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1 FERRITIC/MARTENSITIC STEEL DEVELOPMENT

1.1 FABRICATION OF LOW ACTIVATION FERRITIC-MARTENSITIC STEELS CONTAINING ^{54}FE ISOTOPE—Y. Yamamoto (Oak Ridge National Laboratory) **1**

Four trial EUROFER97 steel plates were successfully fabricated by arc-melting with natural Fe and hot-rolling with a steel guide. The arc-melting was conducted to measure the yield of each alloying element during the melt process, and the trial hot-rolling with a steel guide was performed to produce steel plates without barreling. Based on the process parameter of the trial heats, two RAFM steel plates (targeted to be EUROFER97 and CNA) made of ^{54}Fe isotope powder, with size ~0.25 x 1.4 x 2.5 inches, were successfully fabricated. The detailed planning of the machining of SS-J3 tensile specimens and M4 bend bar specimens, as well as developing an irradiation test plan for HFIR, is currently in progress.

1.2 ADVANCED BAINITIC STEEL DEVELOPMENT FOR FUSION STRUCTURAL APPLICATIONS—Y. Yamamoto (Oak Ridge National Laboratory) **6**

A new alloy design strategy for PWHT-free bainitic steel has been proposed; reducing the as-normalized hardness without losing high hardenability, in order to reduce potential property inhomogeneity across the weldment. Four new heats of 3Cr-3WVTa base bainitic steels with low carbon combined with high Mn and Si were prepared with guidance from computational thermodynamics. The steel with the combination of 0.05C and 2 or 3Mn additions successfully showed fully bainitic microstructure together with less hardness difference between as-normalized and tempered conditions, which will reduce the potential property inhomogeneity in the weldments. High temperature tensile properties also supported potential improvement of mechanical properties at elevated temperatures. Preparation for creep-rupture testing is currently underway.

1.3 ON THE EFFECTS OF HE-DPA INTERACTIONS ON CAVITY EVOLUTION IN TEMPERED MARTENSITIC STEELS UNDER DUAL ION IRRADIATION—Takuya Yamamoto, Yuan Wu, G. Robert Odette (University of California Santa Barbara), Kiyohiro Yabuuchi, Sosuke Kondo, Akihiko Kimura (Kyoto University) **12**

We filled some gaps in our cavity evolution database on normalized and tempered 9Cr martensitic steels (TMS) F82H under Fe^{3+} plus He^{+} dual ion beam irradiation (DII) at 500°C. New experiments were conducted at ≈ 30 appm He/dpa at relatively low nominal damage rate of 6.5×10^{-4} dpa/s. The cavity evolution database at 500°C now includes 321 material-dpa-He-dpa rate DII conditions. Two distinct trends of higher and lower swelling rates versus dpa are observed. Here we compare the detailed evolution of the cavity size distributions with increasing dpa and He to seek clues about the reasons for these differences in behavior. The higher swelling rate case was generally associated with higher dpa rates, fewer cavities and stronger bi-modality, compared to the lower swelling rate case.

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1.4 INFLUENCE OF ION IRRADIATION DIRECTION ON GROWTH OF NANOPRECIPITATES IN MODEL CNAs—L. Tan (Oak Ridge National Laboratory), B.K. Kim (ORNL), G.S. Was (Univ. of Michigan) **17**

Transmission electron microscopy of irradiated CNA alloys and statistical quantitative analysis of the ultrafine particles after heavy ion irradiation indicates that these experiments may not represent the precipitate stability under neutron irradiation. The dependence of nanoprecipitate evolution on ion beam direction is one process that may be unique to ion irradiation.

2 ODS AND NANOCOMPOSITED ALLOY DEVELOPMENT

2.1 Fe-Cr-Al ODS ALLOYS FOR FUSION REACTOR APPLICATIONS—S. Dryepondt , K. A. Unocic, D. T. Hoelzer (Oak Ridge National Laboratory) **20**

Several ODS FeCrAl alloys were fabricated by ball milling Fe-12Cr-5Al gas atomized powder with Y_2O_3 powder and ZrO_2, HfO_2, or TiO_2 powder. The Zr-containing alloy (125YZ) exhibited excellent creep properties at 700-800ºC in air, and good compatibility with Pb-17Li at 700ºC, with the formation of a thin $LiAlO_2$ layer. Extensive TEM characterization of the 125YZ revealed the presence of $Y_3Al_5O_{12}$ (YAG), Al_2O_3 and Zr(C,N) nano precipitates. A second generation of ODS FeCrAl alloys was fabricated by ball-milling Zr or Hf-containing Fe-12Cr-5.5Al powder with Y_2O_3 powder. Initial characterization of these 2nd generation alloys showed that the alloy tensile properties are very dependent on the extrusion conditions.

