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# FOREWORD

This is the thirty-ninth in a series of semiannual technical progress reports on fusion materials science activities supported by the Fusion Energy Sciences Program of the U.S. Department of Energy. This report focuses on research addressing the effects on materials properties and performance from exposure to the neutronic, thermal, and chemical environments anticipated in the chambers of fusion experiments and energy systems. This research is a major element of the national effort to establish the materials knowledge base of an economically and environmentally attractive fusion energy source. Research activities on issues related to the interaction of materials with plasmas are reported separately.

The results reported are the product of a national effort involving a number of national laboratories and universities. A large fraction of this work, particularly in relation to fission reactor irradiations, is carried out collaboratively with partners in Japan, Russia, and the European Union. The purpose of this series of reports is to provide a working technical record for the use of program participants, and to provide a means of communicating the efforts of fusion materials scientists to the broader fusion community, both nationally and worldwide.

This report has been compiled and edited under the guidance of R. L. Klueh and Teresa Roe, Oak Ridge National Laboratory. Their efforts, and the efforts of the many persons who made technical contributions, are gratefully acknowledged.

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between the half-cylinders of Cu. Each composite disk was then dimple ground to a central thickness of ~ 100 µm, and ion milled using a Gatan Precision Ion Polishing System. Ion milling was performed with 5 KV Ar ions to perforation so that the hole grew into the area of interest, followed by ion polishing at 2 KV for up to 1800 s to minimize Ar ion damage near the surface. Microstructural examinations were performed on a JEOL 2010F operating at 200 KeV in transmission with images recorded digitally.



Tensile and Charpy specimens of normalized-and-tempered ORNL 9Cr-2WVTa reduced-activation steel and that steel composition containing 2% Ni (9Cr-2WVTa-2Ni) were irradiated at 376–405ºC in the Experimental Breeder Reactor (EBR-II) to 23–33 dpa. Steels were irradiated in two tempered conditions: 1 hr at 700ºC and 1 h at 750ºC. The mechanical properties before and after irradiation of the 9Cr-2WVTa-2Ni steel were quite similar to those of the 9Cr-2WVTa steel, indicating no adverse effect of the nickel. Neither of the steels showed excessive hardening or a large increase in ductile-brittle transition temperature.



Martensitic steels are considered for structural applications for fusion power plants, but they are limited by strength to temperatures of 550–600ºC. For increased plant efficiency, steels for operation at 650ºC and higher are sought. Based on the science of precipitate strengthening, a thermo-mechanical treatment (TMT) was developed that increased the strength from room temperature to 700ºC of commercial nitrogen-containing steels and new steels designed for the TMT. At 700ºC an increase in yield stress of 80 and 200% was observed for a commercial steel and a new steel, respectively, compared to commercial steels after a conventional heat treatment. Creep-rupture strength was similarly improved. Depending on the TMT, precipitates in the steels were up to eight-times smaller at a number density four orders of magnitude greater than those in a normalized-and-tempered steel.



Experimental investigations have demonstrated that neutron irradiation of prime aged CuCrZr at temperatures below ~ 473K leads to a substantial increase in strength, formation of a tensile instability, and a severe loss of work hardening ability and uniform elongation [1, 2]. The precipitates in this alloy are unable to inhibit localized deformation via dislocation channeling in the irradiated materials, namely because the precipitates are small Guinier-Preston (G-P) zones too weak to effectively prevent or hinder dislocation motion once dislocations become mobile at stress concentrations. It was therefore decided to coarsen the precipitate microstructure by annealing the prime aged CuCrZr so that larger and hopefully stronger precipitates, albeit in lower density, might prove more effective at preventing the initiation of plastic flow localization by resisting dislocation motion. As a starting point, we hoped to achieve a precipitate microstructure in the over-aged CuCrZr that was coarsened to a level near that of the GlidCop Al25, that is, particles with an average size of ~ 7–8 nm with a density of ~ 1022 particles per $m^{-3}$.

Multi-layer coatings are being investigated to reduce the MHDpressure drop in a lithium-cooled blanket.As the fabrication process is improved, the performance of the coatings is improving with adequate as-deposited and in-situ resistance, and good compatibility being demonstrated in a recent capsule test. Thecompatibility of a thin (10-100µm) vanadium overlayer is now critical to coating durability. Initialexperiments showed no dissolution of V-4Cr-4Ti after 1,000h at 800°C although the specimens wereembrittled after exposure. Aplanned monometallic loop experiment will help verify the compatibility of V-4Cr-4Ti in Li at 700°C. New insulating ceramic materials are being investigated with $Y_2Ti_2O_7$showingsome promise for this application.



