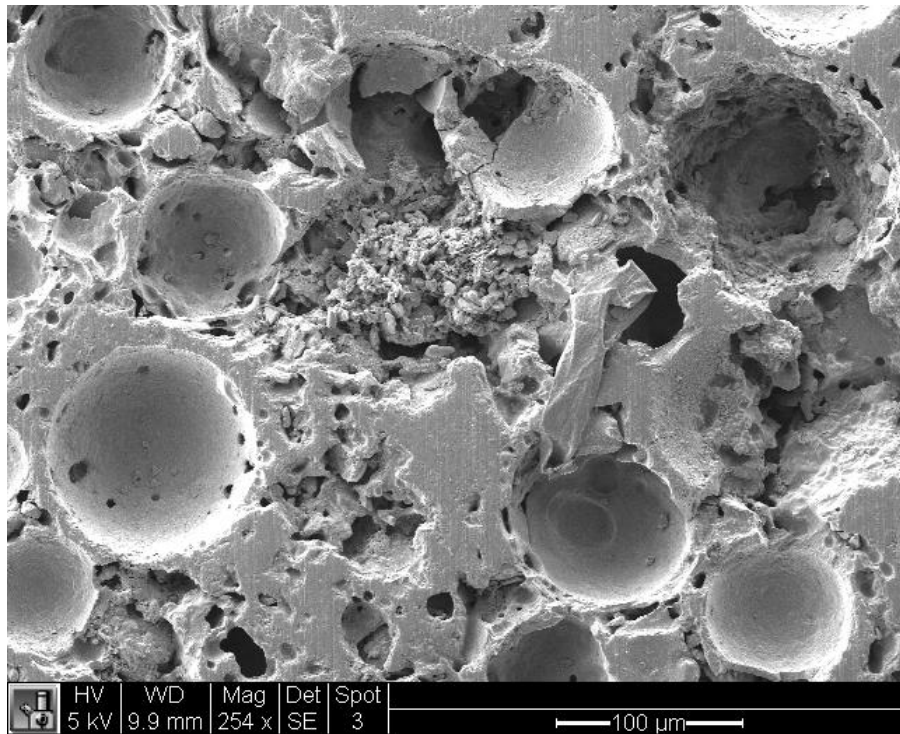


Figure N-422: SEM image of polished CB1100 surface.

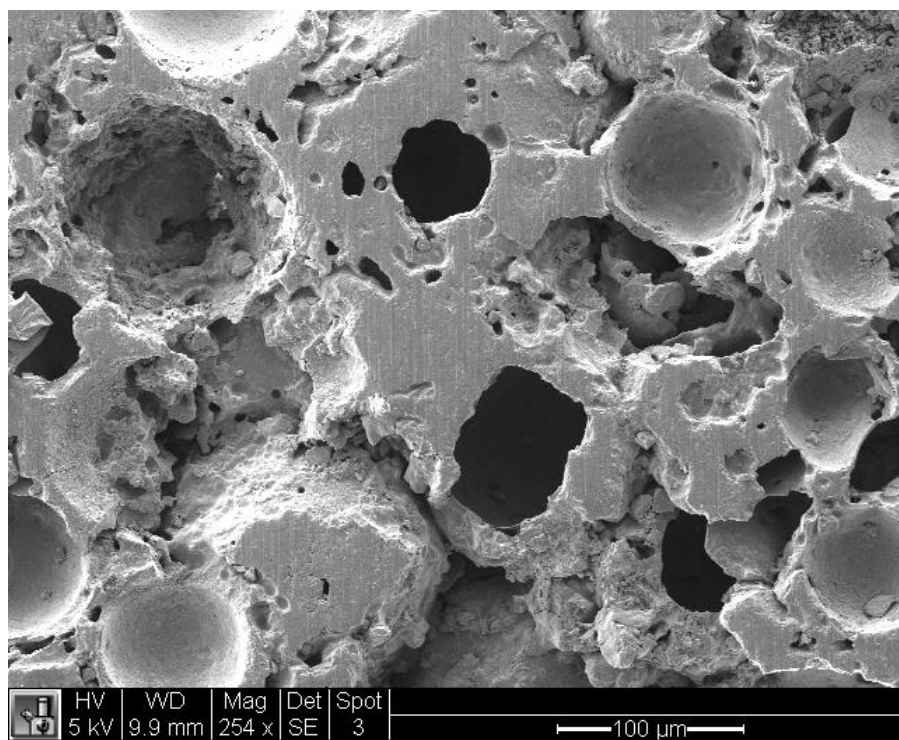


Figure N-423: SEM image of polished CB1100 surface.

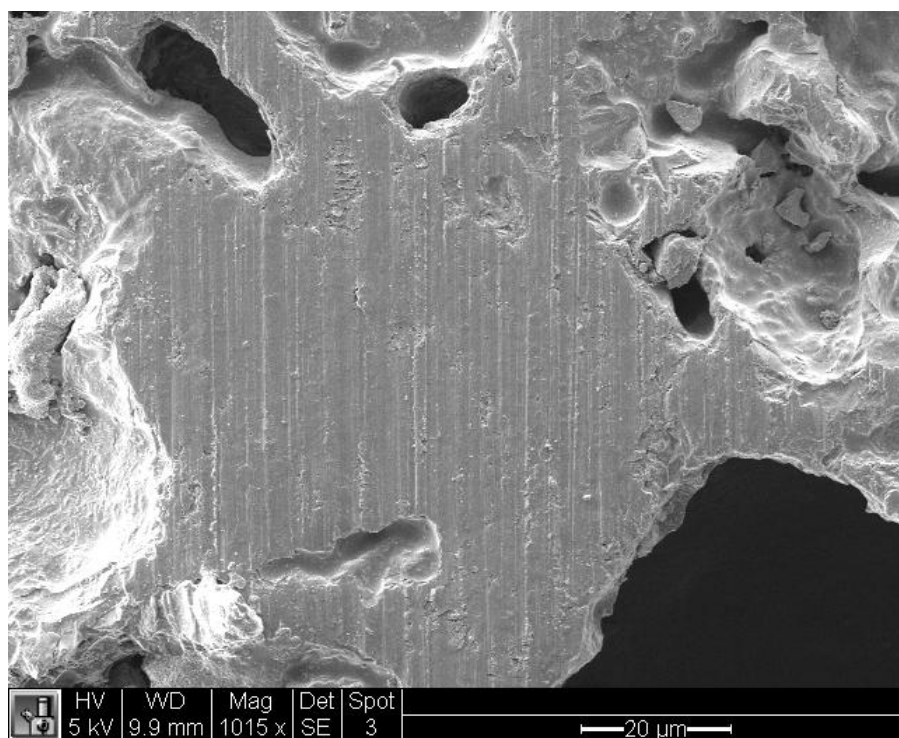


Figure N-424: SEM image of polished CB1100 surface.

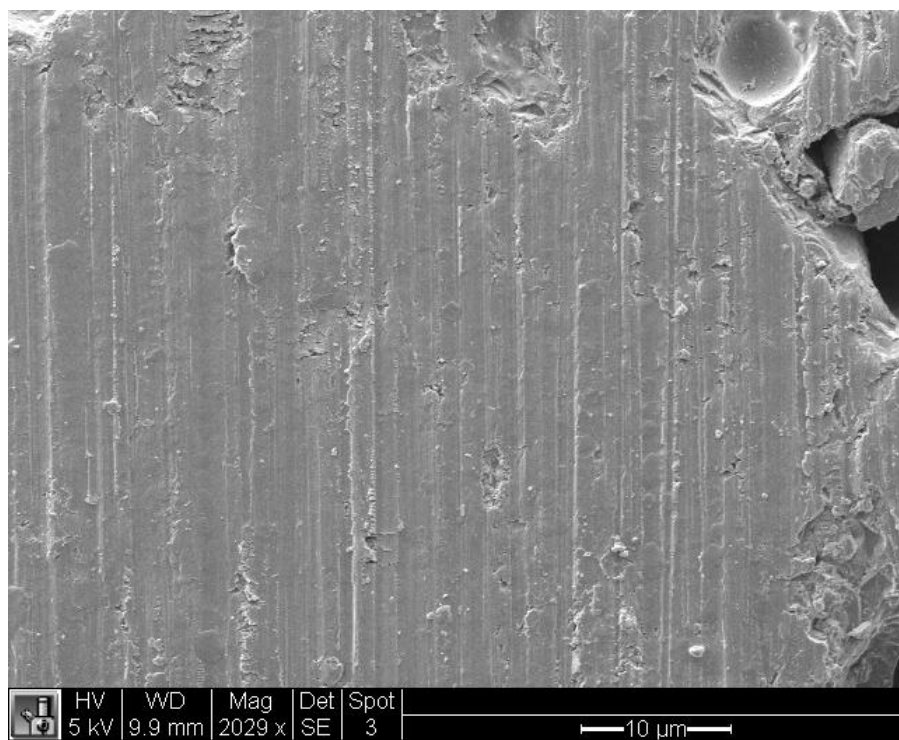


Figure N-425: SEM image of polished CB1100 surface.

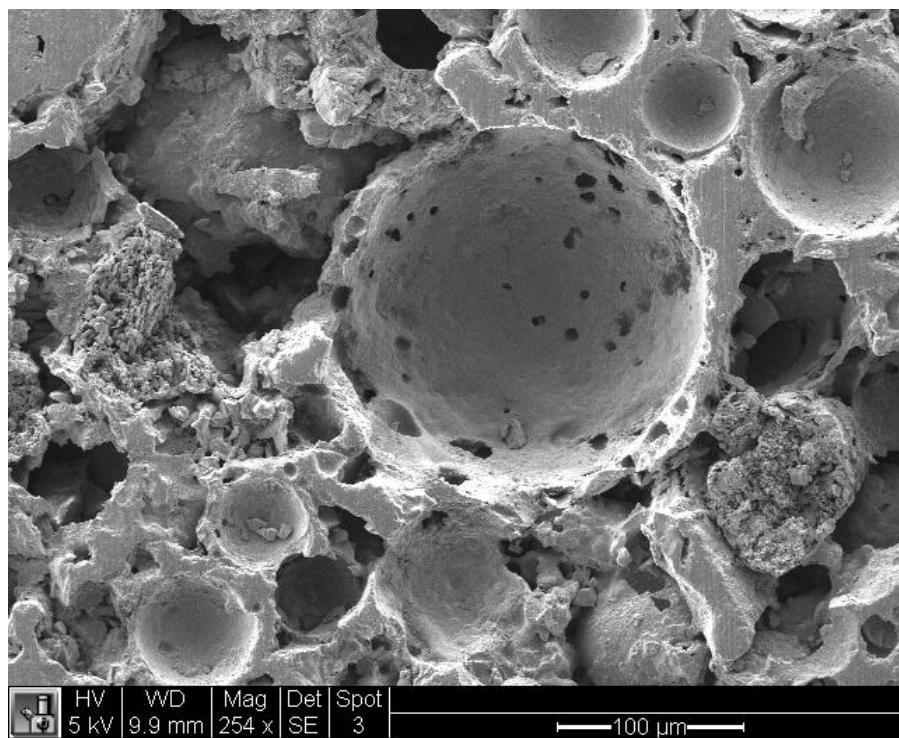


Figure N-426: SEM image of polished CB1100 surface.

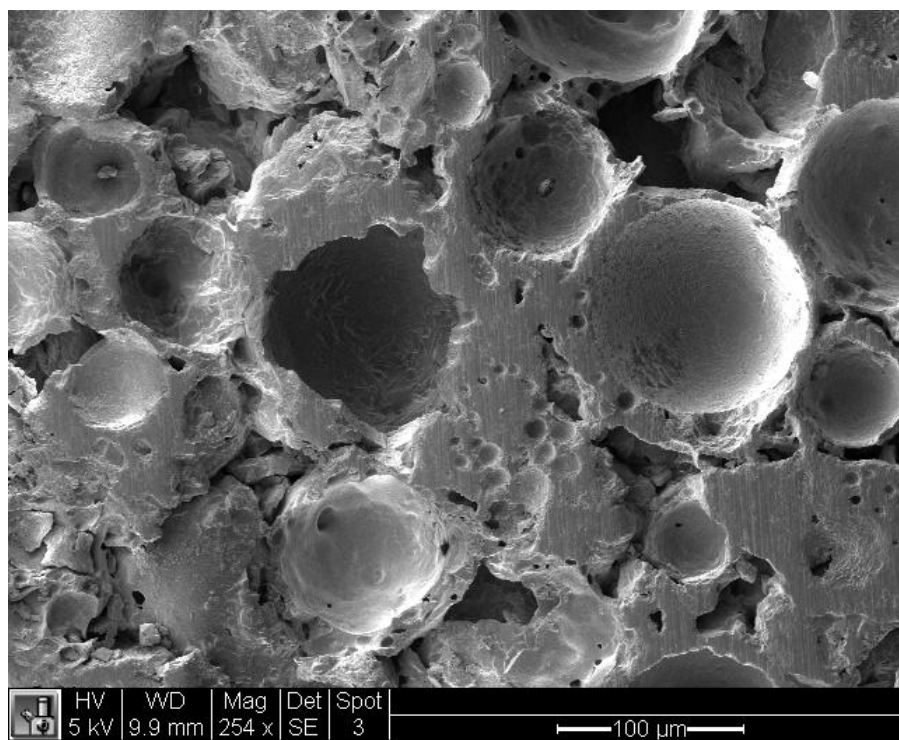


Figure N-427: SEM image of polished CB1100 surface.

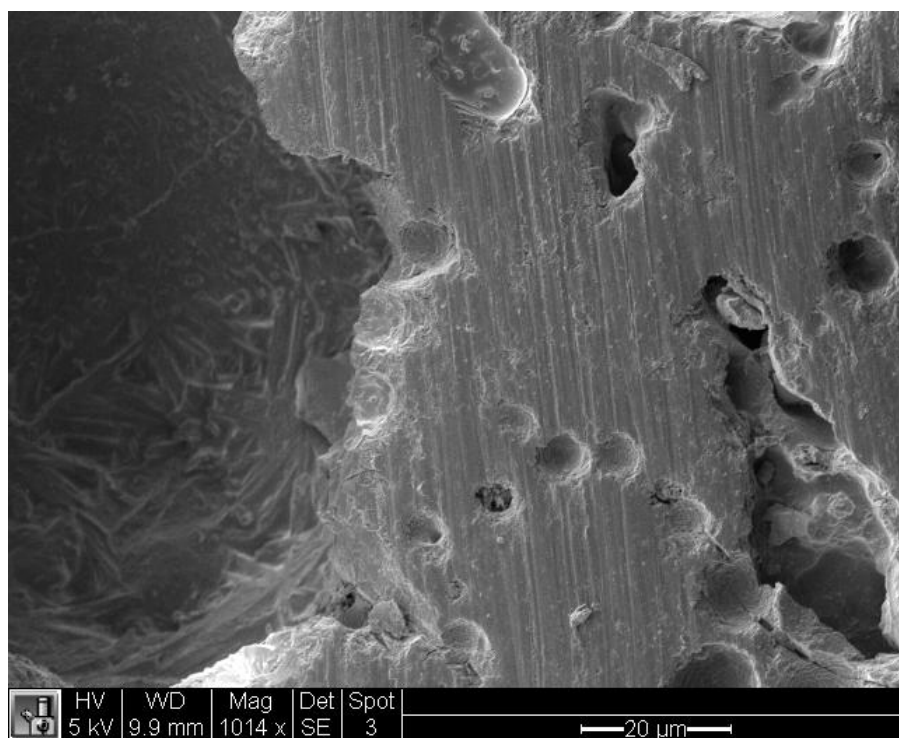


Figure N-428: SEM image of polished CB1100 surface.

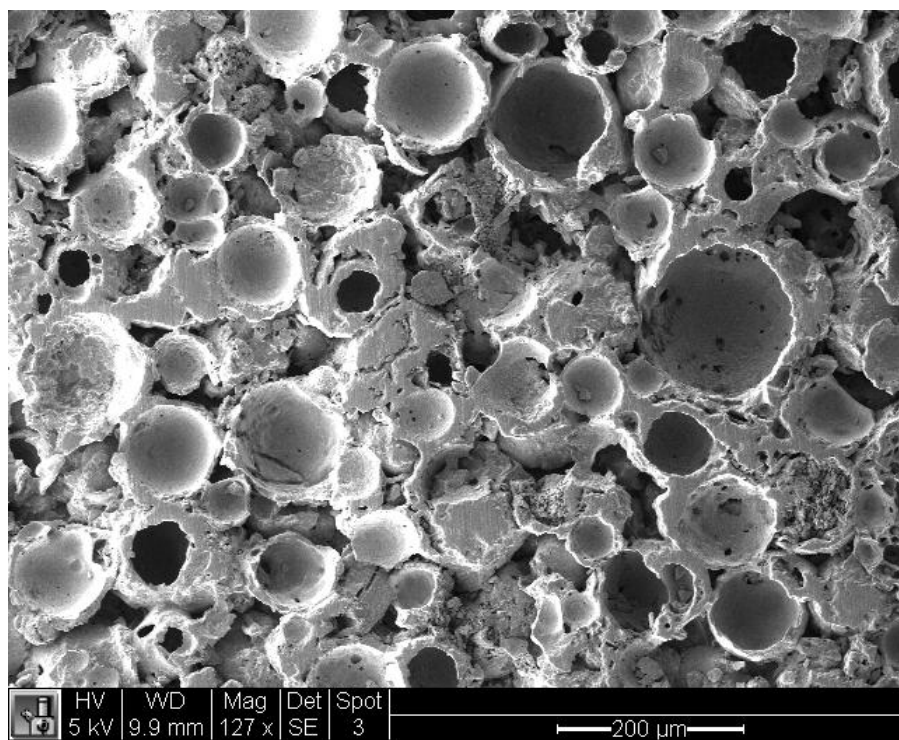


Figure N-429: SEM image of polished CB1100 surface.

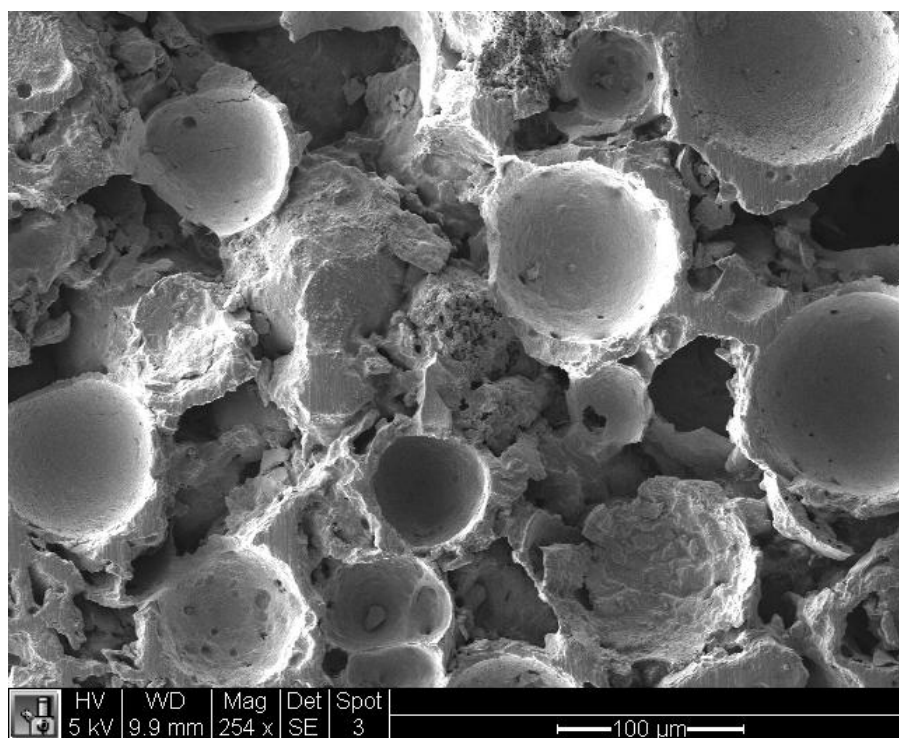


Figure N-430: SEM image of polished CB1100 surface.