2.2 X-RAY ABSORPTION SPECTROSCOPY OF EMBEDDED AND EXTRACTED NANO-OXIDES IN NANOSTRUCTURED FERRITIC ALLOY MA957—T. Stan, G.R. Odette (University of California Santa Barbara), D. Sprouster, A. Ofran, L. Ecker (Brookhaven National Laboratory) **28**

The chemistries and structures of both embedded and extracted Y-Ti-O nanometer-scale oxides in nanostructured ferritic alloy (NFA) MA957 were characterized by x-ray absorption spectroscopy (XAS). $Y_2Ti_2O_7$ is the primary embedded phase, while the slightly larger extracted oxides are primarily Y_2TiO_5. Analysis of the embedded nano-oxides in MA957 is difficult partly due to the multiple Ti environments associated with different oxides and those still residing in matrix lattice sites. Thus, bulk extraction followed by selective filtration was used to isolate the larger Y_2TiO_5 oxides for XAS. The smaller $Y_2Ti_2O_7$ oxides passed through the filters but were the predominant embedded phase.

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2.3 ESTIMATES OF THE THOUGH THICKNESS RESIDUAL STRESSES IN THE AS-PROCESSED NFA-1 PLATE BASED ON NANOINDENTATION MEASUREMENTS—S. Pal, M. E. Alam and G. R. Odette (UCSB) **35**

Hardness and modulus of the as processed NFA-1 alloy plate have been measured using nanoindentations, including to probe the nature and magnitude of the residual stresses generated by thermo-mechanical processing. The residual stresses were quantified from the nanoindentation load-penetration curves. The plate surfaces (and adjoining mild steel can) are in compression, while the middle of the plate is in tension. The magnitude of the maximum tensile residual stress is ≈ +500 MPa, decreasing to ≈ +75 MPa near to the plate surface; and ≈ -30 MPa at the surface of the can. A microcrack population area density, lying perpendicular to the short thickness direction of the plate, tracks the residual tensile stress profile. The surface residual stresses were further quantified using a conventional $\sin^2\psi$ x-ray diffraction (XRD) method that yielded a value similar to the nanoindentation estimate.

2.4 CHARACTERIZATION OF FE THIN FILMS ON {100} ORIENTED $Y_2Ti_2O_7$ SUBSTRATES—T. Stan, Y. Wu, G.R. Odette (University of California Santa Barbara), and H.D. Zhou (University of Tennessee) **45**

Nanostructured Ferritic Alloys (NFAs), a variant of oxide dispersion strengthened steels, contain a high density (≈ $5x10^{23}/m^2$) of ≈ 2.5 nm average diameter Y-Ti-O nano-oxides (NOs) which help impede dislocation climb and glide, stabilize dislocation and grain structures, and trap He in fine-scale bubbles at matrix-NO interfaces. To complement other studies of the NOs themselves, mesoscopic-scale bilayer interfaces were fabricated by electron beam deposition of a thin Fe film on a {100} $Y_2Ti_2O_7$ (YTO) bulk single crystal substrate. These bilayers were prepared for He implantation and charged particle irradiations to experimentally observe defect interface interactions and the partitioning of He between the Fe, YTO, and the associated interface. We report, for the first time, the dominant epitaxial orientation relationship (OR) for a polycrystalline Fe film on {100} YTO: $\{110\}_{Fe}\backslash\backslash\{100\}_{YTO}$ and $<100>_{Fe}\backslash\backslash<110>_{YTO}$. One large grain region had an OR that is also found in embedded NOs: $\{100\}_{Fe}\backslash\backslash\{100\}_{YTO}$ and $<100>_{Fe}\backslash\backslash<110>_{YTO}$. HRTEM studies show clean semicoherent interfaces, with misfit dislocation spacings consistent with the calculated near coincidence site lattices.

