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Metallic alloys used in implants

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Abstract

Metal alloys made from titanium, zinc, copper, and cobalt-chromium-molybdenum used in medical implants are investigated in helping resolve post-treatment complications such as corrosion, bone resorption, and toxicity due to the body's response to foreign materials. Multiple tests have been done to measure the limits of their mechanical properties such as corrosion resistance, rates, flexibility, and strength. Mechanical testing and finite element method are used to determine the ideal porosity that maintains titanium's mechanical strength but lowers its elastic modulus. Zinc-copper alloys underwent electrochemical and cytotoxicity tests to evaluate its corrosion behavior and toxicity. Tribocorrosion resistance of cobalt-chromium-molybdenum alloys were tested under different conditions. Metal implants are significantly improved in terms of strength and compatibility to help resolve implant complications by including special additives, alloying, and carburizing. However, more research must be done on these materials to ensure optimal quality and functionality to continue improving modern transplant operations.

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1. Introduction

Transplants are one of the most common type of surgical procedures, especially for bone fractures, bone tissue related problems, and bone replacement surgeries. However, the materials used within these procedures still pose risks post-treatment for patients due to loosening of the metals to the bone and complications surrounding degradation of the implant. Studies have been conducted on how to address these issues by further improving the metals through thermal processes to help enhance their beneficial qualities and to change the properties limiting their functionality. Titanium, or more specifically commercially pure titanium (cpTi), is the most common metallic material used for implant procedures, but due to its high elastic modulus, it promotes stress-shielding, which increases bone resorption, causing the overall bone density to decrease while healing [1]. Zinc by itself has great corrosion resistance and biocompatibility, but due to its unsuitable mechanical properties, it must be alloyed with a metal such as copper to make up for its lack in strength [4]. Cobalt-based alloys, have good corrosion and wear resistance, however, they cause tribocorrosion within the body over time and create issues such as toxicity, brain impairment, and aseptic loosening [5]. Therefore, cobalt-chromium-molybdenum (CoCrMo) alloy characterization will help improve the understanding of their corrosion resistance properties. These studies will help aid future developments of implant materials to decrease the risks of complications post-treatment and the need for additional operations to address these issues.

2. Discussion and Observation

2.1. Porous Commercially Pure Titanium (cpTi)

The bioinert response, or the ability to not react with a body host, and biomechanical behavior of commercially pure titanium (cpTi) has made it become the most ideal metal used for bone. A flaw that continues to persist when using cpTi is that it has a high elastic modulus leading to stress shielding, which prevents tissue from being exposed to normal levels of mechanical loading. Stress shielding by cpTi results in bone resorption by the body leading to a decrease in bone density [1]. On the influence of the space holder technique used in obtaining porous titanium material, Munoz et al. investigates methods to create a more porous cpTi used for bone replacement with low elastic modulus [1].

Throughout the study, multiple tests have been conducted to obtain the best form of porous titanium. In the first part, they analyze the influence of the space-holder technique, which is mixing metal powder with special additive to be removed before sintering to obtain 30, 40, 50, 60, and 70 vol% space-holder concentration [1]. The additive used was ammonium bicarbonate, which was mixed with cpTi powder, compressed into a die, and sintered. The different vol% concentrations correspond to 28, 37, 47, 57, and 66% total porosity. Porosity was obtained using Archimedes' method. Observation and comparison were made through image analysis, which also proved that total porosity would be lower than space-holder content. Mechanical properties were also observed using a compression tester. The researchers used compression testing to calculate the Young's modulus as strain was applied. Although the calculation of the modulus with varying porosities is still being evaluated due to its differing results, it had shown from the data that an increase in the space-holder concentration lead to a reduction in Young's modulus as well as yield strength. Also, when using a finite element model, it was observed that the mechanical properties of the material were more significant with the presence of bigger pores [1].

In conclusion on this research, significant trends were difficult to determine when analyzing titanium material modified with different porosities. The varying porosities still had a wide range of different elastic moduli and yield strength. From the FE models, stress distributions have been noted to be efficiently different with different porosity levels until it reaches a certain high porosity due to increasing pore coalescence. Biological and cross-sectional analysis were also investigated to finding the ideal porosity of titanium [1]. Cell adhesion was also observed to have improved from moderate to high space holder concentrations (40-50 vol%), but not at 60 and 70 vol%.