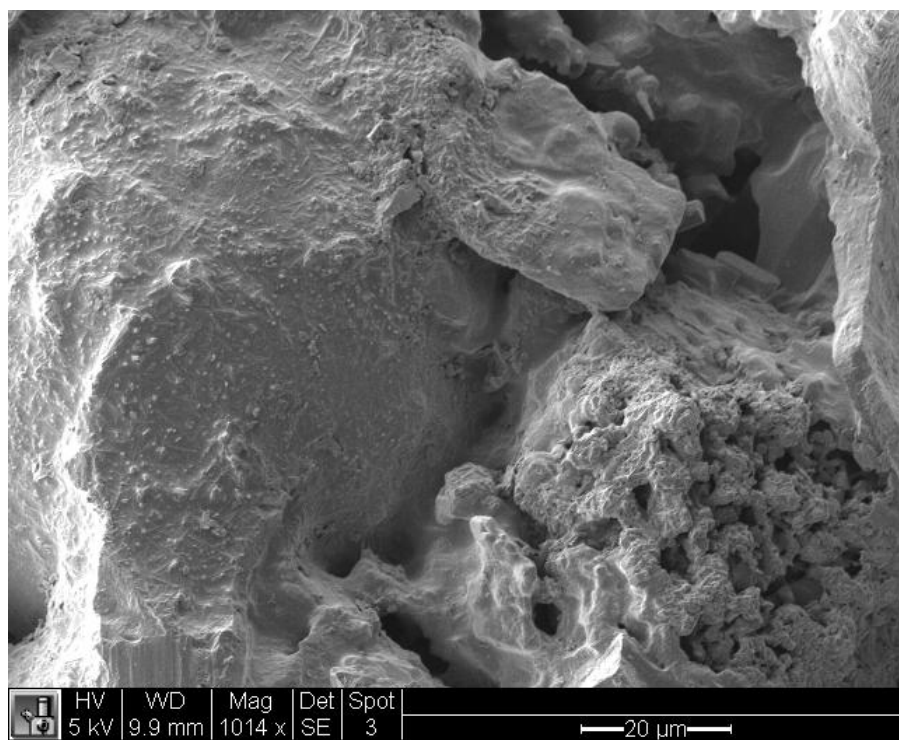


Figure N-431: SEM image of polished CB1100 surface.

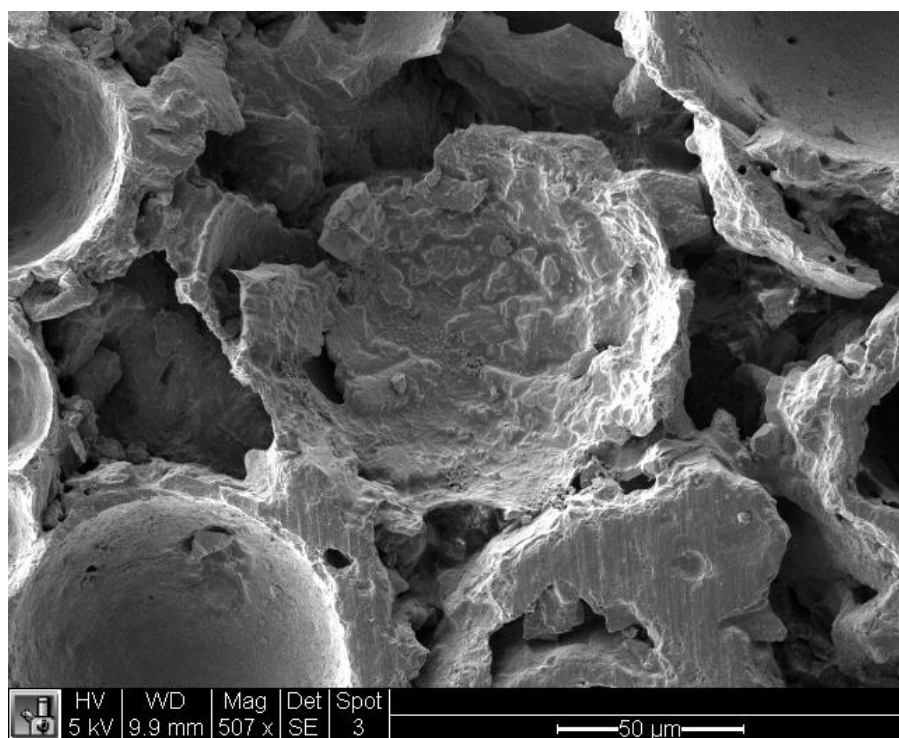


Figure N-432: SEM image of polished CB1100 surface.

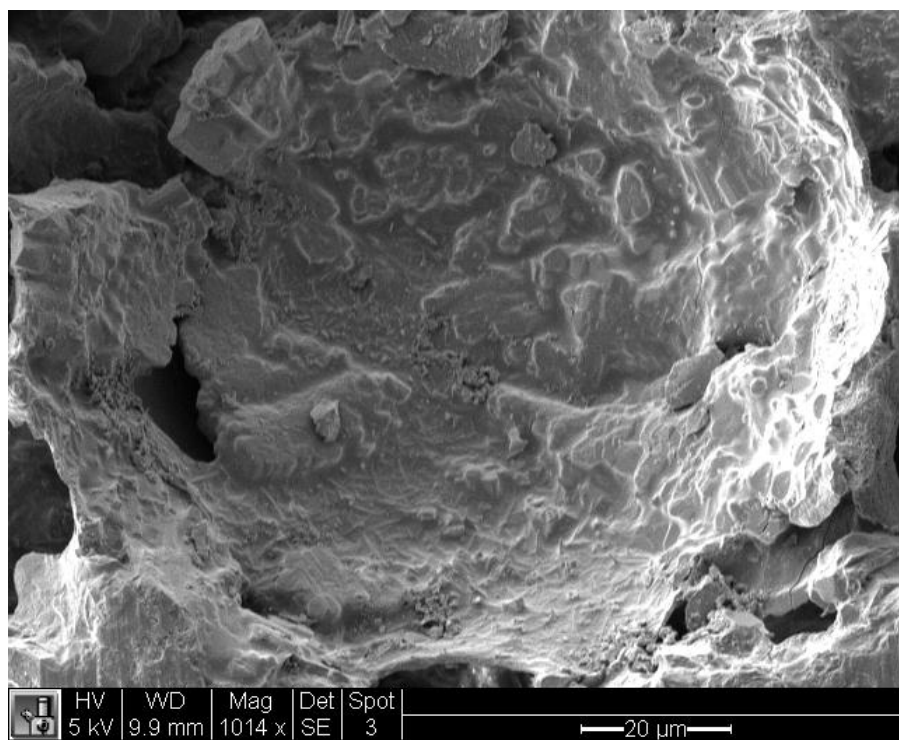


Figure N-433: SEM image of polished CB1100 surface.

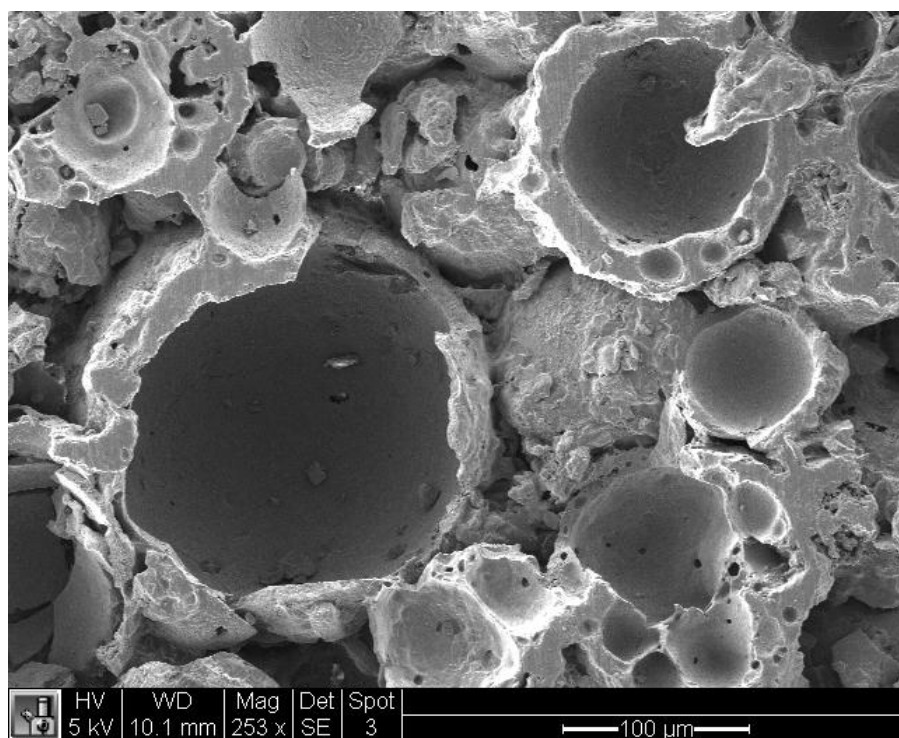


Figure N-434: SEM image of polished CB1100 surface.

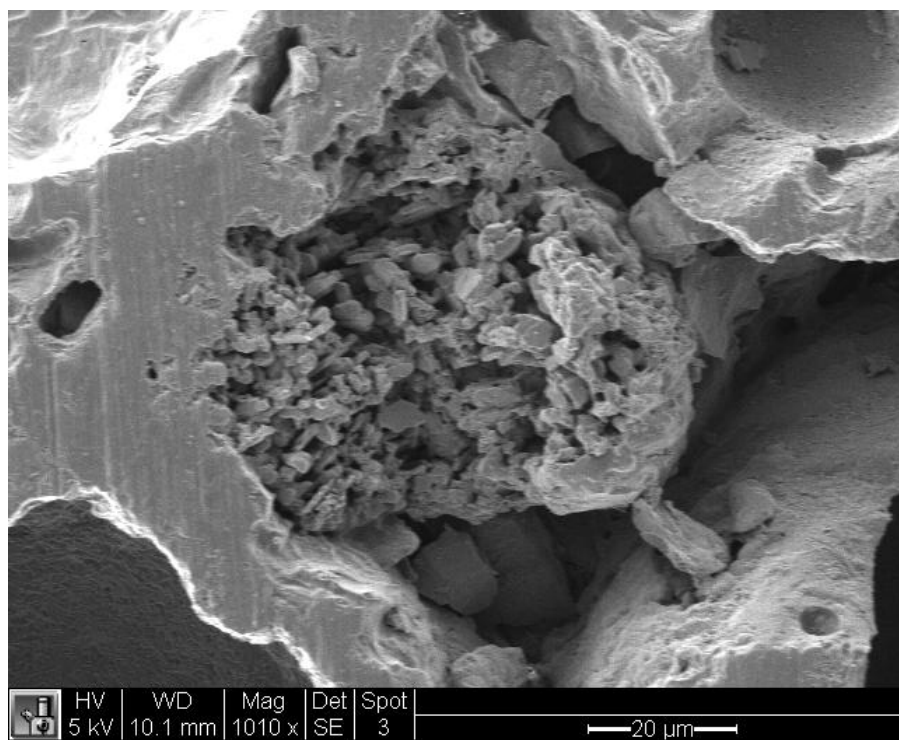


Figure N-435: SEM image of polished CB1100 surface.

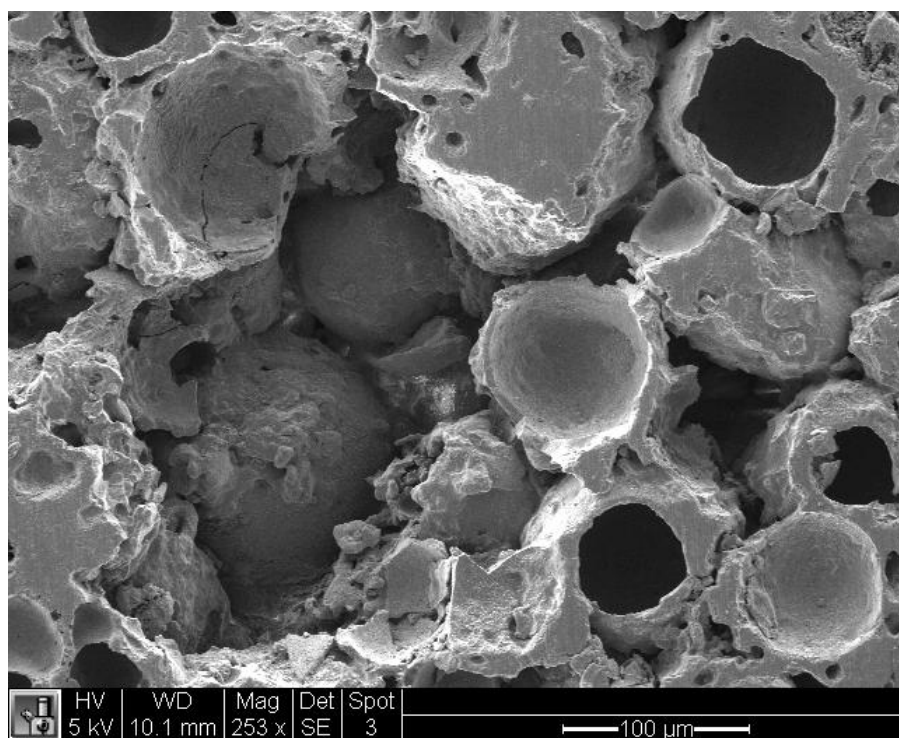


Figure N-436: SEM image of polished CB1100 surface.

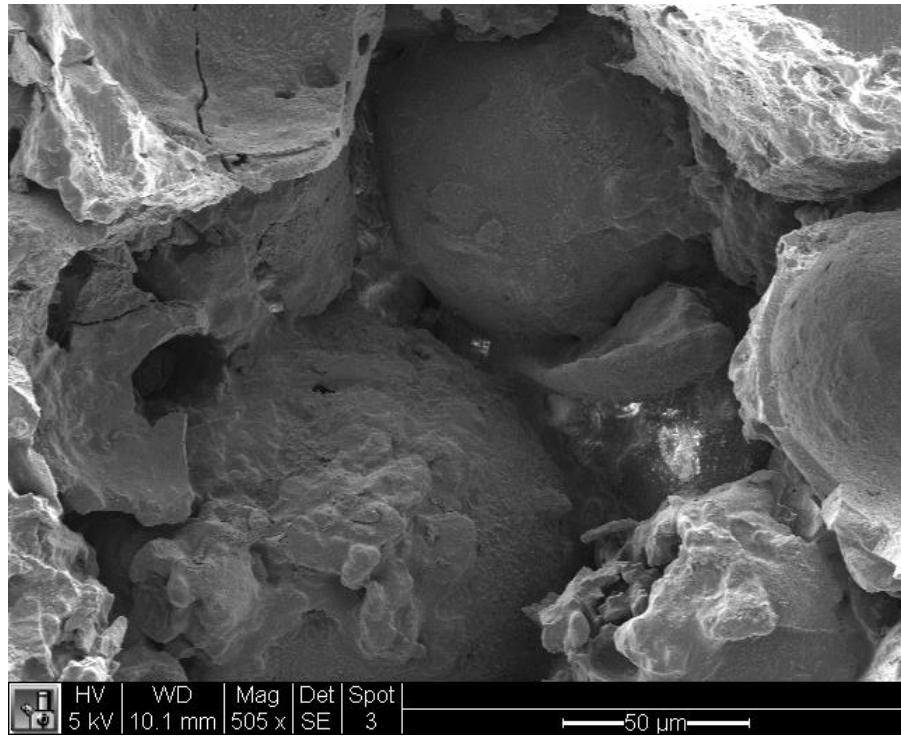


Figure N-437: SEM image of polished CB1100 surface.

