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Materials in nuclear energy applications

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Abstract

Nuclear energy is growing in importance as a form of clean energy, and many of the limiting factors for its development are materials based. There is a need for materials that can make reactor components that are resilient to extreme environments. This review article highlights multiple studies regarding the state of materials development for nuclear energy. Among the topics discussed are tritium production and how it causes failure, methods of simulating component damage, thermomechanical properties of multi-principal element alloys, and corrosion resistance of nickel alloys. Simulations involving the conditions found in fast and fusion reactors show that fast neutrons cause much shallower and more uniform damage compared to the heavier ions found in fusion reactors. Another important finding is that nickel-based alloys have much higher corrosion resistance than steels, and higher nickel content in these alloys translates to higher resistance.

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1. Introduction

Nuclear energy is a growing area of research as alternatives to fossil fuels become more necessary. While nuclear energy is not defined as a renewable energy source, it is among the least environmentally impactful sources of energy. The only hazardous output of the reactors is spent nuclear fuel, which is contained and able to be stored. This means nuclear energy has virtually zero impact on the environment, making it one of the most important areas of research and development. The largest obstacle for the development of this technology is the ability of components within the reactors to handle extreme environments. This is why materials must be developed with these various parameters in mind. Articles discussed in this paper cover obstacles and evaluation regarding materials used in the structural components of reactors as well as storage of spent nuclear fuel. Multiple types of nuclear reactors are addressed by these articles, including fast neutron reactors, molten salt reactors, and traditional fusion reactors. The advancement of nuclear energy is driven by the development of structural materials that have minimal reactivity with fuels, controllable thermomechanical properties, and limited corrosion under volatile conditions.

2. Interactions between components and fuel

Tritium can react with structural materials, either leaking from the reactor or creating hydrides that can affect the mechanical properties of the vessel. Tritium forms in both fuels and structural materials as a result of the nuclear reactivity within the tank. In fast reactors tritium is much more prevalent than in other types of reactors. According to an article from *Atomic Energy*, tritium levels were monitored for fuel tanks using zirconium and steel alloy components. In the zirconium alloy (Zircaloy) up to 99% of the tritium was contained within the fuel compartment [1]. This was attributed the oxide layer on the inner surface of the zirconium alloy. On the other hand, tritium was able to diffuse through vessels using steel alloys. In this study, about 95% of the tritium either completely diffused through the steel into the coolant or formed hydrides within the steel [1]. This can be very hazardous as steel components may be leading to the leakage of reactive particles. The formation of hydrides is also cause for concern as it greatly reduced the strength of the steel.

A method of analyzing the possible damage to structural materials by neutrons in reactors has been developed at the Kurchatov Institute. This method involves high energy neutrons being accelerated at tungsten to simulate damage that could occur to structural materials [2]. The interaction between the accelerated particles and structural materials was seen as displacement of atoms within the lattice, causing defects that could lead to failure. This study showed that neutrons cause shallower, more uniform damage compared to the heavier ions that are typically seen in fusion reactors [2]. This could support the development of fast neutron reactors over other types.

An unexpected issue that occurs in fast reactors is the reaction between debris formed in the fuel and the inner walls of the fuel tank. Boron carbide can form within the fuel and precipitate out. As this debris collects on the bottom of the tank, it can have a eutectic reaction with stainless steel structural materials. Reactors typically operate at temperatures below the melting temperature of stainless steel, but the product of this reaction is much weaker than stainless steel at these temperatures. This study found that the rate of formation is a function of temperature, size of debris particles, and pressure [3]. These factors all affect the rate of diffusion of the boron carbide into the stainless steel. Identifying this rate can help scientists predict when the vessels need to be cleaned or replaced to prevent failure and improve longevity of reactors.

