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FOREWORD

This is the fortieth 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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Fully consolidated nanostructured ferritic alloys (NFAs) were prepared by attritor milling pre-alloyed Fe-14Cr-3W-0.4Ti and 0.3wt% Y_2O_3 powders, followed by hot isostatic pressing (HIPing) at 1000°C and 1150°C and 200 MPa for 4 h. Transmission electron microscopy (TEM) revealed similar bimodal distributions of fine and coarse ferrite grains in both cases. However, as expected, the alloy microhardness decreased with increasing in HIPing temperature. Three point bend tests on single edge notched specimens, with a nominal root radius ρ = 0.15 mm, were used to measure the notch fracture toughness, K_ρ, as a function of test temperature. The K_ρ curves were found to be similar for both alloys. It appears that the coarser ferrite grains control cleavage fracture, in a way that is independent of alloy strength and hipping temperature.

The nanostructured ferritic alloy (NFA) MA957 was joined by friction stir welding (FSW) and electro-sparked deposition (ESD) welding. Transmission electron microscopy (TEM) and small angle neutron scatter (SANS) characterization studies showed a uniform fine-scale equiaxed ferrite structure with a high density of dislocations and only slightly coarsened nm-scale particles in the joint region of the FSW weld compared to the base metal. Microhardness and tensile measurements on the FSW showed a modest reduction in the strength of the joint compared to the as-processed MA957. In contrast, the ESD welds contained considerable porosity and the nm-scale particles dissolved or coarsened significantly, resulting in a larger degradation of the joint region strength. Thus FSW is a promising method for joining NFAs.

The 9Cr-1MoVNb and 12Cr-1MoVW steels and these steels with 2% Ni additions were irradiated in HFIR to ≈10 dpa at 300ºC and ≈12 dpa at 400ºC and in FFTF to ≈15 dpa at 393ºC. After irradiation in HFIR, steels with 2% Ni hardened more than steels without a nickel addition. When 9Cr-1MoVNb-2Ni, 12Cr-1MoVW, and 12Cr-1MoVW-2Ni steels were irradiated in HFIR at 400ºC, they hardened more than when irradiated in FFTF at 393ºC. The 9Cr-1MoVNb steel hardened to the same level in both FFTF and HFIR. For all but the 9Cr-1MoVNb steel, shifts in DBTT of the steels irradiated in HFIR were greater than shifts for the same steels irradiated in FFTF. Irradiation in HFIR at 300 and 400ºC caused a larger shift for the steels containing 2% Ni than for the steels with no nickel addition. The increase in DBTT was related to the increase in yield stress. Despite the uncertainty inherent in the experiments, the results lead to the conclusion that helium caused an increment of hardening that contributed to the extra shift in DBTT over that observed after irradiation in FFTF where little helium formed.

Irradiation hardening produces increases in the cleavage transition fracture toughness reference temperature (ΔT_o). It is traditional to relate ΔT_o to the corresponding changes in the yield stress, $\Delta\sigma_y$, as Co = $\Delta T_o/\Delta\sigma_y$. However, it is a strain-hardened flow stress, σ_{fl}, in the fracture process zone that controls cleavage, rather than σ_y. Thus, irradiation induced decreases in the strain hardening $\Delta\sigma_{sh}$ (< 0) must be considered along with $\Delta\sigma_y$ (> 0) in evaluating ΔT_o. The $\Delta\sigma_{sh}$ in reactor pressure vessel (RPV) steels irradiated to low doses at around 300°C are small, even for large $\Delta\sigma_y$. However, the $\Delta\sigma_{sh}$ are much greater for high dose irradiations of tempered martensitic steels (TMS) that are candidates for fusion applications. As a result, for the TMS case the C_o are less, and in some instances much less, than for RPV steels and irradiation conditions. We address two key questions. First, how does $\Delta\sigma_{sh}$ influence the $C_o = \Delta T_o/\Delta\sigma_y$ relation? Second, is it possible to derive a universal relation between ΔT_o and $\Delta\sigma_{fl}$ averaged over a pertinent range of ε, $\langle\Delta\sigma_{fl}\rangle$, such that a $C_{o'} = \Delta T_o/\langle\Delta\sigma_{fl}\rangle$ is independent of the individual values of $\Delta\sigma_y$ and $\Delta\sigma_{sh}$? The results of this study suggest that $\langle\Delta\sigma_{fl}\rangle$ averaged between 0 and 0.1 provides a similar $C_{o'}$ for various assumptions about the effect of irradiation on $\Delta\sigma_{sh}$. Notably, changes in indentation hardness, ΔH, are also directly related to this same $\langle\Delta\sigma_{fl}\rangle$. Hence, measurements of ΔH should provide a good basis for assessing ΔT_o for a wide range of alloys and irradiation conditions.