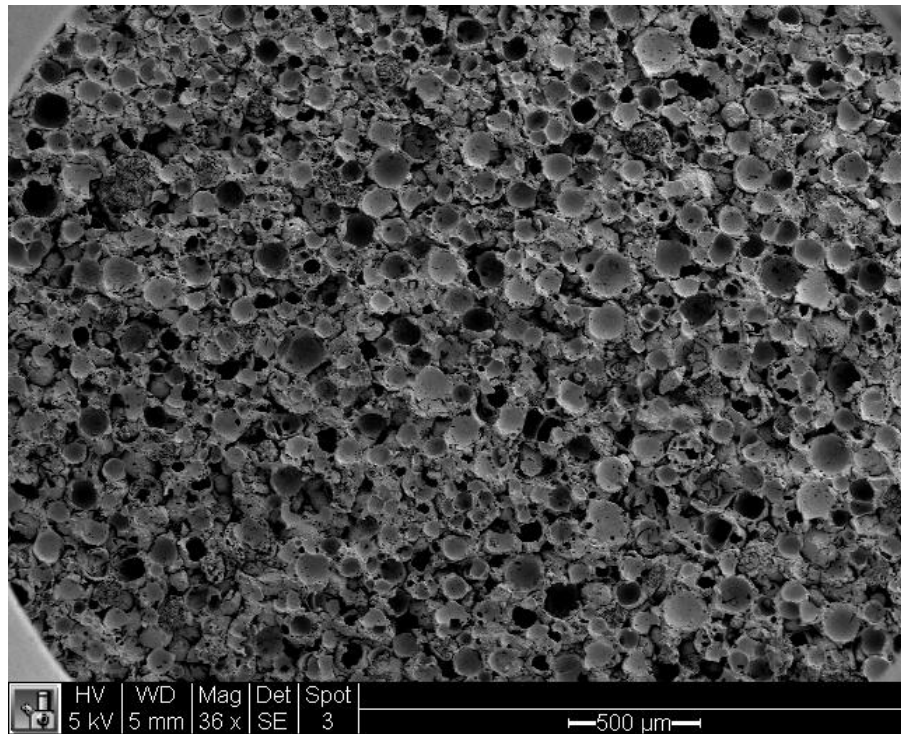


Figure N-438: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

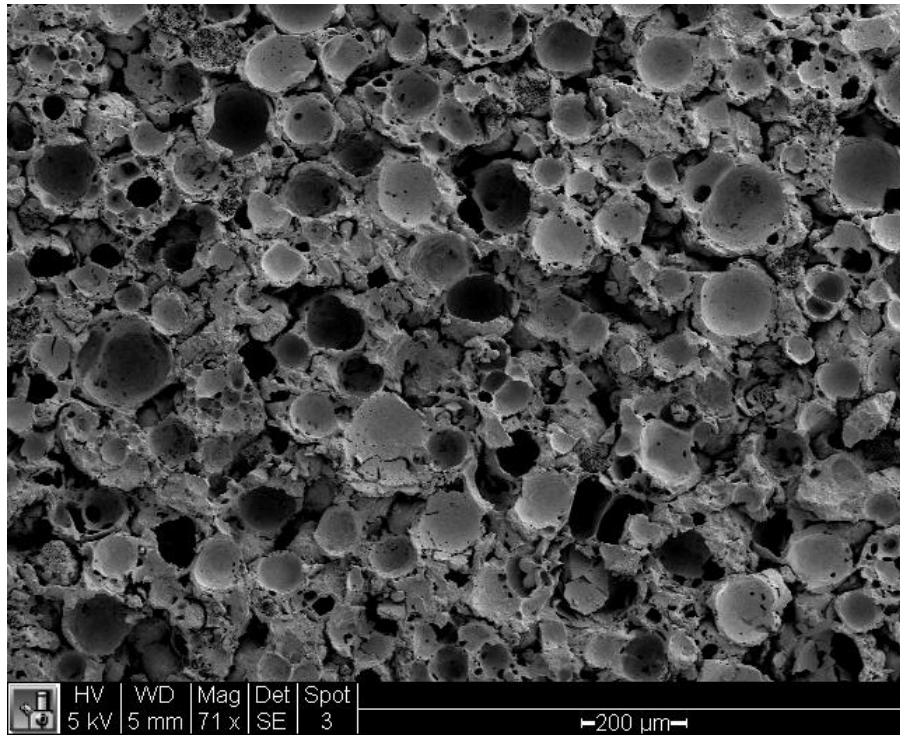


Figure N-439: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

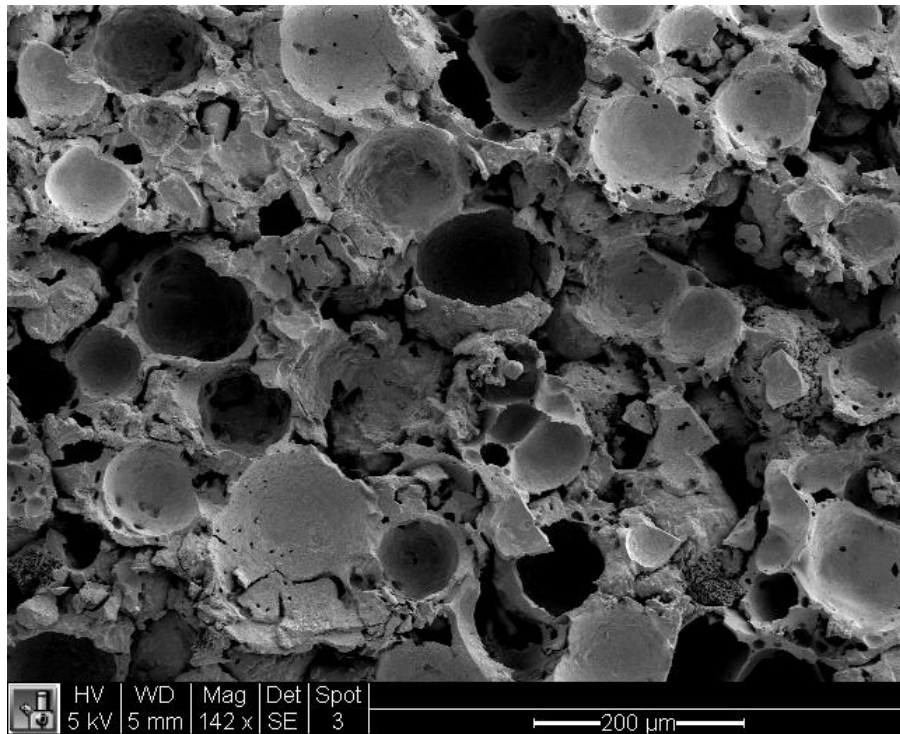


Figure N-440: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

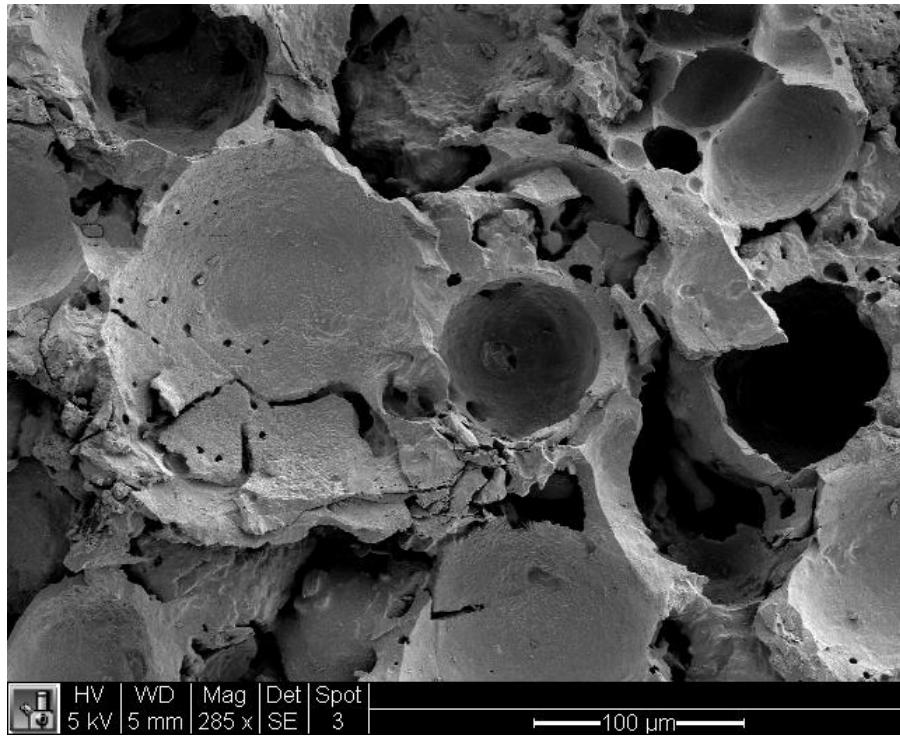


Figure N-441: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

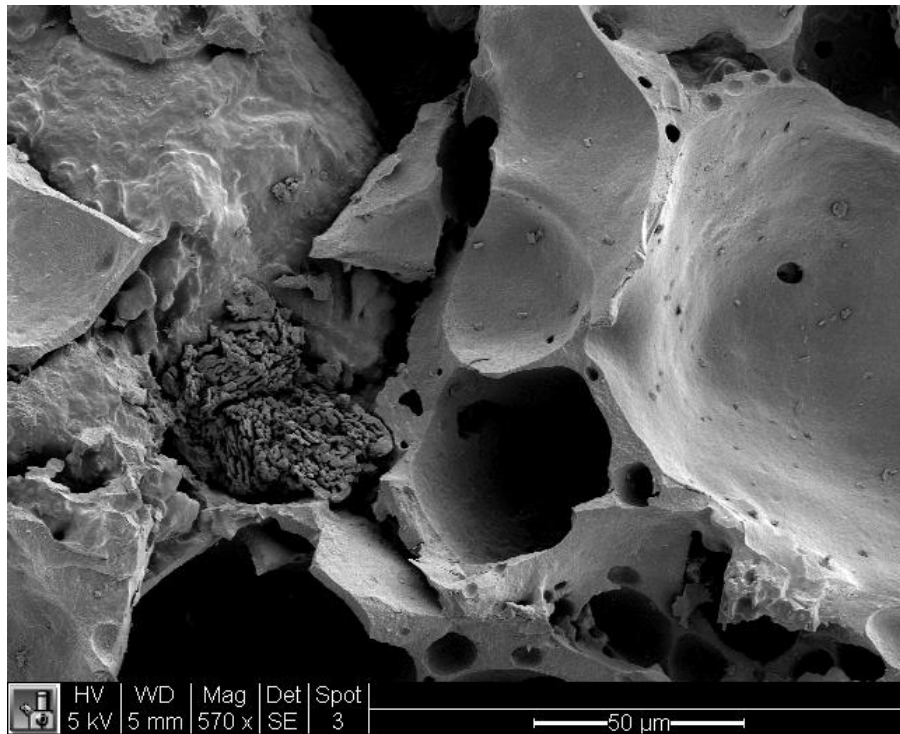


Figure N-442: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

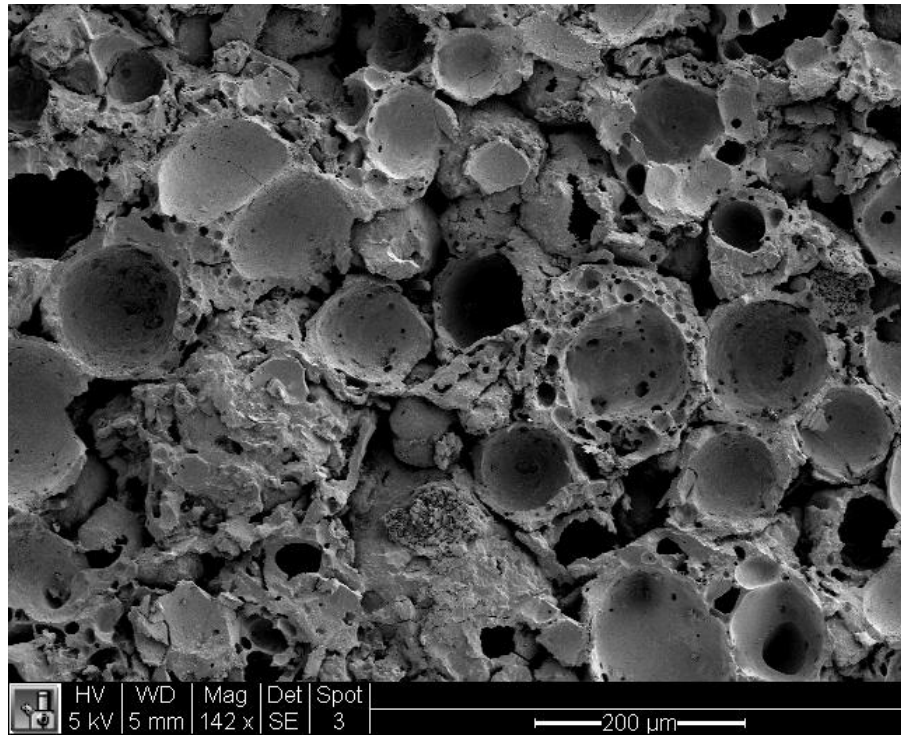


Figure N-443: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

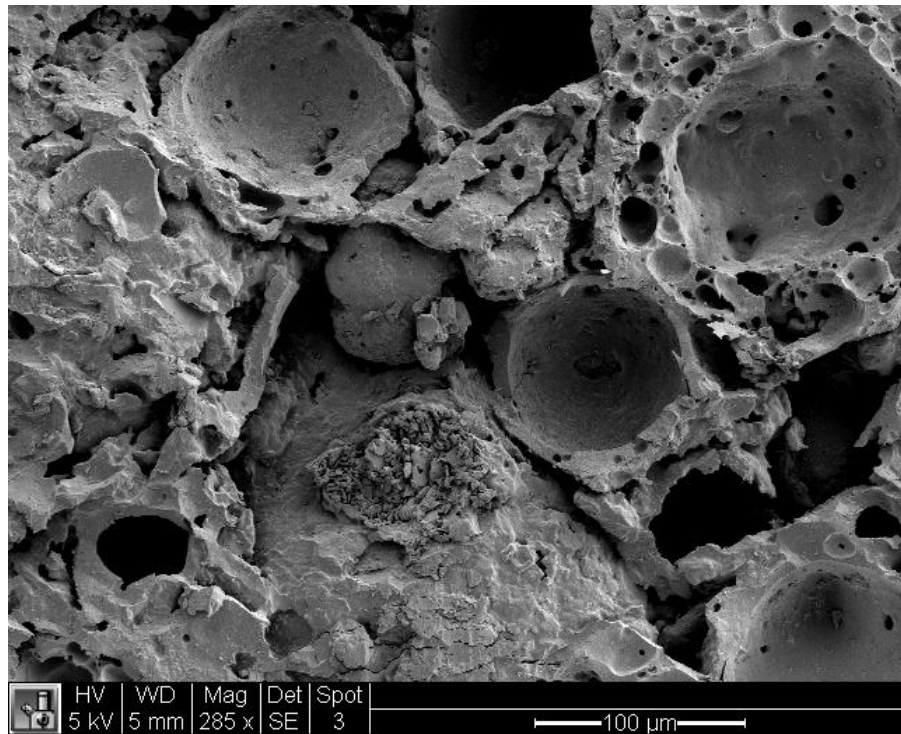


Figure N-444: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

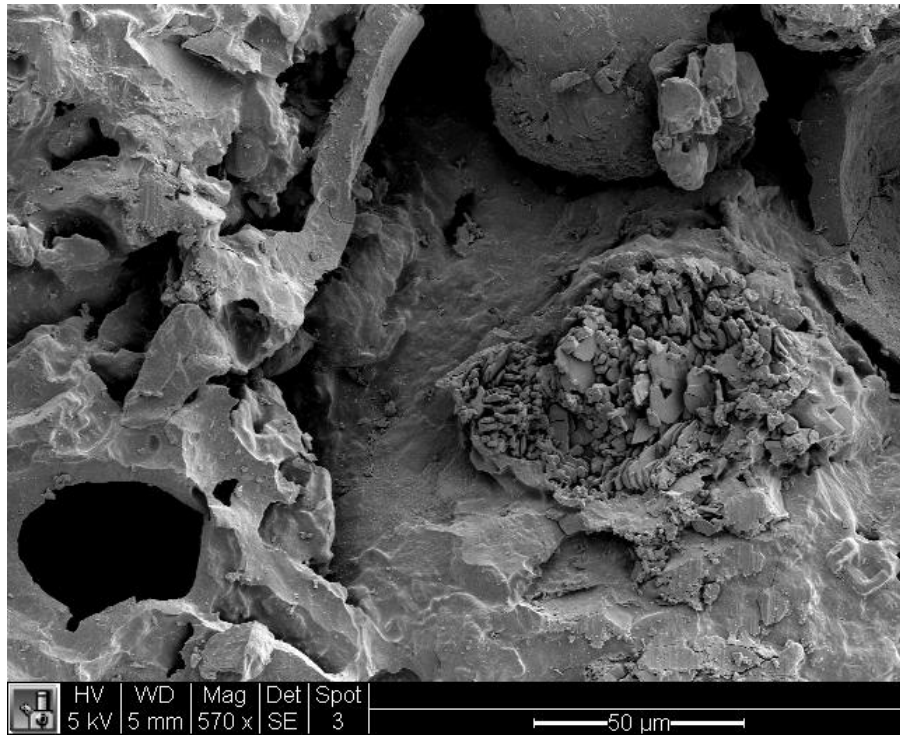


Figure N-445: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

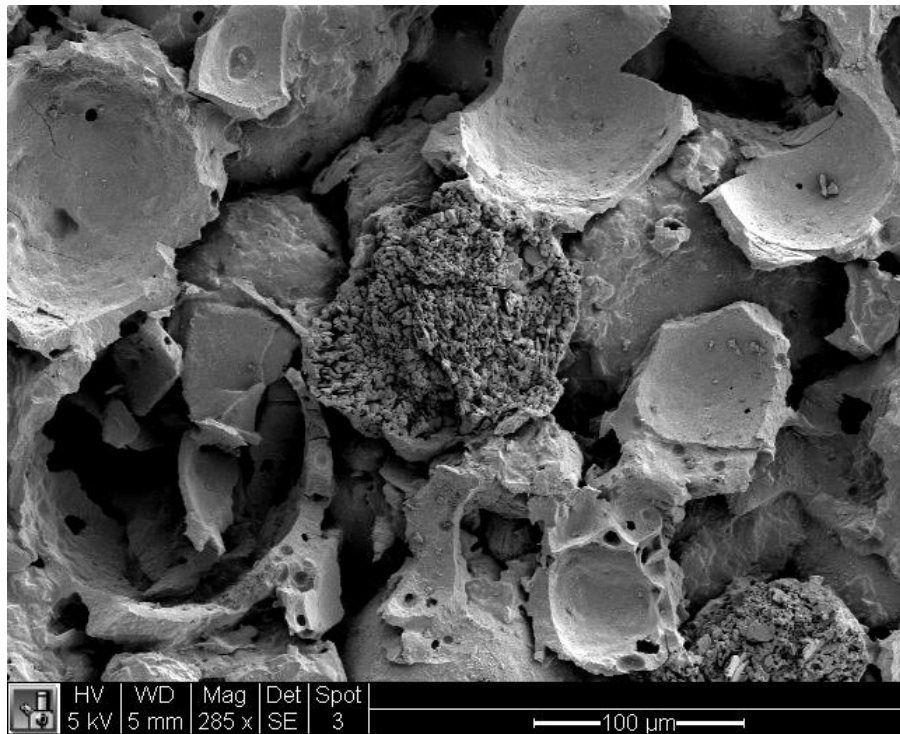


Figure N-446: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

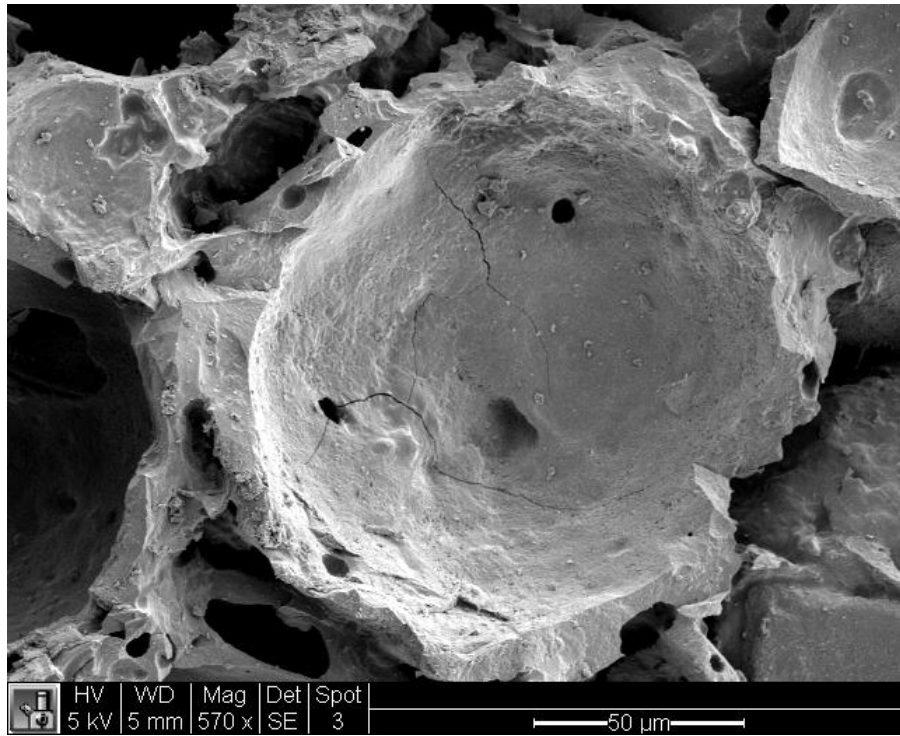


Figure N-447: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

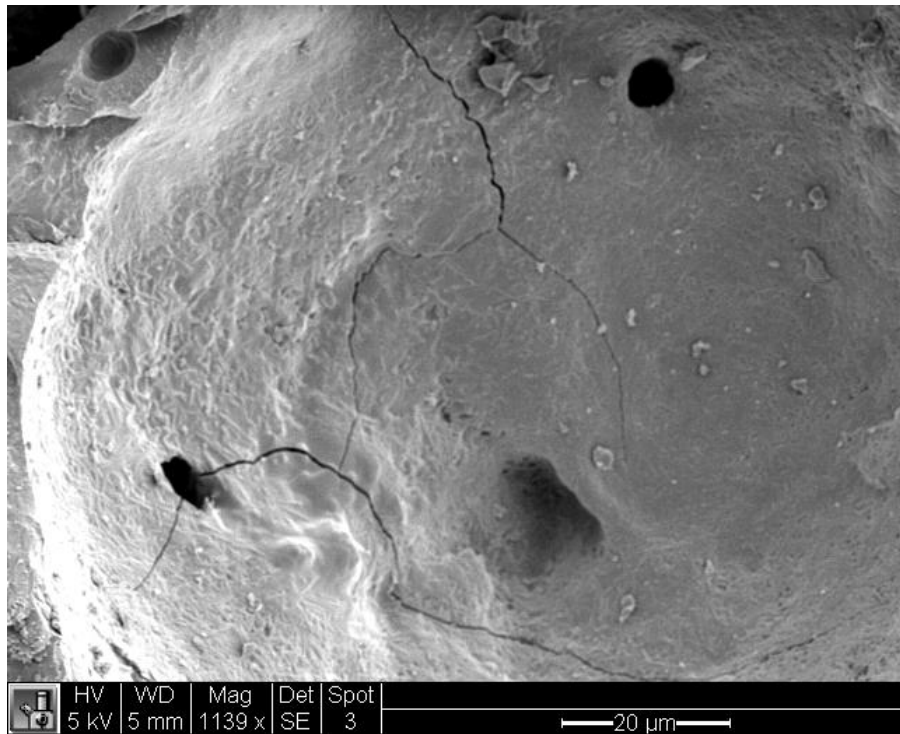


Figure N-448: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

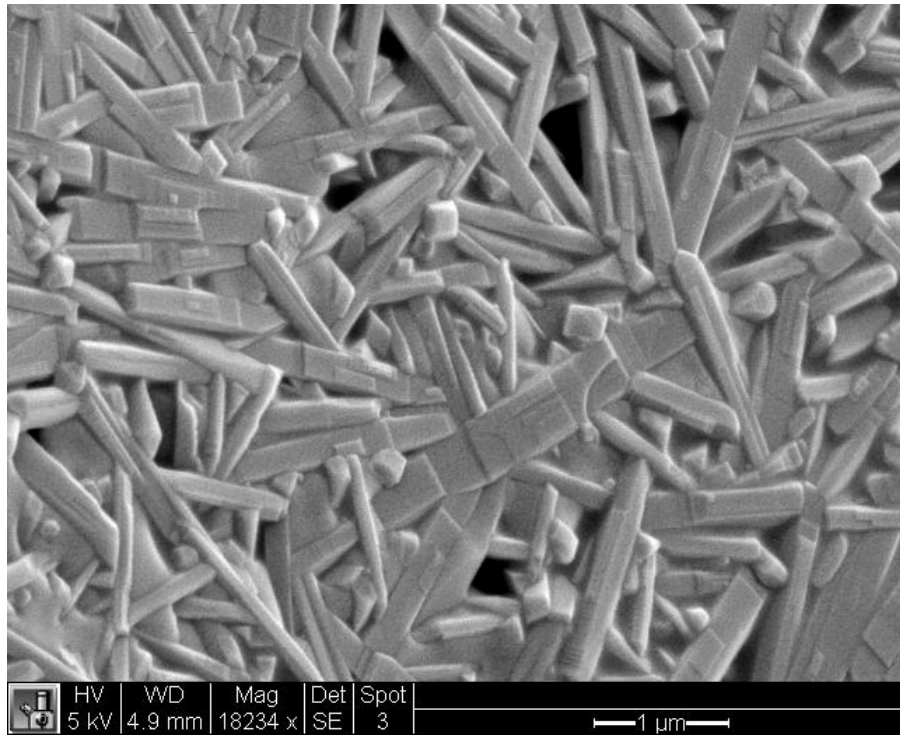


Figure N-449: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min

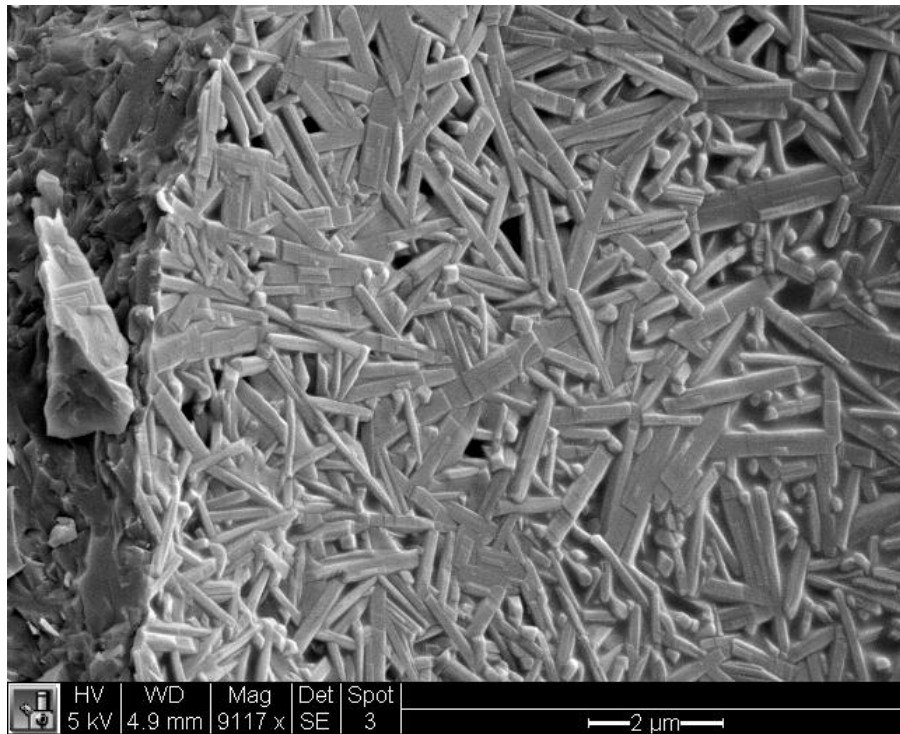


Figure N-450: SEM image of CB1100 surface machined at 6000RPM and 2.54 m/min.