2.5 TEM OBSERVATION OF ANNEALED AND He IMPLANTED NANOSTRUCTURED FERRITIC ALLOYS—Y. Wu, T. Stan, T. Yamamoto, G. R. Odette (University of California Santa Barbara) **54**

Transmission electron microscopy (TEM) studies were carried out on two 700°C He implanted NFAs that had been previously annealed to coarsen their initially ultra-high density of nano-scale oxides (NOs). All the coarsened Y-Ti-O oxides were found to be associated with at least one, and in many cases more than one, interface helium bubble.

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2.6 **THREE DIMENSIONAL ATOM PROBE TOMOGRAPHY OF 14YW AND 14YWT NEUTRON IRRADIATED AT 500ºC TO 21.2 DPA**—D.J. Edwards, K. Kruska, J. Wang, R. J. Kurtz (Pacific Northwest National Laboratory), G.R. Odette, T. Yamamoto and Y. Wu (University of California-Santa Barbara) **59**

Work has progressed on the characterization of two ferritic alloys, 14YW and 14YWT, irradiated in the JP27 experiment in the High Flux Isotope Reactor as part of the In-situ Helium Injection (ISHI) experiments. While much of the work has focused on high resolution analytical TEM of the bubble and dislocation structures formed during neutron irradiation, this TEM analysis has not been able to effectively characterize the nano-oxide particles present in 14YWT, which are usually less than 2 nm in size. To investigate microstructural features at this scale in a statistically meaningful manner, 3D-APT has been initiated to probe the oxide dispersion in the 14YWT. For comparative purposes, the 14YW alloy is also examined, however, the oxide dispersion is noticeably coarser due to the lack of titanium, and it is better characterized using TEM. APT of the 14YWT alloy revealed that significant precipitation of Mn-rich phases had occurred, as well as the formation of a Cr-rich α'-type phase at a composition that appears to contain less than the expected 85% Cr.

3 **CERAMIC COMPOSITE STRUCTURAL MATERIAL DEVELOPMENT**

3.1 **LOW ACTIVATION JOINING OF SiC/SiC COMPOSITES FOR FUSION APPLICATIONS: THERMOMECHANICAL MODELING OF DUAL-PHASE MICROSTRUCTURES AND DISSIMILAR MATERIAL JOINTS**—B.N. Nguyen, C.H. Henager, Jr., and R.J. Kurtz; (Pacific Northwest National Laboratory, Richland, WA, USA); M. Ferraris, (Politecnico di Torino, Torino, Italy); Y. Katoh, (Oak Ridge National Laboratory, Oak Ridge, TN, USA) **65**

Miniature torsion specimens were designed for joint testing and irradiation in test reactors with limited irradiation volumes since SiC and SiC-composites used in fusion environments are thought to require joining methods for component assembly. HFIR irradiation results indicated two broad types of joint damage due to irradiation at either 500˚C or 800˚C to 3 dpa or 5 dpa. One type of damage can be categorized as microcracking within multi-phase joints at the micron length scale. The other type of damage can be categorized as cracking within the miniature torsion sample and within the joint where the cracks are now on the scale of the joint thickness and are not considered to be microcracks. This report expands the methods developed and discussed in our previous report to model both types of cracking due to thermal stresses caused by the mismatch of thermoelastic properties (i.e., elastic properties and thermal expansion coefficients) in the constituent phases or between the joint and joint materials for a specimen uniformly heated from 28˚C to 800˚C.

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3.2 CHARACTERIZATION OF PRECIPITATES IN CUBIC SILICON CARBIDE IMPLANTED WITH $^{25}Mg^{+}$ IONS—W. Jiang, S. R. Spurgeon, J. Liu, D. J. Edwards, D. K. Schreiber, C. H. Henager, Jr., R. J. Kurtz (Pacific Northwest National Laboratory), and Y. Wang (Los Alamos National Laboratory) **72**

This progress report presents results from high-resolution scanning transmission electron microscopy (STEM), electron energy loss spectroscopy (EELS) and atom probe tomography (APT). The APT study has been performed for cubic silicon carbide (3C-SiC) implanted to 9.6×10^{16} $^{25}Mg^{+}/cm^{2}$ at 673 K and subsequently annealed at 1073 and 1573 K for 2, 6, and 12 h in an Ar environment. The ^{25}Mg isotope was chosen to differentiate it from $^{12}C_2$ clusters in APT. STEM and EELS characterizations have been carried out for the same 3C-SiC sample annealed at 1573 K for 12 h. The APT results show a faster Mg clustering process during isochronal annealing (12 h) at a higher temperature while growth to larger Mg clusters on the average occurs during isothermal annealing (1573 K) for a longer time. The STEM-EELS study suggests that some of the precipitates have a core (MgC_2)-shell (Mg^2Si) microstructure. The precipitate size and number density are determined to be 2-8 nm and ~$10^{18}/cm^3$, respectively.