3. Thermomechanical properties of reactor materials

Multi-principal element alloys are studied for their ability to maintain their mechanical properties at a wide range of temperatures. The alloy studied was composed of iron, titanium, chromium, vanadium, and tungsten, and was compared before and after a homogenization treatment [4]. Prior to the treatment, it did not have desirable properties, as there were many defects within various lattices of different elements. After homogenization, the alloy a had much more isotropic response to temperature change, and less phase transformation across high temperatures [4]. This is desirable for an alloy to be used in reactors, as they will experience very high temperatures as well as relatively low temperatures. Materials with this type of response have very few changes in mechanical properties with temperature.

The dependence of mechanical properties on the rate of heating and cooling is also important. Different alloys may undergo phase transformations during heating and cooling, and a study on commonly used materials show how properties may change. Stainless steel, grade 91 steel, and nickel-based alloys were evaluated, and temperature rate constants were found to aid in computational models. These models are used to predict the viscoelastic response of these alloys to different temperature differentials [5]. The models that were designed operate as a function of strain rate and temperature. This allows parameters for temperature and heating rates to be evaluated safely without taking the risks of testing on actual reactors.

4. Corrosion and methods of prevention

Nickel alloys are very common in molten salt reactors, which have highly corrosive fuel. The corrosive effect that fluoride based molten salt fuels have on these alloys is studied in multiple ways. Total loss of mass after being suspended in molten fluoride salt is used to characterize three nickel-based alloys; Inconel 718, Inconel C-276, and Nimonic 80A. Nimonic had the highest resistance to corrosion. This was attributed to the high nickel and chromium content [6]. Another study compares three more nickel-based alloys; HASTELLOY-N, GH3535 and MONICR. After being suspended in molten fluoride salt, these alloys were evaluated in more ways than just loss of mass. The main aspects investigated were grain size, carbide presence, and high angle grain boundaries. It was determined that MONICR had the highest corrosion resistance also due to its high nickel and chromium content, as well as its microstructure [7]. This alloy had the largest grain size, leading to less corrosion along grain boundaries. The presence of carbides also limited the diffusion of corrosive salts through the alloys.

Corrosion can be prevented by using certain surface treatments. Radio frequency plasma nitriding is used on stainless steel components to give them more corrosion resistant surfaces. Stainless steel alloys were compared with and without plasma nitriding, and the treated steels performed better in all the tests [8]. Among these tests were surface microhardness, fracture resistance, and neutron shielding. It was concluded that plasma nitriding improved these properties by increasing surface energy with the presence of nitrides within the lattice. This makes it harder for corrosive compounds like nuclear fuel to break down the surface.

5. Storage of spent nuclear fuel

Disposal of nuclear waste is arguably the most important aspect of developing better nuclear energy. The materials used as cladding in the storage of spent fuel must be able to resists exposure to these harsh conditions for hundreds of years. The primary issue for storage is delayed hydride cracking. This occurs as spent fuel decays, releasing both heat and tritium particles. Tritium can form hydrides with the cladding materials, reducing strength and possibly cracking with the combination of thermal expansion [9].

In a study from *Ceramics International*, gadolinium oxide metal matrix composites were studied for their ability to retain strength in the presence of high temperatures for extended periods of time, which is necessary for spent fuel storage. Gadolinium oxide is also desired for its tritium-shielding properties. This study determined that aluminum particles within the gadolinium matrix allow for the strength to be retained best at high temperatures. As temperature increases, the gadolinium oxide transforms from cubic to monoclinic, with lower strength [10]. However, the presence of aluminum particles reduces the loss of strength within the lattice as a whole. This could identify these metal matrix composites as candidate cladding materials.

6. Conclusions

The development of suitable materials is the main factor influencing the progress and integration of nuclear energy as a clean source of electricity. Structural materials must have limited reactivity with fuels, predictable thermomechanical properties, and high resistance to corrosion. These factors are studied in many ways and have multiple solutions. Among the types of nuclear reactors discussed in this paper, there are common issues as well as unique obstacles for each. These materials problems are addressed with materials of different composition and structure, as well as different processing methods like surface treatment or homogenization. Overall, nuclear energy has great potential to power the world and materials scientists can be on the forefront of progress in this field.

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Conflict of Interest

The author has no conflict of interest.

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