3.) Cfoam

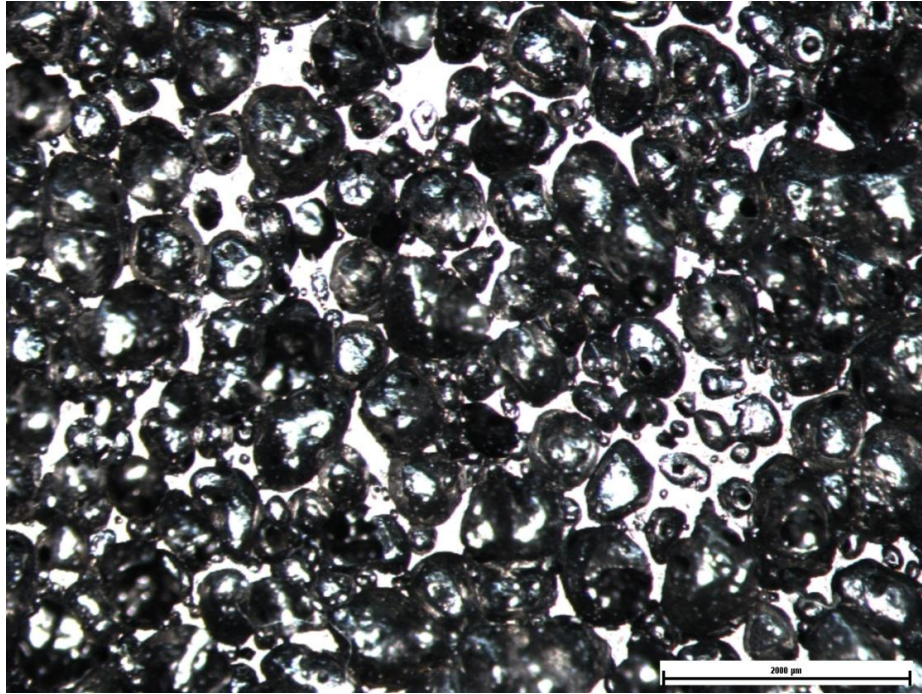


Figure N-451: Photo image of polished surface in Cfoam

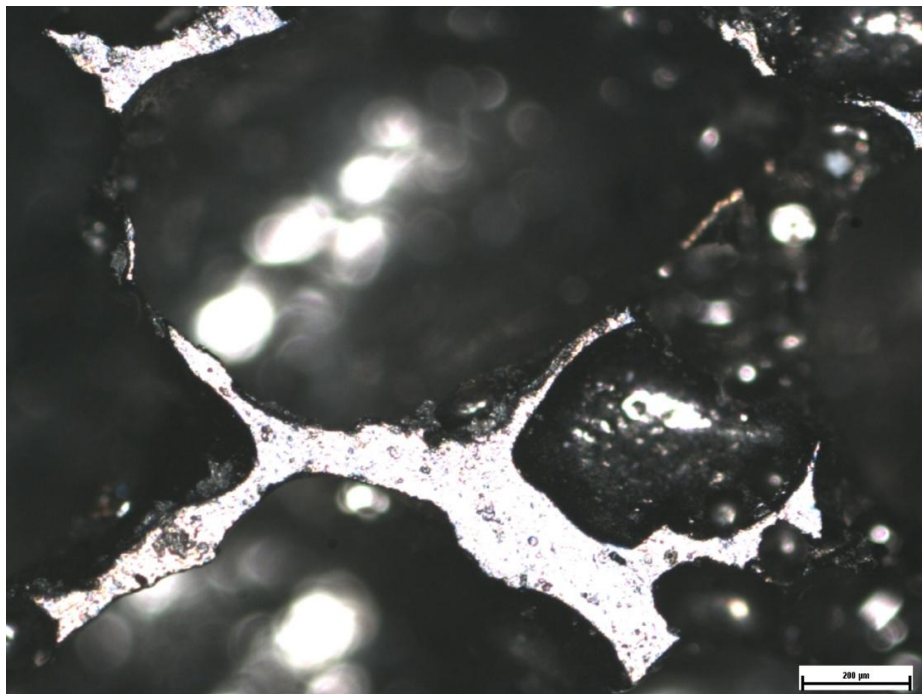


Figure N-452: Photo image of polished surface in Cfoam.

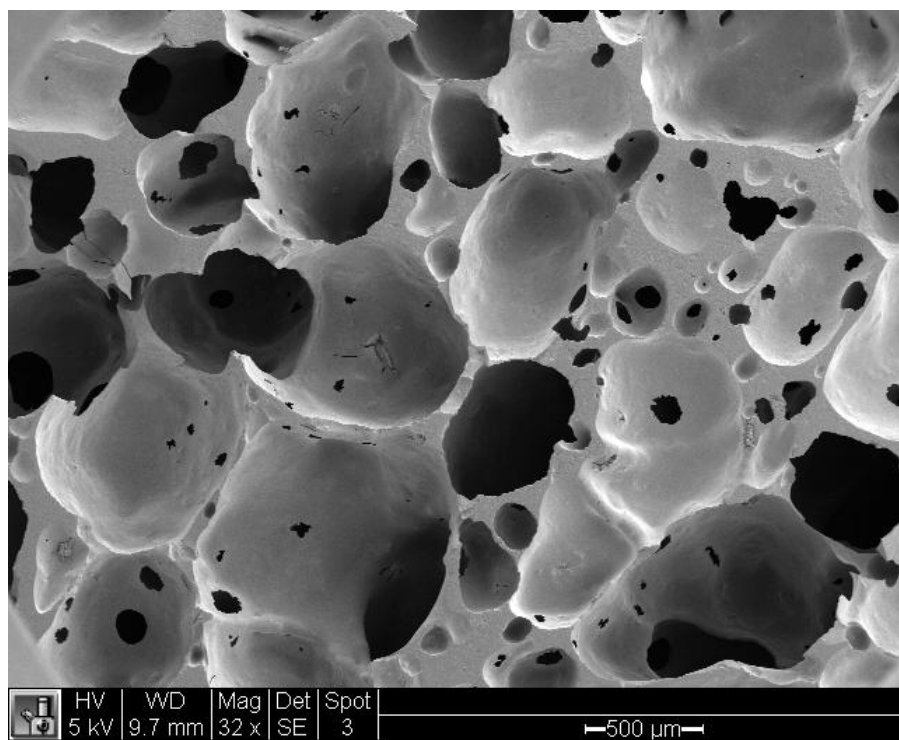


Figure N-453: SEM image of polished surface in Cfoam.

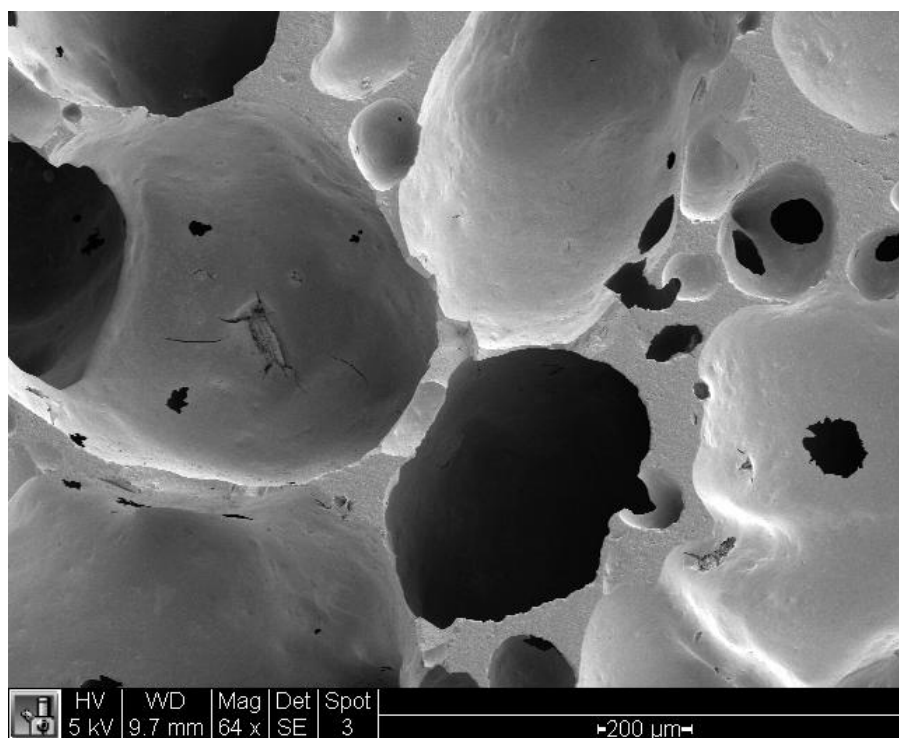


Figure N-454: SEM image of polished surface in Cfoam.

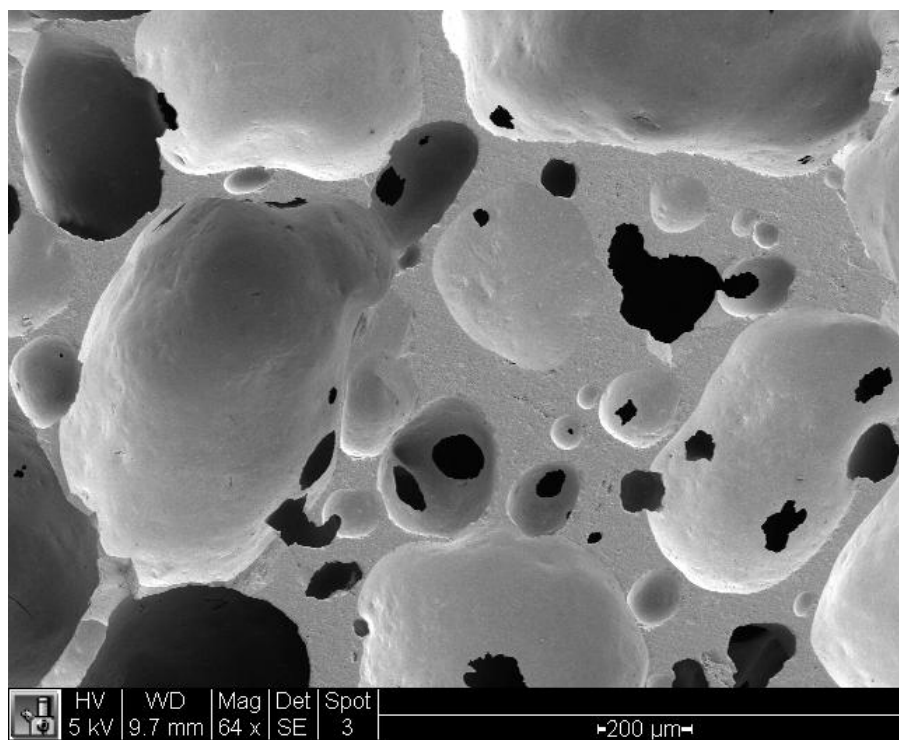


Figure N-455: SEM image of polished surface in Cfoam.

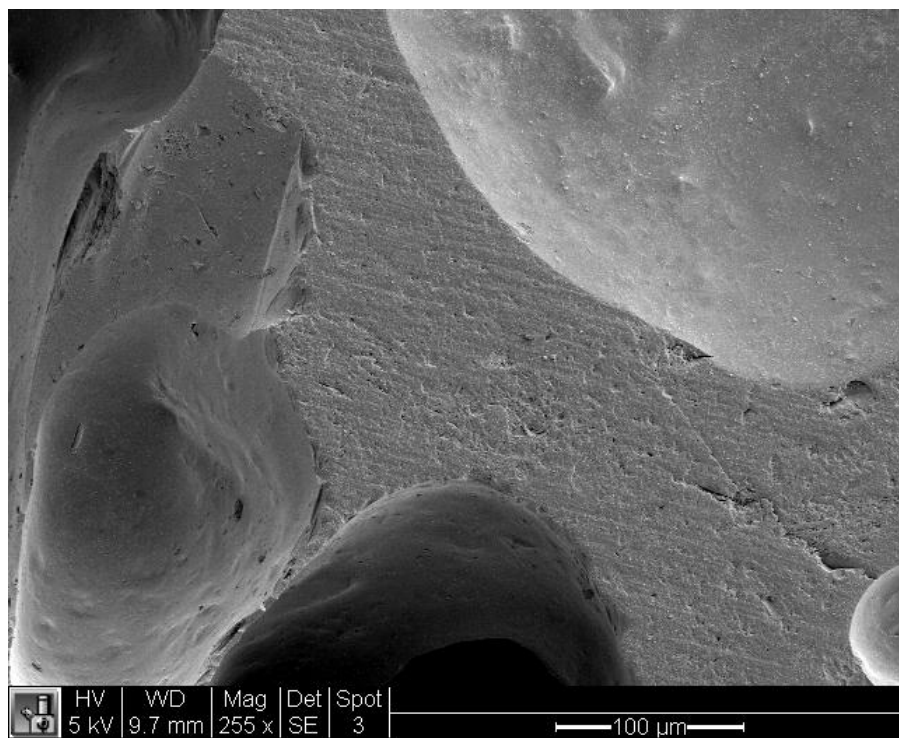


Figure N-456: SEM image of polished surface in Cfoam.

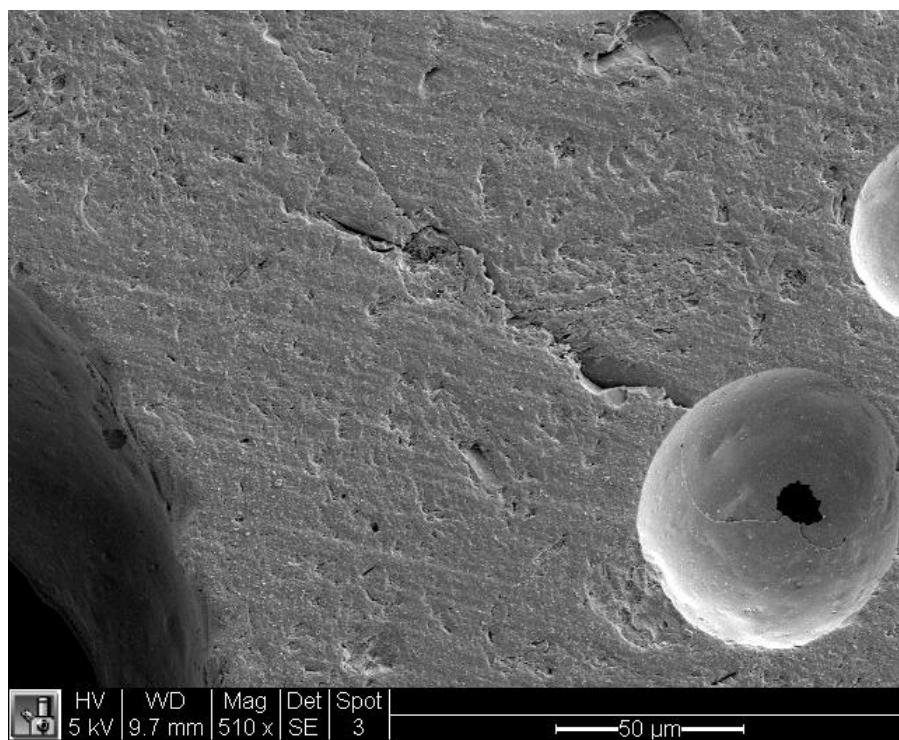


Figure N-457: SEM image of polished surface in Cfoam.

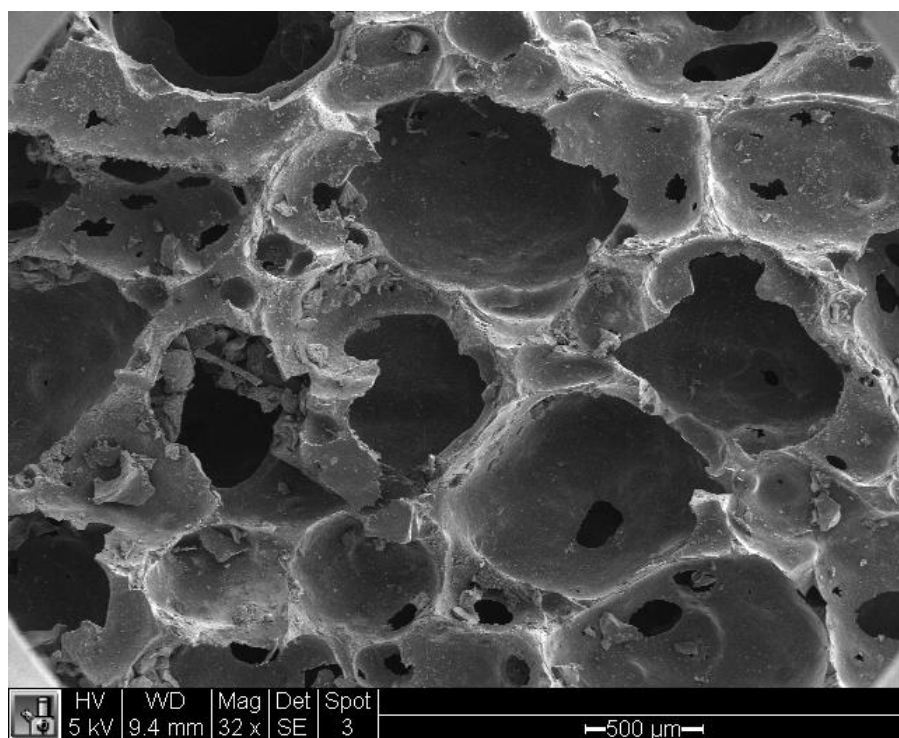


Figure N-458: SEM image of Cfoam 'as-received' sample.

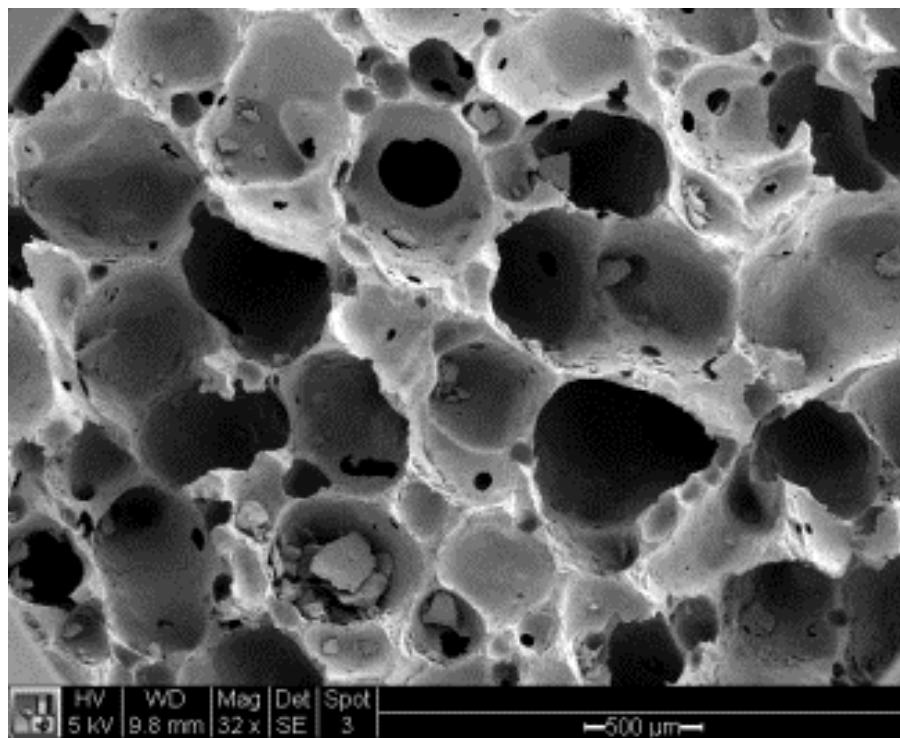


Figure N-459: SEM image of Cfoam 'as-received' sample.