3.3 NEUTRON-IRRADIATION CREEP OF SILICON CARBIDE MATERIALS BEYOND THE INITIAL TRANSIENT—T. Koyanagi, Y. Katoh (Oak Ridge National Laboratory), K. Ozawa (Japan Atomic Energy Agency), K. Shimoda, T. Hinoki (Kyoto University), L.L. Snead (Massachusetts Institute of Technology) **78**

Irradiation creep beyond the transient regime was investigated for various SiC materials. The materials examined included polycrystalline or monocrystalline high-purity SiC, nanopowder sintered SiC, highly crystalline and near-stoichiometric SiC fibers, and a Tyranno SA3 SiC fiber reinforced SiC matrix composite fabricated through a nano-infiltration transient eutectic phase process. Findings are 1) the stress exponent of the post-transient creep was near unity, 2) the small apparent steady-state creep rate was ~1×10^{-7} [$dpa^{-1}MPa^{-1}$] at ~300 to ~800°C for most polycrystalline SiC materials, and 3) the effect of material quality on the creep rate, including structure of grain boundaries and crystal orientation, increased with increasing irradiation temperature. The results have been published in J. Nucl. Mater. and a condensed version is given here.

4 HIGH HEAT FLUX MATERIALS AND COMPONENT TESTING

4.1 DESIGN AND DEVELOPMENT OF NOVEL COPPER ALLOYS FOR FUSION ENERGY APPLICATIONS—Ying Yang (Oak Ridge National Laboratory) and Steven J. Zinkle (University of Tennessee and Oak Ridge National Lab) **83**

A computation thermodynamics tool for designing and developing Cu-Cr-Nb-Zr alloys have been successfully developed. Thermodynamic modeling results based on this tool enabled a rapid development of a novel CuCrNbZr alloys with targeted microstructure using an economical, conventional ingot making method following by simple heat treatment procedures. The new alloys display uniform grain structure with bimodal distribution of precipitates.

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4.2 PRELIMINARY PROGRESS IN THE DEVELOPMENT OF DUCTILE-PHASE TOUGHENED TUNGSTEN FOR PLASMA-FACING MATERIALS: DUAL-PHASE FINITE ELEMENT DAMAGE MODELS—C. H. Henager, Jr., B. N Nguyen, R. J. Kurtz (Pacific Northwest National Laboratory) **89**

A promising approach to increasing fracture toughness and decreasing the ductile-brittle transition temperature (DBTT) of a W-alloy is by ductile-phase toughening (DPT) [1-3]. In this method, a ductile phase is included in a brittle matrix to prevent fracture propagation by crack bridging or crack deflection. Liquid-phase sintered W-Ni-Fe alloys and hot-pressed and sintered W-Cu composites are two examples of such materials that PNNL and UCSB are investigating. However, there is a need for improved mechanical property models of such composite systems in order to begin to optimize these structural materials with regard to strength and fracture toughness. This report describes such a model that is currently under development at PNNL.

4.3 DUCTILE PHASE TOUGHENING OF 90-97wt% W-NiFe HEAVY METAL ALLOYS—M.E. Alam, S. Pal, K. Field, G. R. Odette (UCSB) **93**

Ductile phase toughening (DPT) is a promising approach to improving toughness of brittle materials like tungsten (W). The fracture toughness of commercial liquid phase sintered W-based composites, containing 90, 92.5, 95 and 97 wt.% W, with the balance a 7:3 Ni:Fe ductile solid solution phase, has been characterized. Pre-cracked single edge notch bend bar fracture toughness tests were conducted at room temperature. The average maximum load initiation toughness averaged 102 ± 17 MPa√m, relatively independent of the W fraction up to 95 wt.%, but dropped to 71± 17 MPa√m for the 97%W alloy. However, crack blunting beyond the peak load (down to $P/P_{max} \approx 0.8$), prior to any significant crack growth (da), resulted in an even higher toughness of 168 ± 31 MPa√m. The toughness of the W-Ne:Fe composites compare to typical monolithic-W values of ≈ 8 MPa√m. Composite fracture occurs by stable crack growth. The enormous toughening is due to crack bridging and especially very large plastic zone deformation energy dissipation.