The results of the crack arrest fracture toughness (K_a) measurements on cleavage oriented Fe single crystals from -196 to 0°C are reported. Arrest measurements were performed on four low toughness cleavage orientations; (100)[010], (100)[011], (110)[001] and (110)[110]. Reliable and consistent measurements were obtained for the (100) cleavage planes, however inconsistent measurements were observed for the (110) planes as cleavage cracks always reverted back to the (100) planar orientation. The corresponding static (K_{Ic}) and dynamic (K_{Id}) cleavage initiation toughness for the (100) planes from -196 to 50°C were also measured over a range of applied stress intensity rates ($\dot{K}$) from ≈ 0.1 to 10^4 MPa√m/s. The $K_{Ia}(T)$, $K_{Ic}(T)$ and $K_{Id}(T)$ gradually increase with temperature from a minimum average K_{Ia} value of approximately 4 MPa√m up to a rapid BDT at ≈ 0°C. The BDT temperature increases with higher $\dot{K}$, and is highest for K_{Ia}. The $\dot{K}$ dependence of $K_{Ic/d}(T)$ is consistent with the strain rate dependence of thermally activated flow stress of Fe. The $K_{Ic}(T)$ for single crystal Fe and W are also reasonably similar when plotted on a homologous temperature scale. The $K_{Ia}(T)$ for Fe at ≈ -40°C is similar to that for Fe-3wt%Si at ≈ 110°C. This 150°C shift can be reasonably rationalized by the solid solution lattice strengthening of Si. The $K_{Ia}(T)$ for Fe must be shifted up by ≈ 220°C to approximate the temperature dependence of the $K_\mu(T)$ that is consistent with a universal $K_{Jc}(T)$ master curve shape. This magnitude of shift may be caused by a combination of thermally activated (rate-dependent) solid solution lattice strengthening, complemented by long-range internal stress fields.

desorption peaks within both the bcc and fcc temperature ranges. These peaks are well fit with first order reaction kinetics, which reveal activation energies ranging from ~1.9 to ~3.5 eV. The number and the relative intensities of detected desorption peaks within the bcc temperature range appear to increase with decreasing implantation energy. Previously reported spurious peaks and a non-1st-order sharp peak are now better understood and described in the current report.

Helium is produced in neutron-irradiated metals as the result of (n, α) transmutation reactions and plays a significant role in microstructure evolution and mechanical properties degradation [1,2]. Due to helium's high mobility via an interstitial migration mechanism and its strong binding with vacancies, information on its atomistic behavior is hard to assess from experiments. The only way to obtain such information is from first-principles electronic structure calculations. However, electronic structure calculations can not be used on the time and size scales needed to simulate the important evolution of helium-vacancy clusters that ultimately leads to bubble formation. A multi-scale approach, based on constructing an empirical potential and employing this potential in classical molecular dynamics, seems to be the only practical approach currently available to study He behavior in metals on the desired scale**.**

Molecular statics, molecular dynamics and the dimer method of potential surface mapping are being used to study the fate of helium in the vicinity of dislocations and grain boundaries in alpha-iron. Even at very low temperatures interstitial helium atoms can migrate to dislocations and grain boundaries, where they are strongly bound. The binding energies of helium to these microstructural features, relative to the perfect crystal, and the migration energies of helium diffusing within them have a strong correlation to the excess atomic volume that exists in these extended defects. Helium atom migration energies within the dislocations and grain boundaries studied are in the range of 0.4–0.5 eV. Helium "kick out" mechanisms have been identified within dislocations and grain boundaries by which interstitial helium atoms replace a Fe lattice atom, creating a stable He-vacancy complex that may be a nucleation site for a He bubble.

No contributions.

No contributions.

Tensile and miniature Compact Tension specimens of eight high chromium steels of fusion relevance have been irradiated in the BR2 reactor in the framework of a collaborative project between Oak Ridge National Laboratory (ORNL) and SCK•CEN. All samples have been irradiated at a nominal temperature of 300°C in the in-pile section 2 (IPS-2) for five cycles (02/2005 to 01/2006) up to an average fast neutron fluence of 8.02

× 1020 n/cm^2 or 1.20 dpa. The rig was rotated three times by 180° in order to reduce the radial and azimuthal neutron flux gradients.