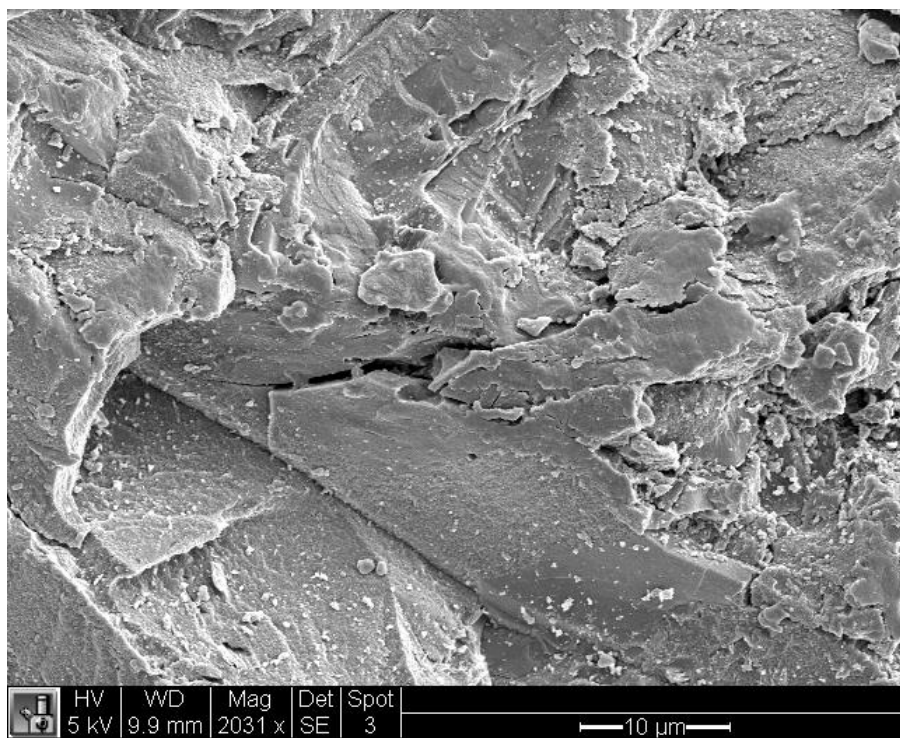


Figure N-460: SEM image of Cfoam 'as-received' sample.

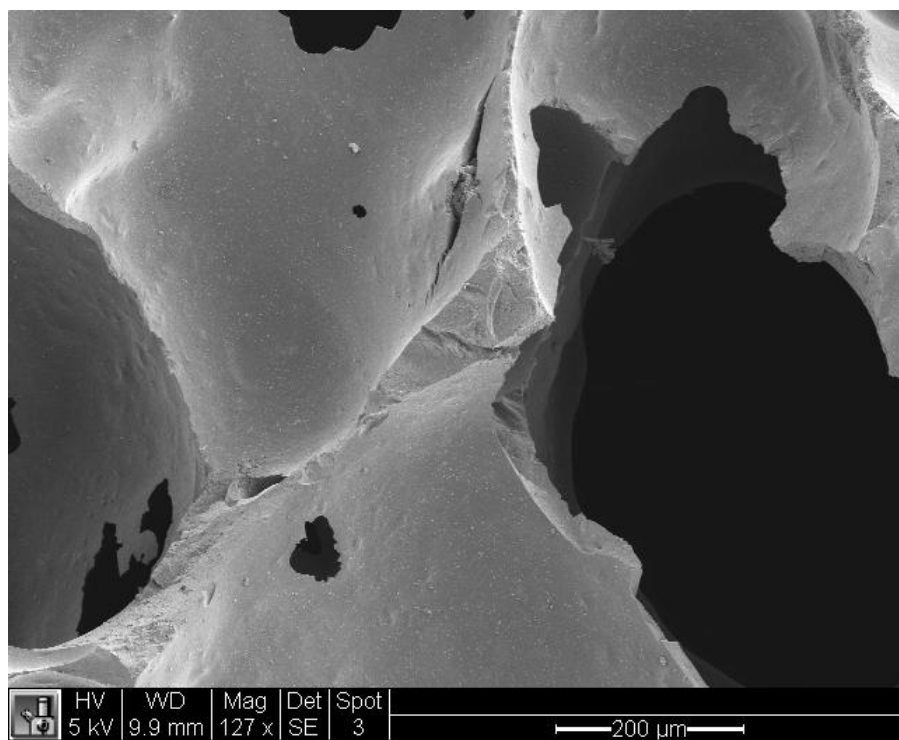


Figure N-461: SEM image of Cfoam sample.

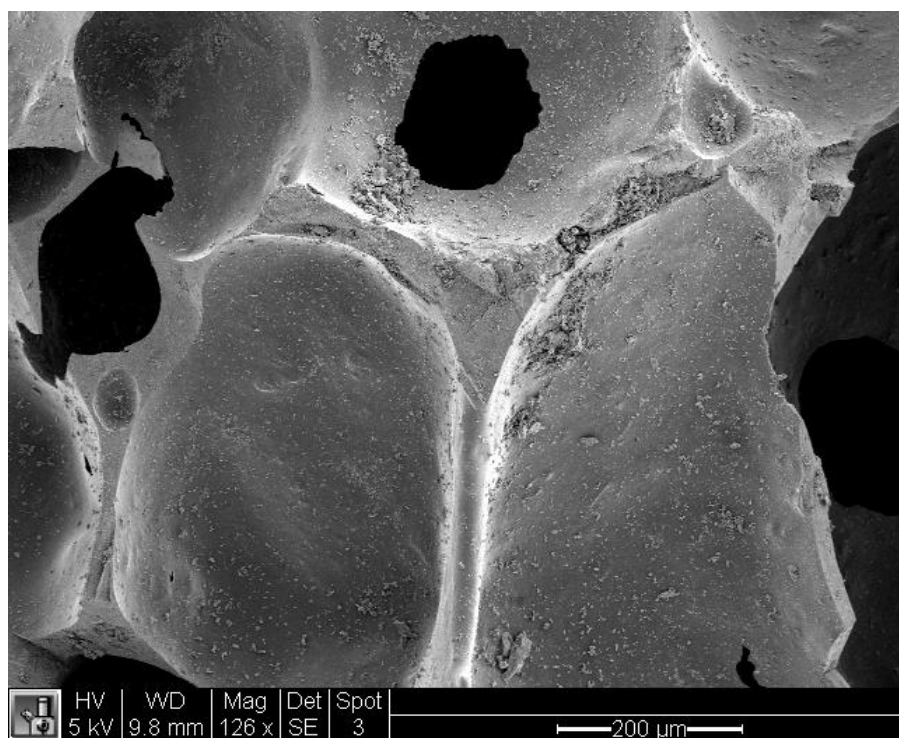


Figure N-462: SEM image of Cfoam 'as-received' sample.

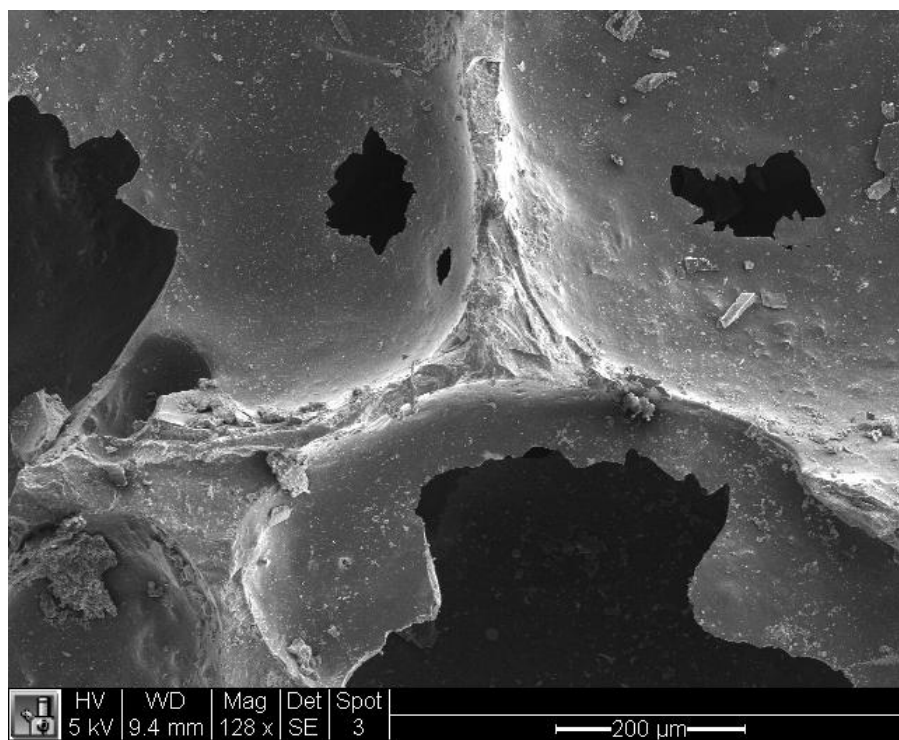


Figure N-463: SEM image of ligament fracture in Cfoam.

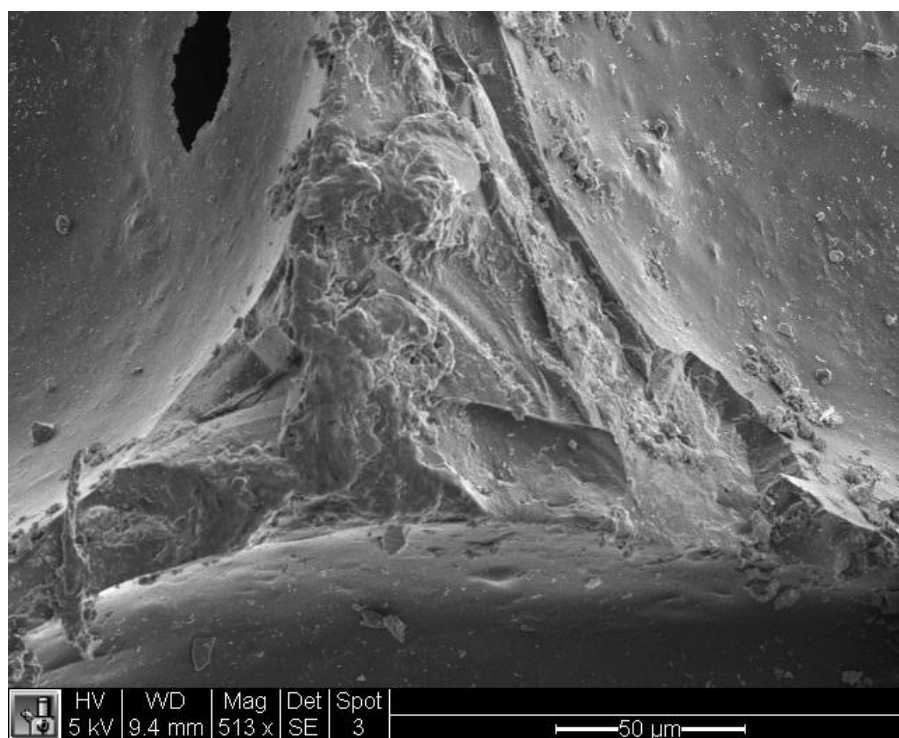


Figure N-464: SEM image of ligament fracture in Cfoam.

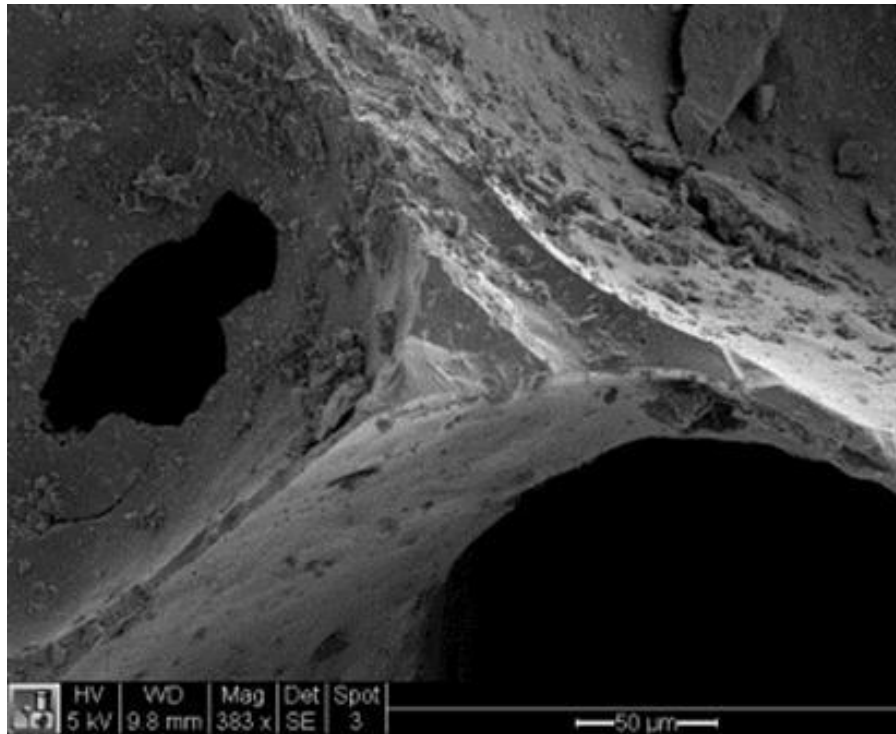


Figure N-465: SEM image of ligament fracture in Cfoam.

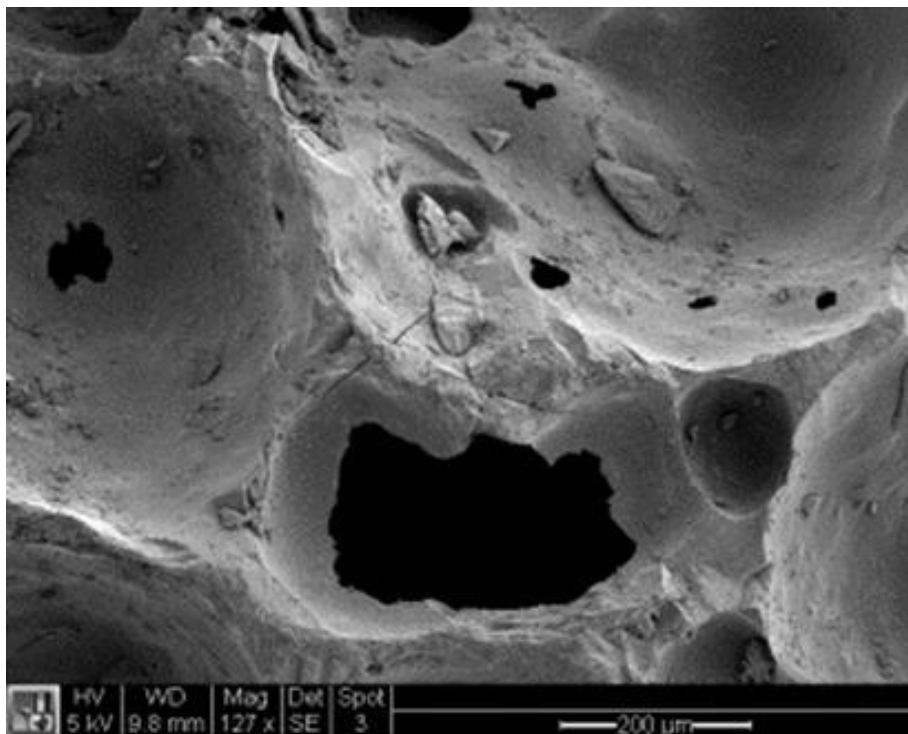


Figure N-466: SEM image of micro-cracking in Cfoam ligament.

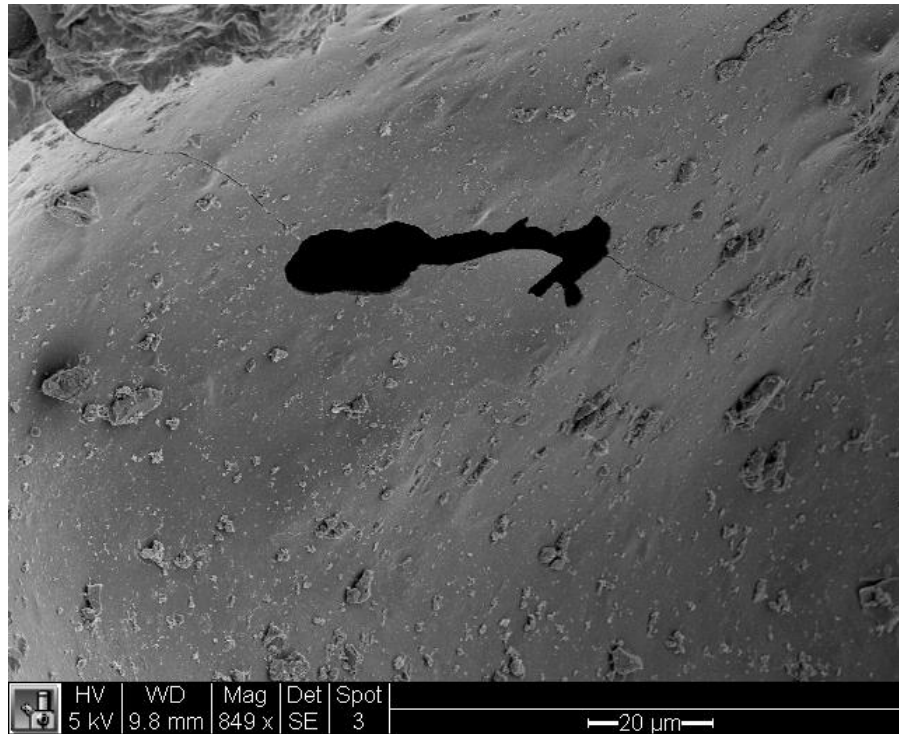


Figure N-467: SEM image of micro-cracking in Cfoam cell wall.

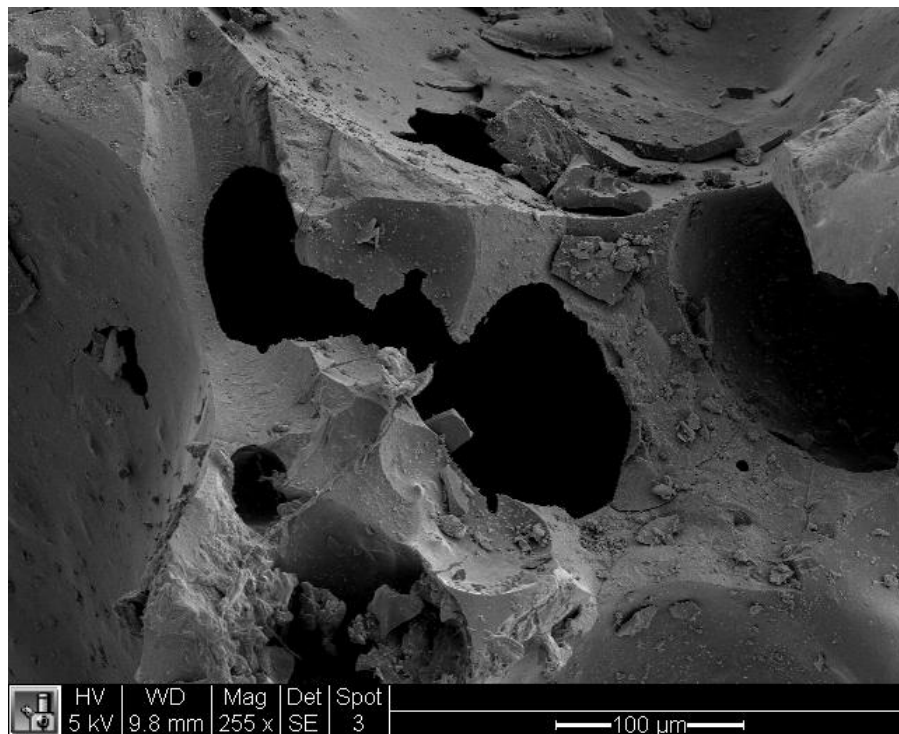


Figure N-468: SEM image of damage in Cfoam machined using diamond abrasive cutting tool.