Finally, from the cross-sectional analysis, depending on the bone, the 37% (for cortical bone replacement) and 47% (for trabecular bone, are the most ideal options for replacing cpTi due to their results on maintaining their high mechanical strength and showing a low enough elastic modulus. The results from mechanically testing the 37% and 47% porosity prove that the specimen is able to endure a significant amount of stress as it is being strained. Although these conclusions were made, testing for more porous titanium materials is continuing with different additives as well as further analysis methods [1].

2.2. Zinc-Copper Alloys

P. Li et al. investigates the potential of zinc-copper alloys to be used for craniomaxillofacial osteosynthesis implants. Craniomaxillofacial is the anatomical description of parts relating to the area of the mouth, jaws, face, and skull and osteosynthesis is a type of implant procedure that stabilizes fractured bones with metal plates, pins, rods, or screws [2,3]. Although titanium is still the most superior material used for implants due to its biocompatibility and mechanical strength, the metal still has complications including infection, foreign body host response, and bone resorption, which could create postoperative complications for the patient [4]. By developing a material for an absorbable osteosynthesis system, long term complications relating to the implants could be prevented. Therefore, many researchers have been looking at polymers or metal alloys to provide absorbable properties, a slow corrosion rate, and a high mechanical performance. However, results have been negative upon researching polymers and magnesium alloys to replace titanium, but zinc-based alloys have proved to have potential in replacing titanium regarding their desirable corrosion behavior [4]. Unlike the magnesium alloys, zinc does not accumulate hydrogen and is safely metabolized and tolerated by the body proving great biocompatibility. The downside of using zinc alone is that it does not have satisfactory mechanical properties, therefore it is not suitable to use for clinical applications [4]. To improve this issue, when zinc is alloyed it can prove to be much stronger, therefore copper has been chosen to pair alongside it since it significantly enhances the mechanical properties of the pure zinc.

The relevant experiments that have been done to ensure the potential of the zinc-copper alloys as transplant material are tensile tests, immersion test, cytotoxicity tests, which evaluates the potential of the alloy being toxic to cells, and in vitro antibacterial test. The alloys used in experimentation varied in weight percentages created from rolling. The tensile tests observed the tensile mechanical properties whereas the immersion test observed the corrosion behavior of both zinc and its alloys.

From these tests, it had proved that after rolling, the zinc-copper alloy had increased significantly in its mechanical properties and fine grains of zinc were formed, which can be proven from the figure as the rolled alloys are able to withstand enough plastic deformation before fracture. The corrosion rate did not increase, nor did it increase with the addition of copper to zinc, but there was a uniform mode of corrosion. For the cells tested with the alloys to show any cytotoxic effects, the zinc copper alloys proved to show no apparent toxic response. This could have resulted based on the low concentration of zinc ions during the extracts, therefore increasing its cell tolerance [4]. From the antibacterial tests, the alloys showed to hinder the potential formation of mixed oral bacteria with increased copper incorporated in the alloy. However, the results for the antibacterial tests are quite insufficient, therefore more research must be done to provide stronger evidence that the zinc-copper alloy can withstand the bacteria. Besides the in vitro test, rolled zinc-copper alloys show great potential in being used for craniomaxillofacial osteosynthesis implants, but more testing on the material should be made.

2.3. Cobalt-Chromium-Molybdenum (CoCrMo) Alloys

To resolve the tribocorrosion consequences caused from Cobalt-based implants, research by J. Cassar et. al. has been done on Cobalt-Chromium-Molybdenum (CoCrMo) alloys to improve its resistance through the diffusion treatment, carburizing. The process of carburizing introduces a super

