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Toward a Mechanistic Understanding of Radiation Effects in Materials*

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TOWARD A MECHANISTIC UNDERSTANDING OF RADIATION EFFECTS IN MATERIALS

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Substantial progress has been made toward the understanding of radiation effects in materials, and in formulating and testing a metallurgical approach for developing radiation-resistant alloys. This understanding has been derived from a combination of theoretical modeling with experiments using mixed spectrum fission reactors (with and without spectral and isotopic tailoring), fast reactors and ion irradiations. The development of materials with properties tailored to meet the challenges of advanced reactors involves four major steps: (1) the development of a mechanistic understanding of the behavior of materials during irradiation in appropriate environments; (2) selection of candidate materials based on physical, chemical, and mechanical properties; (3) development of these candidate materials through compositional and microstructural control to achieve the necessary properties and radiation damage resistance; and (4) the development of a database sufficient to support engineering design, performance analysis, and safety assessment. This paper will present a brief overview of the present understanding of radiation effects in materials, with emphasis on work performed at Oak Ridge National Laboratory as part of the U.S. fusion materials and basic energy sciences programs.

An understanding of the evolution of the microstructure and microchemistry during irradiation has been developed in its most complete form through research on austenitic stainless steels. Progress in fundamental understanding of void swelling, phase formation and stability, irradiation creep, and post-irradiation mechanical properties has been gained through comparison of experimental data with the predictions of theoretical models. In more critical tests of the models, experiments have been designed to specifically address certain aspects of the relevant models.

Applications of the understanding of radiation effects in materials have led to the development of candidate structural materials for use in aggressive radiation environments such as fast breeder reactors and proposed fusion energy systems. Compositional and microstructural control have been used to achieve the necessary properties and radiation damage resistance. In particular, compositions and heat treatments that lead to the formation of stable, finely-dispersed carbide and phosphide precipitates can produce alloys resistant to swelling, high temperature creep, and embrittlement through the stabilization of the dislocation structure and control of the distribution of helium. Because of the successes associated with the development of radiation resistant austenitic stainless steels, it is believed that these principles will provide the basis for addressing radiation issues in a variety of materials systems.

Development and optimization of materials systems will focus on the usual engineering characteristics of fabricability, joining, mechanical properties at relevant temperatures, chemical compatibility, and potential for enhancing safety and environmental considerations. In addition to these, the material must be resistant to neutron irradiation damage.

The key issue associated with current light water reactors is embrittlement of the ferritic steel used to fabricate the pressure vessel (RPV). Although the expected dose at end-of-life is low, ≤ 0.02 dpa, the low irradiation temperature of 290°C can lead to a significant increase in the ductile-to-brittle transition temperature in sensitive steels. The desire to extend the life of older plants increases the need to understand and mitigate the causes of RPV embrittlement. Thermal annealing is a promising technique for restoring toughness, but raises such prospects as temper embrittlement and questions about the rate of subsequent re-embrittlement. RPV embrittlement is driven by the radiation-induced point defects and mediated by key compositional variables. While many of the concepts developed to predict the flow and fate of solutes and point defects at higher temperatures remain applicable, the low RPV operating temperature provides new challenges.

The fusion reactor represents one of the most difficult challenges of any energy system from the viewpoint of developing materials which will allow fusion to be realized as an economic, safe, and environmentally acceptable energy source. The mechanical performance of the first wall and blanket structure of the International Thermonuclear Experimental Reactor (ITER) is determined by the radiation-response of stainless steel and copper alloys to damage levels up to about 10 dpa at temperatures in the range of 100 to 350°C. Important phenomena related to the nature of the defect structure include radiation hardening and the appearance of an upper yield point, reduction in work hardening capability, dislocation channeling and severe strain localization. These phenomena, which were the focus of radiation damage studies 30 years ago, affect fracture toughness, fatigue life, and the thermomechanical behavior of copper alloy-stainless steel laminated structures. Radiation-induced particle coarsening and dissolution, and void swelling are important issues for copper alloys in both first wall and divertor structures for ITER. Ceramics insulators play an important role in the plasma heating, diagnostic, and blanket systems for ITER. The effects of ionizing and displacive radiation on the physical properties of materials such as Al_2O_3 are of critical concern and require complex in-situ measurements. Materials with improved thermomechanical performance, radiation damage resistance, and reduced activation characteristics must be developed for the long term realization of fusion as a major energy source. International research and development programs are currently focused on vanadium, ferritic-martensitic steels, and SiC/SiC composite materials. For both BCC alloy systems the effects of low temperature neutron irradiation damage on the transition from ductile to brittle fracture behavior are key issues; significant progress has been achieved in recent years in improving the performance of both alloy systems. Relatively little is known about how to develop radiation-resistant structural ceramics. For SiC/SiC composites, current efforts are focused on the development of dimensionally-stable fibers and radiation-resistant interfacial layers.