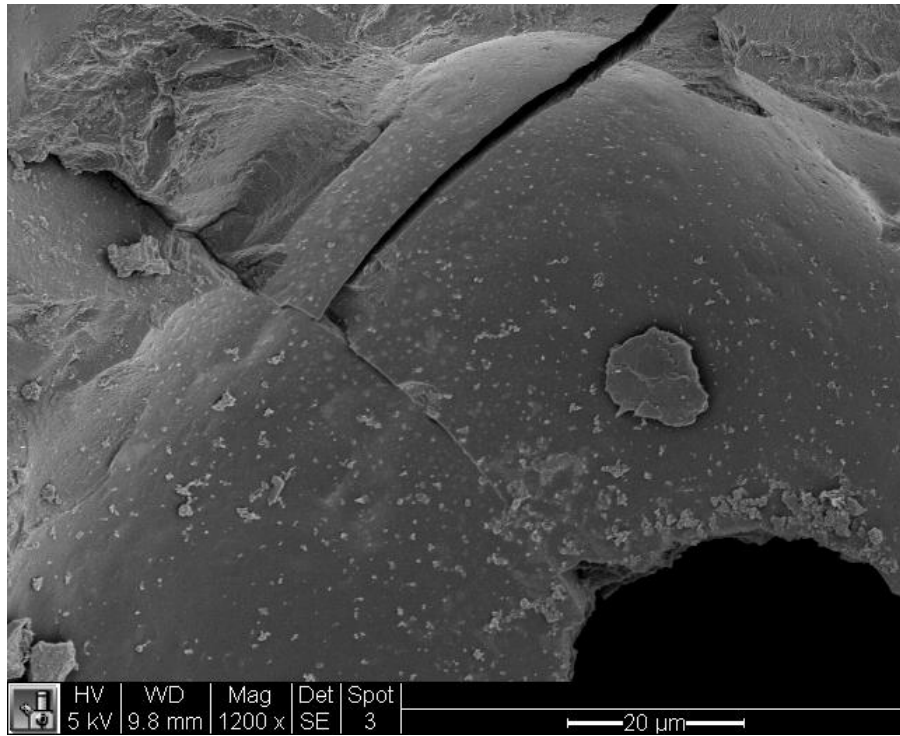


Figure N-469: SEM image of damage in Cfoam machined using diamond abrasive cutting tool.

Appendix: O. Tabulated cutting force simulation results

1.) AAC

Table O-5: AAC simulated average cutting forces.

RPM	Feed [m/min]	ADOC [mm]	RDOC [mm]	Ft pred avg [N]	Fr pred avg [N]
6000.00	10.16	3.18	6.35	24.47	9.50
6000.00	10.16	3.18	3.18	28.98	12.84
6000.00	10.16	3.18	6.35	21.05	12.02
6000.00	10.16	3.18	3.18	17.68	4.03
6000.00	10.16	3.18	6.35	27.32	14.24
6000.00	10.16	3.18	3.18	27.29	14.85
6000.00	10.16	6.35	6.35	44.34	58.01
6000.00	10.16	6.35	3.18	19.85	4.94
6000.00	10.16	6.35	3.18	45.79	19.88
6000.00	10.16	6.35	6.35	15.78	3.84
6000.00	10.16	6.35	6.35	41.34	23.56
6000.00	10.16	6.35	3.18	32.42	16.53
6000.00	5.08	3.18	3.18	16.26	4.18
6000.00	5.08	3.18	6.35	54.12	38.83
6000.00	5.08	3.18	6.35	40.79	17.41
6000.00	5.08	3.18	3.18	28.60	9.05
6000.00	5.08	3.18	6.35	14.92	2.87
6000.00	5.08	3.18	3.18	19.62	5.73
6000.00	5.08	6.35	3.18	16.27	6.21
6000.00	5.08	6.35	6.35	23.23	7.96
6000.00	5.08	6.35	6.35	20.34	5.35
6000.00	5.08	6.35	3.18	22.71	7.00
6000.00	5.08	6.35	6.35	28.10	19.25
6000.00	5.08	6.35	3.18	16.41	6.46
6000.00	2.54	3.18	3.18	25.58	15.41
6000.00	2.54	3.18	6.35	23.12	23.75
6000.00	2.54	3.18	6.35	44.89	19.09
6000.00	2.54	3.18	3.18	23.68	6.77
6000.00	2.54	3.18	6.35	19.19	7.83
6000.00	2.54	3.18	3.18	15.59	2.90
6000.00	2.54	6.35	3.18	64.30	26.47
6000.00	2.54	6.35	6.35	18.10	4.89
6000.00	2.54	6.35	6.35	50.62	44.00
6000.00	2.54	6.35	3.18	21.99	15.40
6000.00	2.54	6.35	6.35	20.60	6.59

6000.00	2.54	6.35	3.18	27.46	19.98
5000.00	10.16	3.18	3.18	24.38	5.19
5000.00	10.16	3.18	6.35	26.48	11.08
5000.00	10.16	3.18	6.35	42.27	19.53
5000.00	10.16	3.18	3.18	16.29	4.11
5000.00	10.16	3.18	3.18	52.56	41.01
5000.00	10.16	3.18	6.35	21.64	9.70
5000.00	10.16	6.35	6.35	23.89	9.69
5000.00	10.16	6.35	3.18	22.24	5.60
5000.00	10.16	6.35	6.35	40.77	30.17
5000.00	10.16	6.35	3.18	28.79	14.07
5000.00	10.16	6.35	6.35	20.87	5.74
5000.00	10.16	6.35	3.18	15.86	2.99
5000.00	5.08	3.18	3.18	19.79	9.45
5000.00	5.08	3.18	6.35	22.72	11.47
5000.00	5.08	3.18	6.35	18.74	4.11
5000.00	5.08	3.18	3.18	16.50	3.93
5000.00	5.08	3.18	6.35	50.31	37.38
5000.00	5.08	3.18	3.18	25.51	10.81
5000.00	5.08	6.35	3.18	17.54	4.25
5000.00	5.08	6.35	6.35	34.80	17.19
5000.00	5.08	6.35	3.18	27.90	16.80
5000.00	5.08	6.35	6.35	20.17	7.35
5000.00	5.08	6.35	6.35	18.49	6.03
5000.00	5.08	6.35	3.18	20.26	10.34
5000.00	2.54	3.18	6.35	27.41	15.77
5000.00	2.54	3.18	3.18	18.11	5.18
5000.00	2.54	3.18	6.35	27.32	14.12
5000.00	2.54	3.18	3.18	43.45	30.99
5000.00	2.54	3.18	3.18	14.63	2.92
5000.00	2.54	3.18	6.35	33.94	30.70
5000.00	2.54	6.35	3.18	19.22	5.53
5000.00	2.54	6.35	6.35	25.89	17.28
5000.00	2.54	6.35	3.18	20.01	7.66
5000.00	2.54	6.35	6.35	32.45	20.76
5000.00	2.54	6.35	3.18	26.18	9.61
5000.00	2.54	6.35	6.35	27.75	19.06
4000.00	10.16	3.18	6.35	18.34	7.60
4000.00	10.16	3.18	3.18	56.08	25.91
4000.00	10.16	3.18	6.35	28.53	16.00
4000.00	10.16	3.18	3.18	16.93	5.29

4000.00	10.16	3.18	3.18	34.59	22.62
4000.00	10.16	3.18	6.35	24.23	19.18
4000.00	10.16	6.35	6.35	15.66	2.94
4000.00	10.16	6.35	3.18	53.27	38.93
4000.00	10.16	6.35	6.35	23.51	12.63
4000.00	10.16	6.35	3.18	19.86	7.09
4000.00	10.16	6.35	6.35	16.19	3.10
4000.00	10.16	6.35	3.18	20.29	14.08
4000.00	5.08	3.18	6.35	28.40	17.47
4000.00	5.08	3.18	3.18	17.76	4.98
4000.00	5.08	3.18	6.35	15.24	2.56
4000.00	5.08	3.18	3.18	31.53	20.96
4000.00	5.08	3.18	3.18	41.73	12.83
4000.00	5.08	3.18	6.35	27.93	17.70
4000.00	5.08	6.35	6.35	16.38	4.88
4000.00	5.08	6.35	3.18	23.95	18.05
4000.00	5.08	6.35	3.18	18.05	6.89
4000.00	5.08	6.35	6.35	17.73	5.38
4000.00	5.08	6.35	3.18	29.58	11.92
4000.00	5.08	6.35	6.35	24.44	11.34
4000.00	2.54	3.18	6.35	49.15	48.78
4000.00	2.54	3.18	3.18	47.54	37.38
4000.00	2.54	3.18	3.18	22.43	9.90
4000.00	2.54	3.18	6.35	34.62	11.09
4000.00	2.54	3.18	6.35	26.75	11.95
4000.00	2.54	3.18	3.18	23.00	10.63
4000.00	2.54	6.35	3.18	31.98	25.28
4000.00	2.54	6.35	6.35	38.44	33.65
4000.00	2.54	6.35	3.18	27.78	8.76
4000.00	2.54	6.35	6.35	22.19	9.20
4000.00	2.54	6.35	6.35	15.50	4.85
4000.00	2.54	6.35	3.18	23.65	10.59

2.) CB1100

Table O-6: CB1100 simulated average cutting forces.

RPM	Feed [m/min]	ADOC [mm]	RDOC [mm]	Ft pred avg [N]	Fr pred avg [N]
6000.00	10.16	3.18	6.35	40.64	43.87
6000.00	10.16	3.18	3.18	33.72	32.32
6000.00	10.16	3.18	6.35	43.07	39.86
6000.00	10.16	3.18	3.18	32.83	33.28
6000.00	10.16	3.18	6.35	39.61	40.33
6000.00	10.16	3.18	3.18	35.44	37.15
6000.00	10.16	6.35	6.35	86.33	84.59
6000.00	10.16	6.35	3.18	74.49	68.30
6000.00	10.16	6.35	3.18	81.41	75.06
6000.00	10.16	6.35	6.35	90.14	90.97
6000.00	10.16	6.35	6.35	96.13	88.55
6000.00	10.16	6.35	3.18	66.87	68.70
6000.00	5.08	3.18	3.18	20.02	17.20
6000.00	5.08	3.18	6.35	20.36	21.40
6000.00	5.08	3.18	6.35	21.97	19.89
6000.00	5.08	3.18	3.18	17.97	16.13
6000.00	5.08	3.18	6.35	20.82	21.51
6000.00	5.08	3.18	3.18	17.71	16.25
6000.00	5.08	6.35	3.18	32.46	38.41
6000.00	5.08	6.35	6.35	42.20	46.88
6000.00	5.08	6.35	6.35	41.03	44.79
6000.00	5.08	6.35	3.18	30.22	36.01
6000.00	5.08	6.35	6.35	45.06	41.65
6000.00	5.08	6.35	3.18	33.93	32.00
6000.00	2.54	3.18	3.18	8.30	8.64
6000.00	2.54	3.18	6.35	10.21	11.89
6000.00	2.54	3.18	6.35	10.73	9.90
6000.00	2.54	3.18	3.18	8.22	8.78
6000.00	2.54	3.18	6.35	11.14	10.61
6000.00	2.54	3.18	3.18	8.29	7.89
6000.00	2.54	6.35	3.18	16.62	16.51
6000.00	2.54	6.35	6.35	21.47	20.59
6000.00	2.54	6.35	6.35	18.34	21.23
6000.00	2.54	6.35	3.18	16.45	18.82
6000.00	2.54	6.35	6.35	21.41	24.28
6000.00	2.54	6.35	3.18	17.05	17.45
5000.00	10.16	3.18	3.18	42.22	38.50

5000.00	10.16	3.18	6.35	57.79	52.21
5000.00	10.16	3.18	6.35	47.73	53.69
5000.00	10.16	3.18	3.18	42.27	48.57
5000.00	10.16	3.18	3.18	38.53	39.55
5000.00	10.16	3.18	6.35	48.80	52.39
5000.00	10.16	6.35	6.35	102.69	104.64
5000.00	10.16	6.35	3.18	73.38	81.24
5000.00	10.16	6.35	6.35	112.19	103.67
5000.00	10.16	6.35	3.18	79.77	84.84
5000.00	10.16	6.35	6.35	100.90	101.73
5000.00	10.16	6.35	3.18	84.87	88.13
5000.00	5.08	3.18	3.18	19.36	18.79
5000.00	5.08	3.18	6.35	26.83	23.91
5000.00	5.08	3.18	6.35	26.14	29.79
5000.00	5.08	3.18	3.18	19.88	22.18
5000.00	5.08	3.18	6.35	26.53	25.09
5000.00	5.08	3.18	3.18	19.86	20.73
5000.00	5.08	6.35	3.18	38.24	40.04
5000.00	5.08	6.35	6.35	50.29	59.49
5000.00	5.08	6.35	3.18	39.41	45.71
5000.00	5.08	6.35	6.35	53.14	53.50
5000.00	5.08	6.35	6.35	48.54	53.52
5000.00	5.08	6.35	3.18	36.18	41.90
5000.00	2.54	3.18	6.35	12.47	13.40
5000.00	2.54	3.18	3.18	10.70	9.67
5000.00	2.54	3.18	6.35	13.40	13.39
5000.00	2.54	3.18	3.18	10.62	10.47
5000.00	2.54	3.18	3.18	9.08	10.60
5000.00	2.54	3.18	6.35	12.94	14.12
5000.00	2.54	6.35	3.18	19.78	22.18
5000.00	2.54	6.35	6.35	26.46	25.00
5000.00	2.54	6.35	3.18	23.21	18.76
5000.00	2.54	6.35	6.35	26.25	27.31
5000.00	2.54	6.35	3.18	21.12	21.57
5000.00	2.54	6.35	6.35	30.96	26.23
4000.00	10.16	3.18	6.35	65.94	61.87
4000.00	10.16	3.18	3.18	50.32	52.88
4000.00	10.16	3.18	6.35	61.16	74.98
4000.00	10.16	3.18	3.18	49.53	50.85
4000.00	10.16	3.18	3.18	50.74	57.87
4000.00	10.16	3.18	6.35	61.68	60.31

4000.00	10.16	6.35	6.35	124.18	118.21
4000.00	10.16	6.35	3.18	103.23	117.82
4000.00	10.16	6.35	6.35	120.74	134.35
4000.00	10.16	6.35	3.18	104.70	104.68
4000.00	10.16	6.35	6.35	126.53	137.19
4000.00	10.16	6.35	3.18	109.46	100.54
4000.00	5.08	3.18	6.35	35.71	32.16
4000.00	5.08	3.18	3.18	28.87	24.99
4000.00	5.08	3.18	6.35	32.32	30.21
4000.00	5.08	3.18	3.18	29.34	25.68
4000.00	5.08	3.18	3.18	24.36	24.80
4000.00	5.08	3.18	6.35	30.62	32.96
4000.00	5.08	6.35	6.35	73.26	71.62
4000.00	5.08	6.35	3.18	57.47	52.70
4000.00	5.08	6.35	3.18	55.92	54.43
4000.00	5.08	6.35	6.35	60.72	66.05
4000.00	5.08	6.35	3.18	59.58	52.46
4000.00	5.08	6.35	6.35	69.05	63.54
4000.00	2.54	3.18	6.35	16.34	15.83
4000.00	2.54	3.18	3.18	13.18	13.02
4000.00	2.54	3.18	3.18	12.28	13.57
4000.00	2.54	3.18	6.35	17.39	15.83
4000.00	2.54	3.18	6.35	15.50	15.88
4000.00	2.54	3.18	3.18	12.92	14.32
4000.00	2.54	6.35	3.18	23.77	24.68
4000.00	2.54	6.35	6.35	32.75	35.69
4000.00	2.54	6.35	3.18	24.34	23.77
4000.00	2.54	6.35	6.35	31.50	30.68
4000.00	2.54	6.35	6.35	34.31	31.99
4000.00	2.54	6.35	3.18	25.34	29.55

3.) Cfoam

Table O-7: Cfoam simulated average cutting forces.

RPM	Feed [m/min]	ADOC [mm]	RDOC [mm]	Ft pred avg [N]	Fr pred avg [N]
6000.00	10.16	3.18	6.35	37.53	45.36
6000.00	10.16	3.18	3.18	20.59	35.10
6000.00	10.16	3.18	6.35	40.46	31.63
6000.00	10.16	3.18	3.18	5.33	5.53
6000.00	10.16	3.18	6.35	6.72	8.92
6000.00	10.16	3.18	3.18	23.61	26.68
6000.00	10.16	6.35	6.35	14.03	10.34
6000.00	10.16	6.35	3.18	8.90	6.41
6000.00	10.16	6.35	3.18	8.29	9.53
6000.00	10.16	6.35	6.35	6.08	6.08
6000.00	10.16	6.35	6.35	20.82	25.36
6000.00	10.16	6.35	3.18	14.46	14.47
6000.00	5.08	3.18	3.18	13.26	12.66
6000.00	5.08	3.18	6.35	6.12	6.53
6000.00	5.08	3.18	6.35	9.49	11.48
6000.00	5.08	3.18	3.18	25.43	18.29
6000.00	5.08	3.18	6.35	18.80	10.27
6000.00	5.08	3.18	3.18	12.55	15.46
6000.00	5.08	6.35	3.18	19.66	15.49
6000.00	5.08	6.35	6.35	6.54	5.82
6000.00	5.08	6.35	6.35	13.32	10.81
6000.00	5.08	6.35	3.18	17.27	11.82
6000.00	5.08	6.35	6.35	8.37	6.11
6000.00	5.08	6.35	3.18	34.70	38.77
6000.00	2.54	3.18	3.18	5.33	5.70
6000.00	2.54	3.18	6.35	20.25	14.45
6000.00	2.54	3.18	6.35	7.32	17.96
6000.00	2.54	3.18	3.18	13.63	14.14
6000.00	2.54	3.18	6.35	18.86	19.63
6000.00	2.54	3.18	3.18	23.76	18.43
6000.00	2.54	6.35	3.18	7.06	6.39
6000.00	2.54	6.35	6.35	17.86	8.85
6000.00	2.54	6.35	6.35	20.85	14.45
6000.00	2.54	6.35	3.18	18.03	19.14
6000.00	2.54	6.35	6.35	11.29	9.44
6000.00	2.54	6.35	3.18	24.74	16.99
5000.00	10.16	3.18	3.18	10.50	12.93

5000.00	10.16	3.18	6.35	8.26	8.69
5000.00	10.16	3.18	6.35	20.57	13.70
5000.00	10.16	3.18	3.18	8.54	8.87
5000.00	10.16	3.18	3.18	5.66	8.03
5000.00	10.16	3.18	6.35	16.21	12.01
5000.00	10.16	6.35	6.35	15.68	24.37
5000.00	10.16	6.35	3.18	9.57	11.20
5000.00	10.16	6.35	6.35	6.98	7.91
5000.00	10.16	6.35	3.18	8.45	8.94
5000.00	10.16	6.35	6.35	9.02	15.12
5000.00	10.16	6.35	3.18	42.04	40.00
5000.00	5.08	3.18	3.18	8.70	8.63
5000.00	5.08	3.18	6.35	14.32	11.27
5000.00	5.08	3.18	6.35	5.95	6.69
5000.00	5.08	3.18	3.18	8.48	8.42
5000.00	5.08	3.18	6.35	19.52	14.09
5000.00	5.08	3.18	3.18	8.09	8.04
5000.00	5.08	6.35	3.18	43.48	41.54
5000.00	5.08	6.35	6.35	14.03	17.13
5000.00	5.08	6.35	3.18	15.43	15.32
5000.00	5.08	6.35	6.35	5.42	5.89
5000.00	5.08	6.35	6.35	13.00	15.39
5000.00	5.08	6.35	3.18	28.03	30.38
5000.00	2.54	3.18	6.35	18.09	20.25
5000.00	2.54	3.18	3.18	30.44	26.61
5000.00	2.54	3.18	6.35	23.60	31.65
5000.00	2.54	3.18	3.18	20.29	17.91
5000.00	2.54	3.18	3.18	12.06	6.82
5000.00	2.54	3.18	6.35	19.63	16.97
5000.00	2.54	6.35	3.18	8.82	9.39
5000.00	2.54	6.35	6.35	4.53	4.50
5000.00	2.54	6.35	3.18	17.32	11.38
5000.00	2.54	6.35	6.35	6.50	5.61
5000.00	2.54	6.35	3.18	8.89	8.75
5000.00	2.54	6.35	6.35	24.94	26.77
4000.00	10.16	3.18	6.35	47.82	49.82
4000.00	10.16	3.18	3.18	11.23	14.30
4000.00	10.16	3.18	6.35	8.49	12.54
4000.00	10.16	3.18	3.18	28.06	40.68
4000.00	10.16	3.18	3.18	20.81	30.80
4000.00	10.16	3.18	6.35	19.41	26.29

4000.00	10.16	6.35	6.35	9.38	12.15
4000.00	10.16	6.35	3.18	6.12	12.09
4000.00	10.16	6.35	6.35	8.48	13.46
4000.00	10.16	6.35	3.18	50.83	29.02
4000.00	10.16	6.35	6.35	5.03	8.50
4000.00	10.16	6.35	3.18	5.25	8.06
4000.00	5.08	3.18	6.35	15.91	12.20
4000.00	5.08	3.18	3.18	13.23	18.34
4000.00	5.08	3.18	6.35	30.64	27.91
4000.00	5.08	3.18	3.18	12.81	34.66
4000.00	5.08	3.18	3.18	29.56	28.63
4000.00	5.08	3.18	6.35	10.45	12.21
4000.00	5.08	6.35	6.35	6.09	7.71
4000.00	5.08	6.35	3.18	12.11	24.06
4000.00	5.08	6.35	3.18	10.41	12.04
4000.00	5.08	6.35	6.35	3.55	6.69
4000.00	5.08	6.35	3.18	11.39	10.67
4000.00	5.08	6.35	6.35	10.86	16.20
4000.00	2.54	3.18	6.35	3.25	5.33
4000.00	2.54	3.18	3.18	7.21	11.00
4000.00	2.54	3.18	3.18	5.77	8.76
4000.00	2.54	3.18	6.35	2.40	5.42
4000.00	2.54	3.18	6.35	20.06	18.46
4000.00	2.54	3.18	3.18	3.68	7.69
4000.00	2.54	6.35	3.18	8.18	13.06
4000.00	2.54	6.35	6.35	2.64	4.69
4000.00	2.54	6.35	3.18	28.38	21.27
4000.00	2.54	6.35	6.35	13.19	18.86
4000.00	2.54	6.35	6.35	4.00	6.31
4000.00	2.54	6.35	3.18	16.35	11.71

Appendix: P. 9123C Rotating dynamometer testing using an aluminum workpiece.