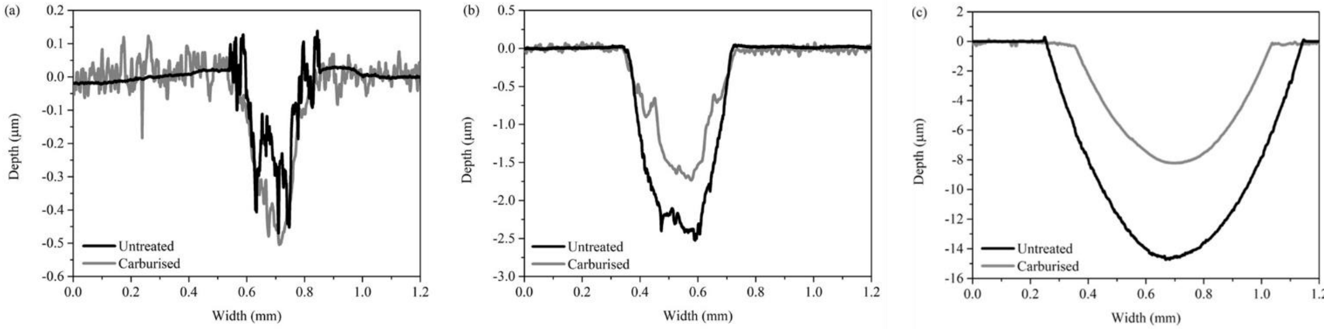

Figure 1. Scar profiles on disc samples for tribocorrosion tests [7]. (a) Sample under cathodic potential, (b) under OCP, (c) under passive potential.

saturated carbon solution known as the S phase, or expanded austenite, that supposedly hardens and augments the corrosion-wear resistance of the alloy to enhance its mechanical strength without being detrimental to its corrosion resistance and biocompatibility [7]. CoCrMo is a common alloy used for orthopedic impacts such as hip implants due to their corrosion and wear properties. However, it has been noted that while these alloys hold these properties, many patients have experienced post-treatment consequences such as toxicity in their body, neurological impairment, and aseptic loosing, which is the "failure of the bond between the implant and bone in the absence of infection" [5]. These are all due to detrimental corrosion and tribocorrosion damage caused by the transplants. Tribocorrosion is the degradation of materials due to mechanical and chemical/electrochemical interactions between surfaces resulting in an irreversible transformation of materials or their functions [6].

Although both samples received scar marks, the scars on the carburized sample were significantly less deep than the scars created on the untreated samples. It can be seen clearly (**Figure 1**) in the OCP and passive potential conditions, that the carburized samples had less deep and wide scars than the untreated samples. In one test, the scar on the carburized sample was not even deep enough to pierce through the S-phase layer. When analyzed under a Scanning Electron Microscope (SEM), it had shown that the abrasion marks were also less evident in the carburized sample than the untreated sample, showing minimal damage and a smooth surface layer. The volumetric losses correspond with the depths of the scars proving that the average material loss from the untreated sample is a lot higher in comparison to the carburized sample [7]. The process of carburizing the alloy had shown positive results in resistance to both wear-enhanced corrosion and corrosion enhanced wear.

From these results, we can conclude the positive impact the carburizing treatment does for CoCrMo alloys. Due to its effect on increasing the hardness of the specimen, it resulted in lower material loss and yielded lower abrasion losses as well. It also shows that tribocorrosion and volumetric losses in both equilibrium and passive potential conditions are also lowered conveying an improvement in resistance to corrosion-wear, one of the main contributors to material loss [7]. This concluding that with the carburizing of CoCrMo alloy, a more preferred transplant material is created to prevent tribocorrosion due to its improvement in hardness.

3. Conclusions

Based off these studies, we can determine that by modifying titanium, zinc, and cobalt metals, improved alloys are developed to help relieve existing post-operative issues from implant procedures. The space holder technique helped to find the ideal porosity in titanium to lower the elastic modulus and maintain the existing mechanical strength. Through this process, a solution was obtained in resolving bone resorption and stress shielding issues following the surgical procedure. Alloying zinc and copper gave an alloy that shows optimal qualities within corrosion resistance that may one day replace titanium as the most suitable transplant material. Finally, providing cobalt-chromium-molybdenum (CoCrMo) alloys that underwent carburizing has contributed in improvements in resistance to corrosion-wear of the implant material. All of these in development metallic alloys have proven to be promising in improving implant surgical procedures. These tests have proved each of their mechanical strengths, highlighting how both the zinc-copper alloy and the CoCrMo alloy have great responses to corrosion. Although these conclusions have supported the idea of progressions within transplant materials, more research must be done to prove these findings. We learn that the characterization of these materials may help aid future development of more suitable materials used in transplant surgeries and that complications that arise may decline from the tests made in the studies.

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Conflict of Interest

The author has no conflict of interest

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