Static Pb-17Li capsule tests were performed on monolithic SiC specimens and Al-containing alloys. Bothsystems showed little or no dissolution in Pb-Li likely due to the formation of a protective surface oxidewhich was expected to be stable based on thermodynamic evaluations.For SiC, Si was detected in thePb-Li only at the highest test temperatures (2,000h at 1100°C and 1000h at 1200°C). The addition of Alto Fe- or Ni-base alloys resulted in a significant decrease in the amount of dissolution after 1000h at 700°and 800°C compared to type 316 stainless steel. Chemical vapor deposited (CVD)aluminide coatings ontype 316 substrates significantly reduced the dissolution rate at 800°C. With or without pre-oxidation, Al-containing alloys or coatings formed an $Al_2O_3$surface layer.These results demonstrate that aluminidecoatings could protect a conventional Fe- or Ni-base tubing alloy to carry Pb-Li between the first wall andthe heat exchanger. Future work will need to include testing in a flowing system with a thermal gradientto fully determine the compatibility of these materials.



***No contributions.***



Formation energies, binding energies, and migration energies of interstitial He atoms in and near the core of an a/2<111> screw dislocation in α-Fe are determined in atomistic simulations using conjugate gradient relaxation and the Dimer method for determining saddle point energies. Results are compared as a function of the proximity of the He to the dislocation core and the excess interstitial volume in regions around the dislocation. Interstitial He atoms have binding energies to the screw dislocation that are about half the magnitude of binding energies to the a/2<111>{110} edge dislocation in α-Fe. Migration energies of interstitial He atoms for diffusion toward the dislocation and for pipe diffusion along the dislocation are about the same magnitude for the screw and edge dislocations, despite a significant difference in their migration mechanisms. Interstitial He atoms diffuse along the dislocation cores with a migration energy of 0.4–0.5 eV.



The reaction kinetics of the various species of mobile defects in irradiated materials are crucially dependent on the dimensionality of their diffusion processes. Sink strengths for one-dimensionally (1D) gliding interstitial loops undergoing occasional direction changes have been described analytically and confirmed by kinetic Monte Carlo (KMC) simulations. Here we report on KMC simulations investigating the transition from 1D to 3D diffusion for 1D gliding loops whose 1D migration is interrupted by occasional 2D migration due to conservative climb by dislocation core diffusion within a plane transverse to their 1D glide direction. Their transition from 1D to 3D kinetics is significantly different from that due to direction changes. The KMC results are compared to an analytical description of this diffusion mode in the form of a master curve relating the 1D normalized sink strength to the frequency of disturbance of 1D migration.



Elemental iron implanted with He at different energies and doses is studied using thermal helium desorption spectrometry (THDS). Currently examined energies and doses include: 100 keV, and 1 x 1011, 1 x 1013, and 1 x 1015 He/cm2, respectively. While no clear desorption signals have been observed for the two lower dose samples, the present results reveal that for the iron implanted to 1 x 1015 He/cm2 the majority of the implanted He atoms desorb at ~ 1000ºC and at > 1100ºC. Both conventional reaction model and Johnson-Mehl-Avrami (JMA) transformation model kinetics were utilized to fit the lower temperature (~ 1000ºC) desorption event of the 1 x 1015 He/cm2 dosed iron. Surprisingly, single (either 1st or higher) order fits can not adequately describe the event. Excellent fits are obtained when combining a lower (n ~ 1.1) order with a higher (n ~ 5.8) order JMA fit. Additionally, spurious desorption peaks and certain complex desorption features have been observed which may affect future THDS studies.



Two different Finnis-Sinclair-type potentials were used to model Fe-1%Cr and Fe-10%Cr alloys, which alternately describe Cr as under- or over-sized in body-centered cubic Fe. In general, the diffusivity of the single interstitials and di- and tri-interstitial clusters was reduced in the Fe-10%Cr alloys, irrespective of interatomic potential, although the underlying mechanism(s) were different. When Cr is undersized, interstitial diffusion is retarded through a trapping mechanism associated with bound Cr-interstitial (mixed dumbbell) complexes, whereas oversized Cr atoms retard interstitial diffusion by enhancing the rotation frequency away from one-dimensionally mobile <111> interstitial dumbbell configurations.



Structural materials of a fusion power system will be exposed to high concentrations of He produced from nuclear transmutation reactions. Helium is essentially insoluble in metals so there is a strong tendency for it to form bubbles that can significantly degrade mechanical properties. A strategy to effectively manage He is to provide a high-density of internal interfaces to serve as He bubble nucleation sites and vacancy-interstitial recombination centers. Nanostructured ferritic alloys are being developed to provide improved creep strength and He management capability compared to conventional steels. A key characteristic of these materials is the high-density (~ 1024 m-3) of nanometer-scale (~ 3 nm diameter) Y-Ti-O clusters. We describe molecular dynamics simulations to assess the interaction of He atoms, vacancies and He-vacancy complexes with coherent Cu nanoclusters in Fe. The potentials employed here were adjusted to explore the effect of nanocluster elastic properties on He trapping efficiency.