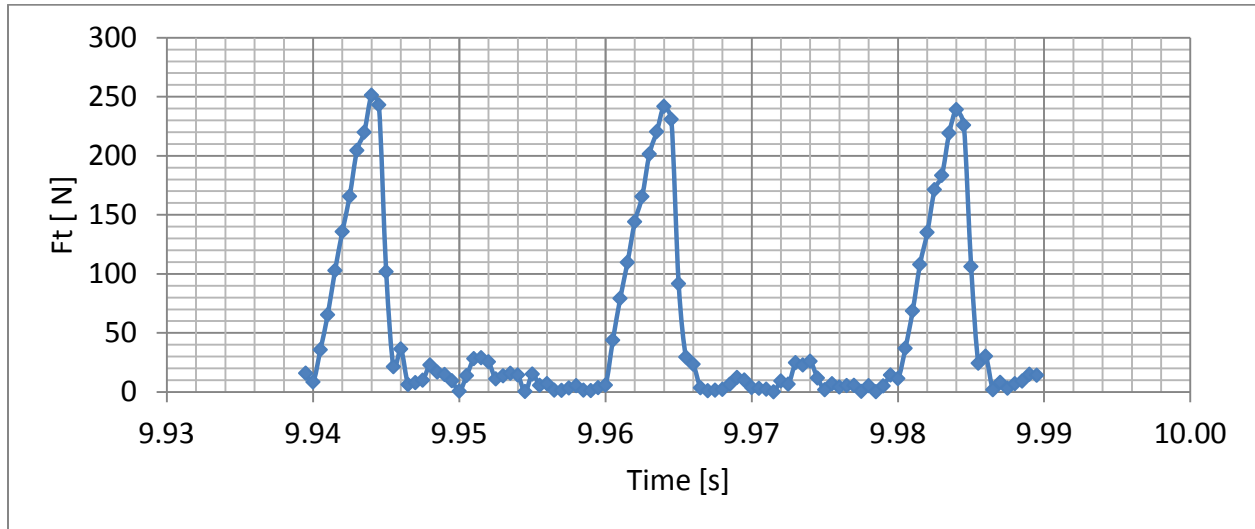


Figure P-470: Tangential cutting force in 6061-T6 aluminum at 3000 RPM.

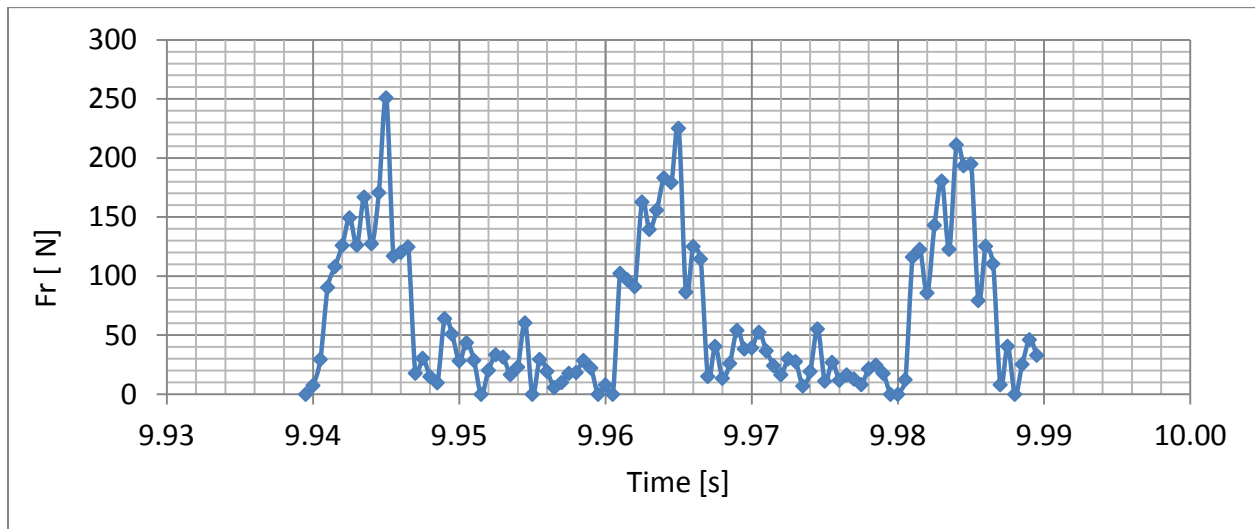


Figure P-471: Tangential cutting force in 6061-T6 aluminum at 3000 RPM.

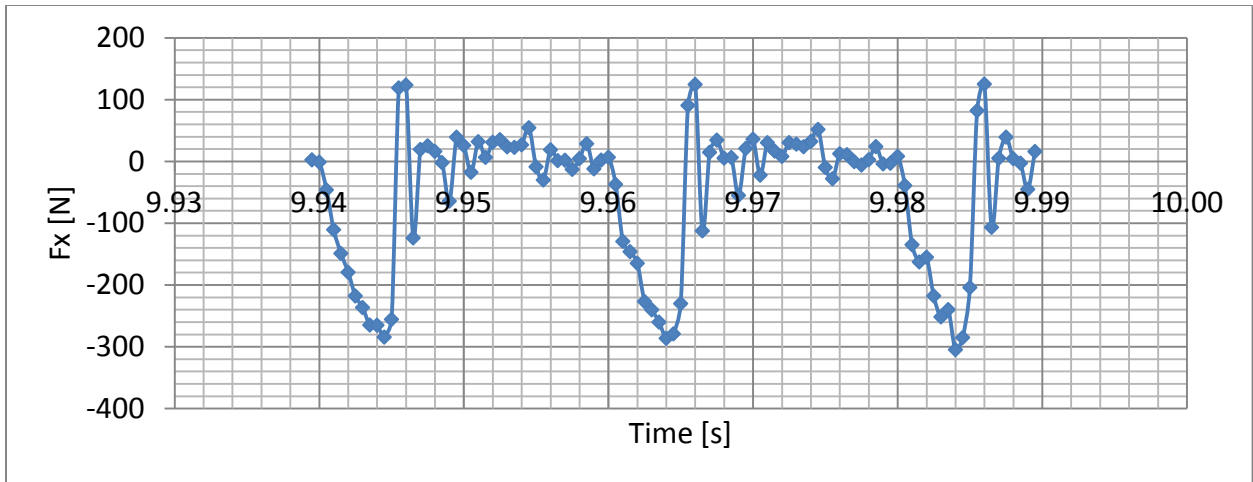


Figure P-472: Cutting force in the X direction in 6061-T6 aluminum at 3000 RPM.

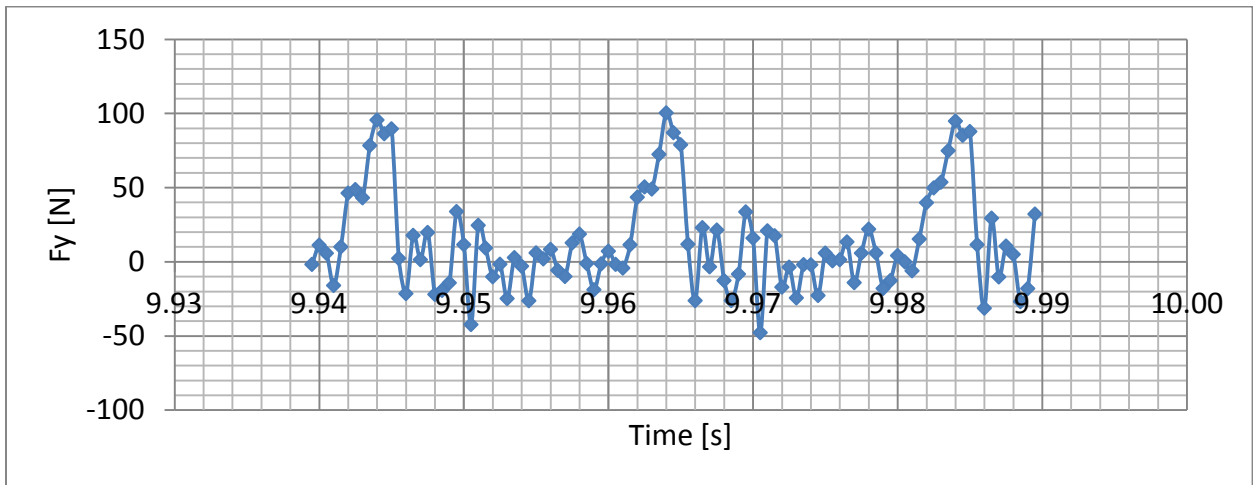


Figure P-473: Cutting force in the Y direction in 6061-T6 aluminum at 3000 RPM.

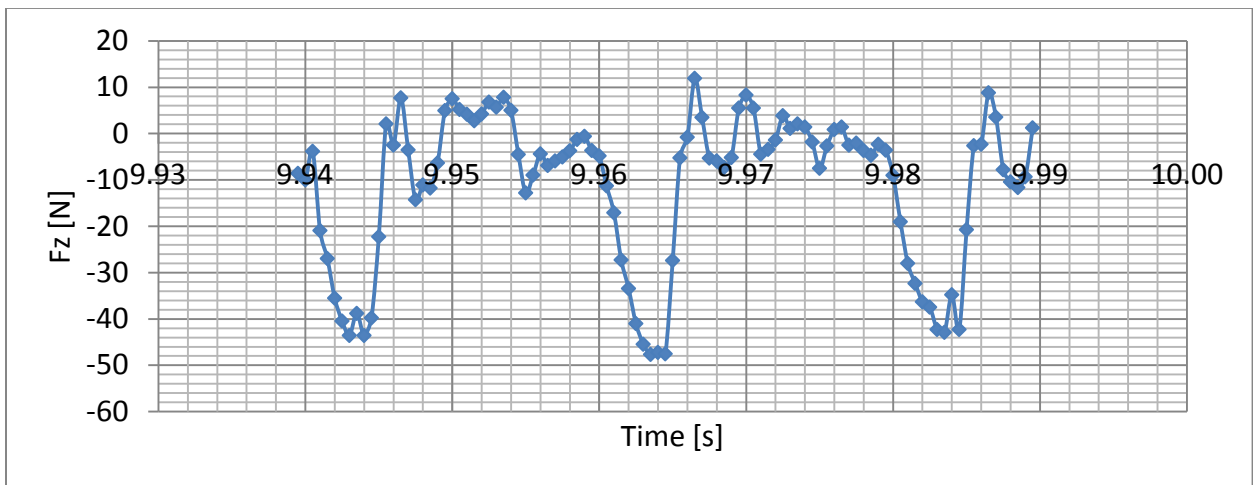


Figure P-474: Axial cutting force in 6061-T6 aluminum at 3000 RPM.

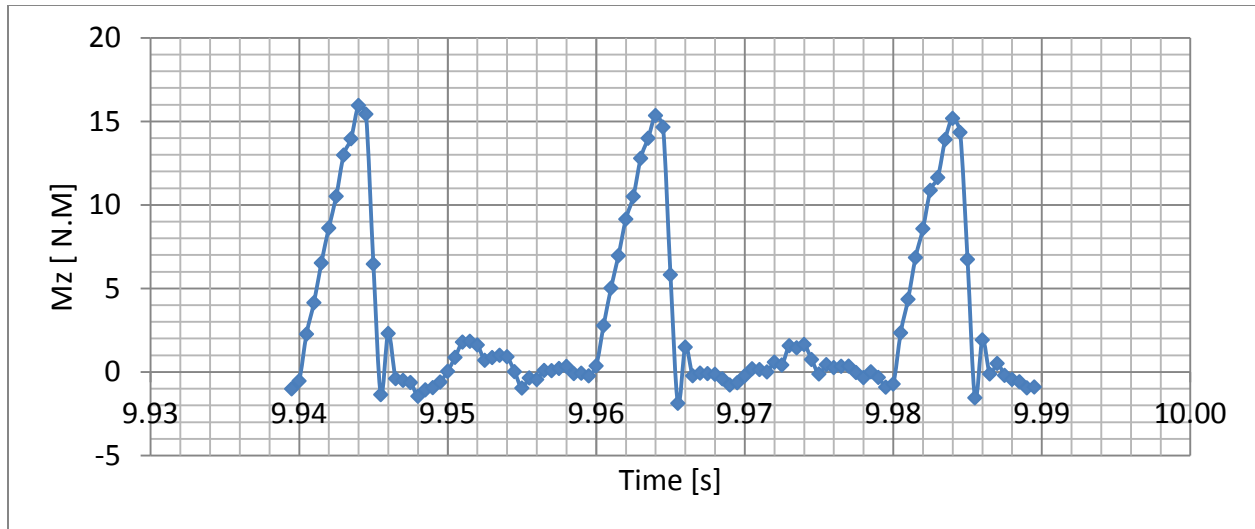


Figure P-475: Cutting torque in 6061-T6 aluminum at 3000 RPM

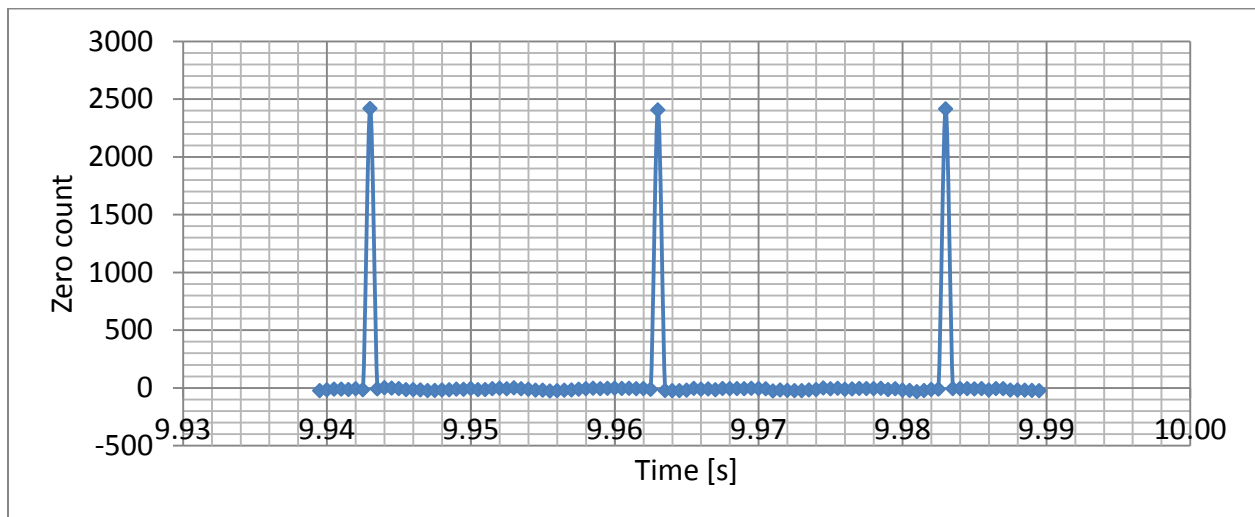


Figure P-476: 9123C dynamometer zero-count signal at 3000 RPM

Appendix: Q. Testing and specimen images



Figure Q-477: Horizontal bandsaw cutting CB1100 blocks



Figure Q-478: Horizontal bandsaw cutting CB1100 blocks



Figure Q-479: Horizontal bandsaw cutting CB1100 blocks



Figure Q-480: Horizontal bandsaw cutting CB1100 blocks

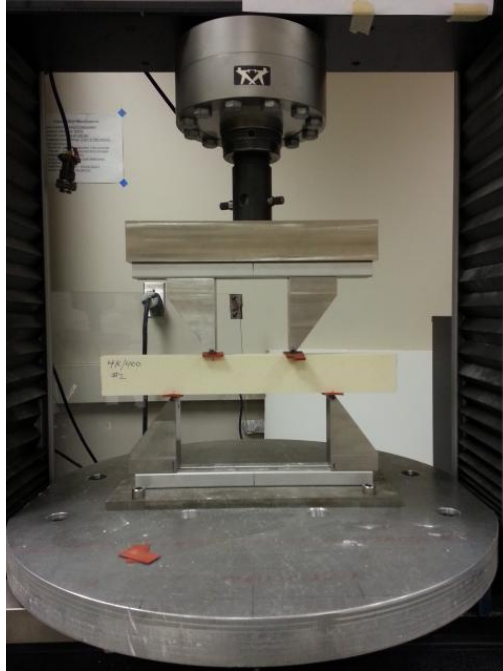


Figure Q-481: CB1100 four point bend specimen in fixture.

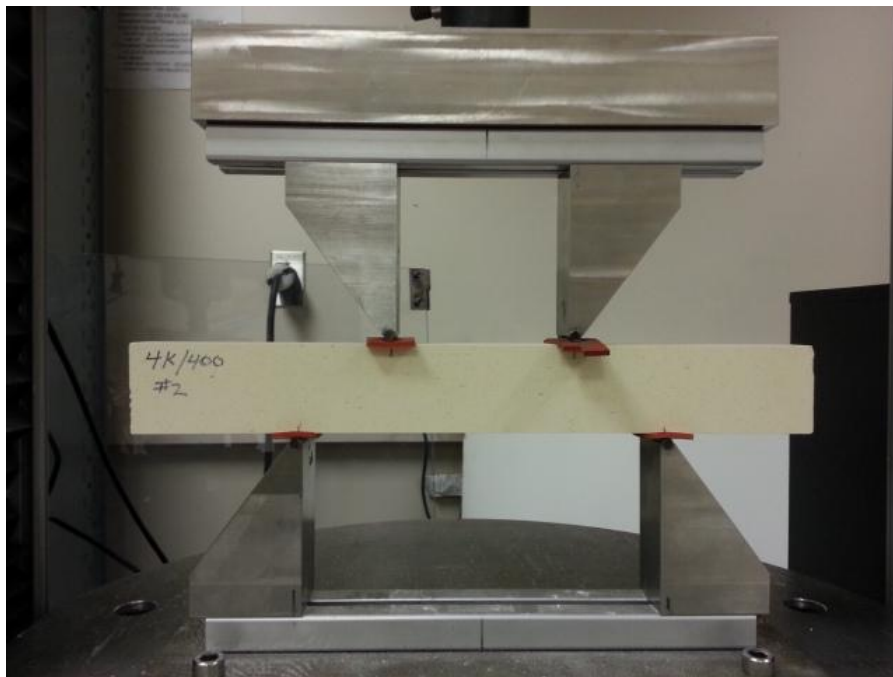


Figure Q-482: CB1100 four point bend specimen in fixture.



Figure Q-483: CB1100 four point bend specimen in fixture.

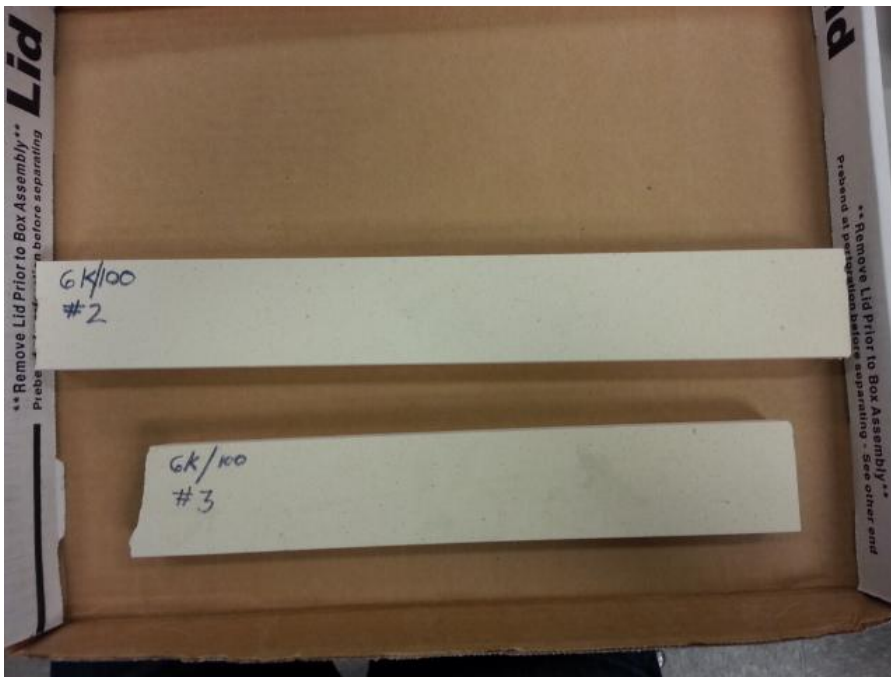


Figure Q-484: CB1100 four point bend specimens.



Figure Q-485: CB1100 surface roughness sample.



Figure Q-486: CB1100 surface roughness sample.



Figure Q-487: CB1100 surface roughness sample.

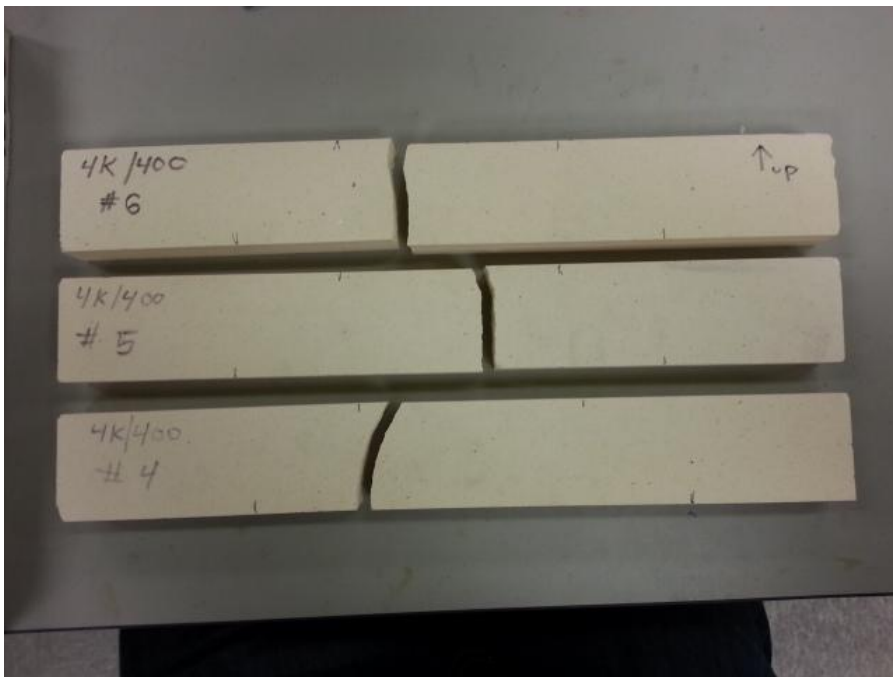


Figure Q-488: Fractured CB1100 four point bend specimens.

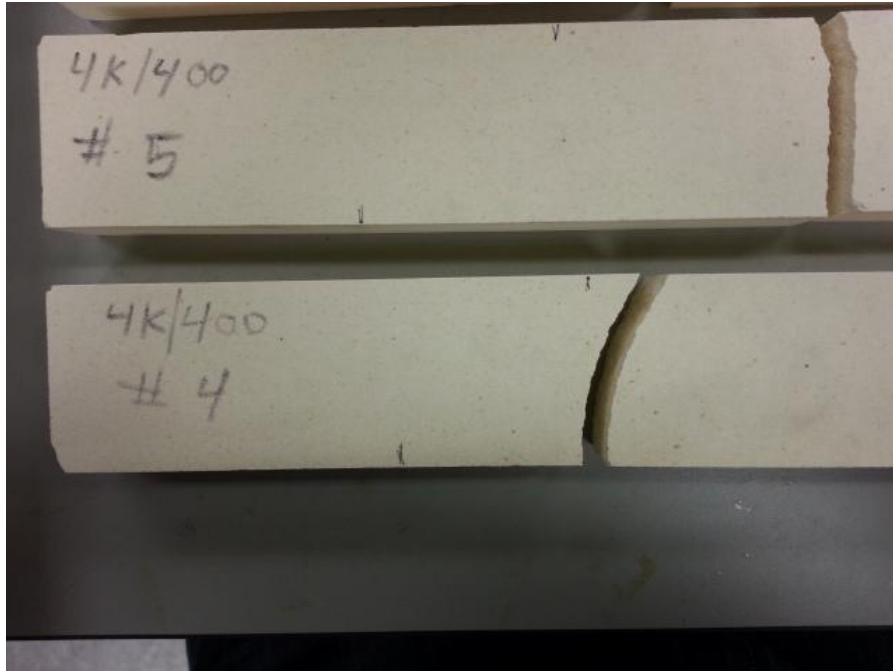


Figure Q-489: Fractured CB1100 four point bend specimens.

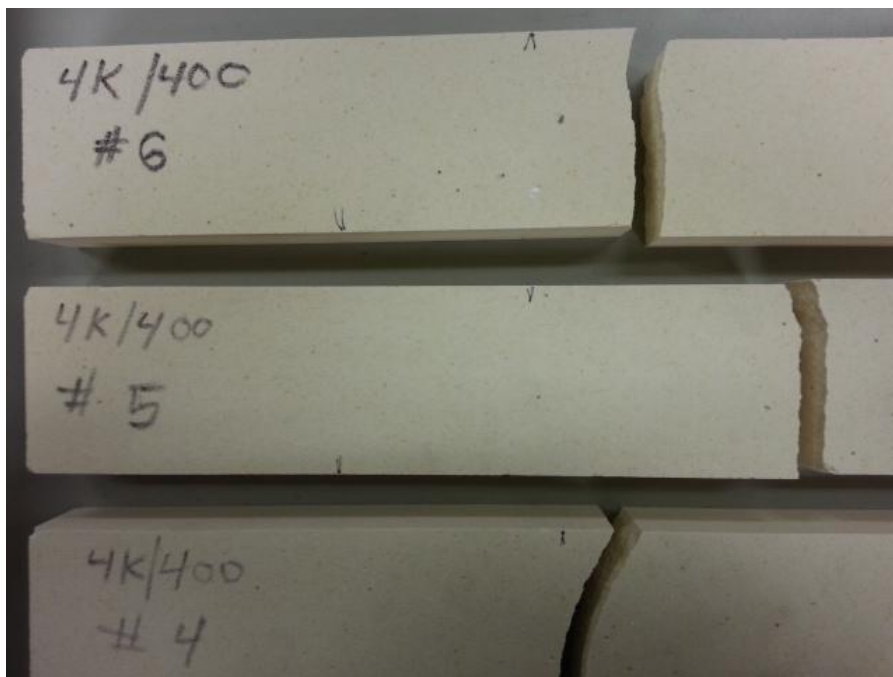


Figure Q-490: Fractured CB1100 four point bend specimens.



Figure Q-491: Fractured CB1100 four point bend specimens.

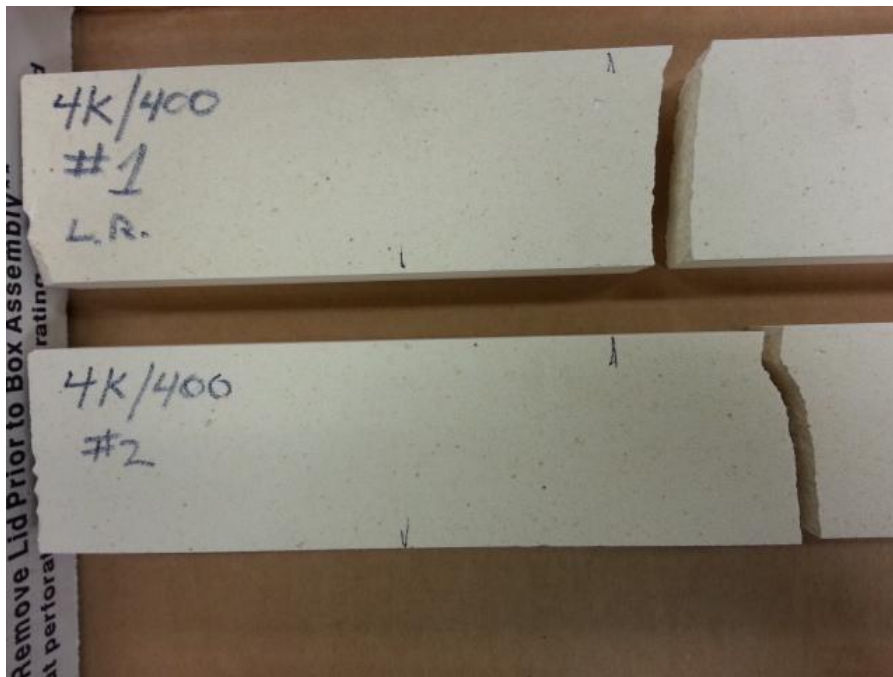


Figure Q-492: Fractured CB1100 four point bend specimens.



Figure Q-493: Fractured AAC four point bend specimen.



Figure Q-494: Fractured AAC four point bend specimen.



Figure Q-495: Fractured AAC four point bend specimen.



Figure Q-496: AAC four point bend specimen.



Figure Q-497: AAC four point bend specimen.



Figure Q-498: Photo image of bonding line in Cfoam.



Figure Q-499: Fractured Cfoam four point bend specimens.

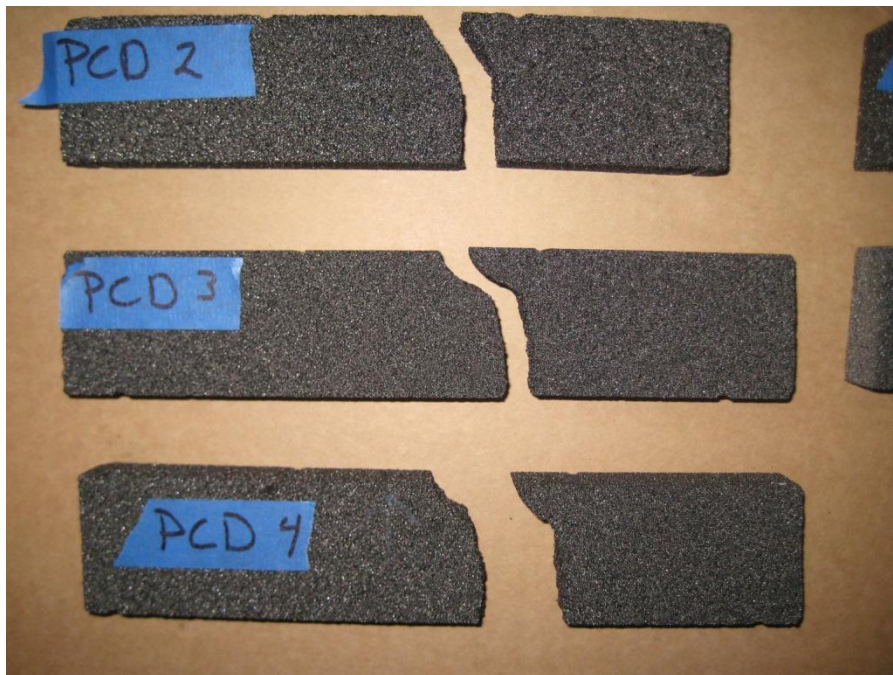


Figure Q-500: Fractured Cfoam four point bend specimens

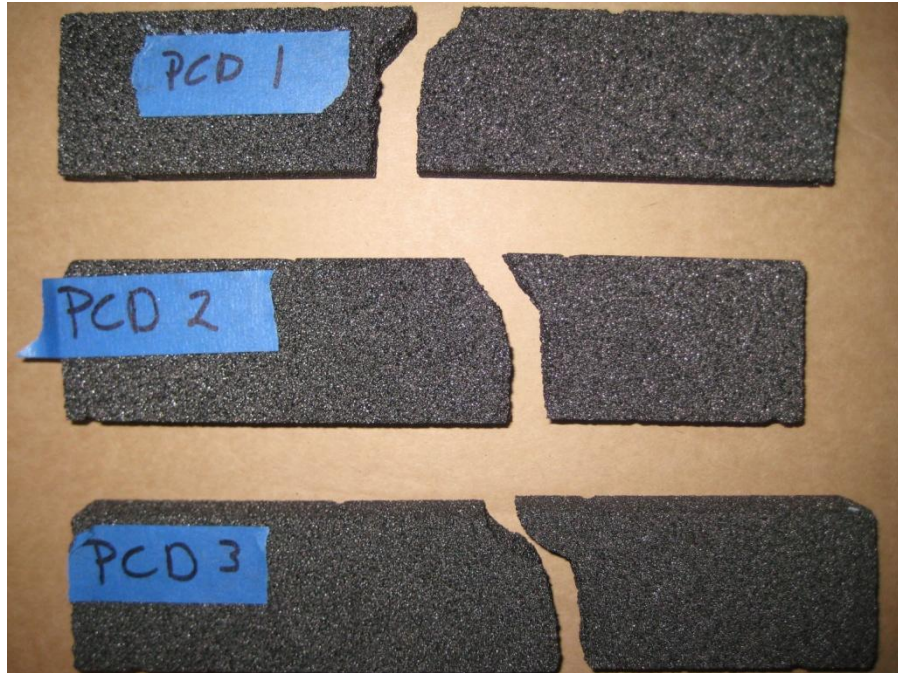


Figure Q-501: Fractured Cfoam four point bend specimens.



Figure Q-502: Fractured Cfoam four point bend specimens.

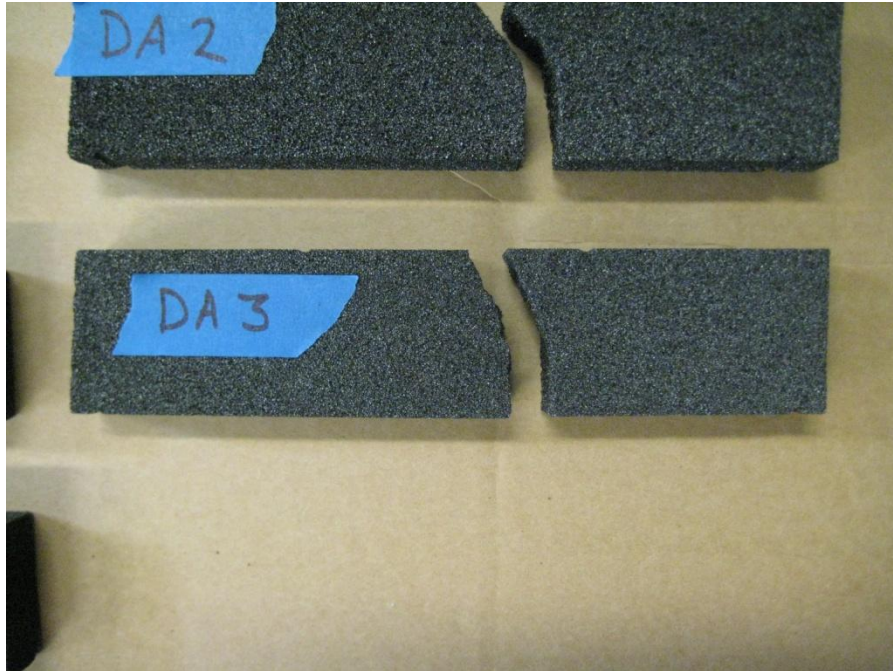


Figure Q-503: Fractured Cfoam four point bend specimens.

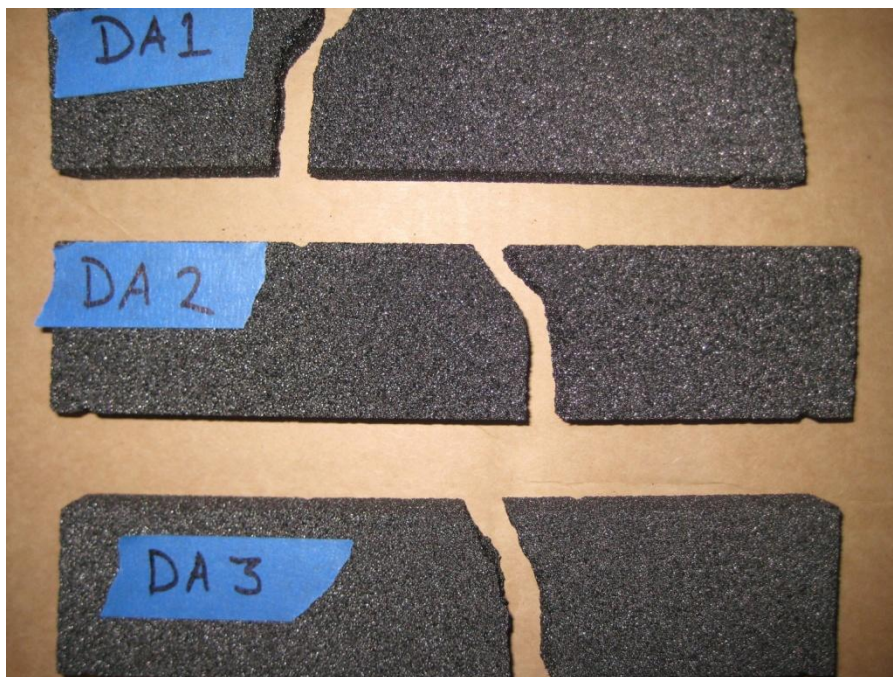


Figure Q-504: Fractured Cfoam four point bend specimens.



Figure Q-505: Photo image of Cfoam four point bend testing.

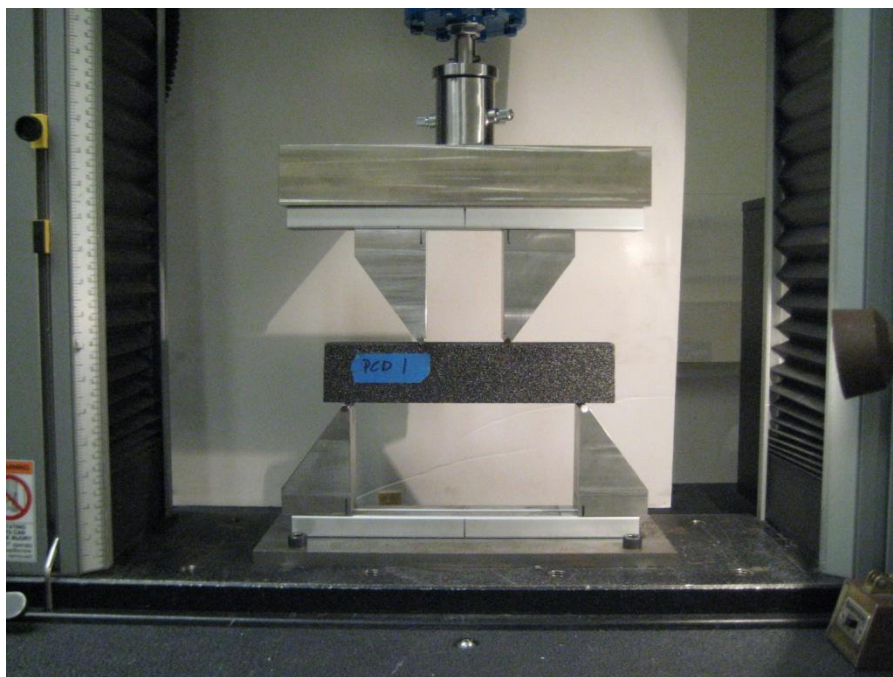


Figure Q-506: Photo image of Cfoam four point bend testing.