4.4 FABRICATION OF FUNCTIONALLY GRADED TUNGSTEN STEEL LAMINATE—L. M. Garrison, Y. Katoh (Oak Ridge National Laboratory), M. Norfolk (Fabrisonic LLC.), J. Wenning (Fabrisonic LLC.), J. Moon (University of Nevada-Reno) **103**

Two roll-bonded tungsten-steel composites have been fabricated. Tensile tests of the Generation 2 composite were completed and showed increasing strength and decreasing ductility with increased tungsten content. A feasibility study for ultrasonic welding tungsten to steel was completed. Thirty-four trials were completed that varied the parameters of foil thickness, interlayer material, welding force, vibration amplitude, and other welding parameters. Promising results were obtained for joining tungsten to steel and tungsten to steel with an aluminum interlayer.

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4.5 **IRRADIATION HARDENING OF PURE TUNGSTEN EXPOSED TO NEUTRON IRRADIATION**—X. Hu, T. Koyanagi, N.A.P Kiran Kumar, Y. Katoh (Oak Ridge National Laboratory), L.L. Snead (Massachusetts Institute of Technology), B.D. Wirth (University of Tennessee, Knoxville) **109**

This manuscript is in the review process for publication in the Journal of Nuclear Materials.

Pure tungsten samples have been neutron irradiated in HFIR at 90 to 850°C to damage levels of 0.03 to 2.2 dpa. A dispersed barrier hardening model informed by the available microstructure data has been employed to predict the hardness. The comparison of the model prediction and the measured Vickers hardness reveals the dominant hardening contribution at various irradiation conditions. For tungsten samples irradiated in HFIR, the results indicated that voids and dislocation loops contributed to the hardness increase in the low dose region (< 0.3 dpa), while the formation of intermetallic second phase precipitation resulting from transmutation started to dominate the radiation-induced strengthening in a relatively modest dose region (> 0.6 dpa). The precipitate contribution is most pronounced for the HFIR irradiations, whereas the radiation-induced defect cluster microstructure can rationalize the entirety of the hardness increase observed in tungsten irradiated in the fast neutron spectrum of Joyo and the mixed neutron spectrum of JMTR.

4.6 **NEUTRON IRRADIATION EFFECTS IN TUNGSTEN**—L.M. Garrison, Y. Katoh, P. Edmondson, X. Hu, C. Parish, T. Koyanagi, M. McAlister, N.A.P. Kiran Kumar (Oak Ridge National Laboratory), M. Fukuda, T. Hwang (Tohoku University, Japan), L. L. Snead (Massachusetts Institute of Technology), T. S. Byun **125**

A total of 440 samples were irradiated in HFIR at temperatures from 70 to 900°C and fast neutron fluences of 0.01 to 20 $\times 10^{25}$ n/m^2 at E>0.1 MeV as part of the TITAN project. Types of tungsten irradiated in this study were [110] single crystal tungsten, [100] single crystal tungsten, wrought tungsten foils, annealed tungsten foils, and tungsten-copper laminates. Analysis is revealing that characterizing precipitation of transmutation products in neutron irradiated tungsten is key to understanding its properties after irradiation. TEM images of higher dose samples revealed that voids tend to be near precipitates in the irradiated tungsten. Analysis of room temperature tensile test data of the single crystal samples reveals that ultimate strength decreases at less than 1 dpa. Further shipments of TITAN samples to LAMDA were completed so that the higher dose samples can be evaluated.

4.7 **NEUTRON IRRADIATION EFFECTS IN TUNGSTEN-COPPER COMPOSITES**—L. M. Garrison, Yutai Katoh (Oak Ridge National Laboratory) Jeremy Moon (University of Nevada-Reno), Joseph Willenborg (University of Tennessee-Knoxville) **130**

As part of the TITAN program, two types of tungsten-copper composites were irradiated in HFIR at temperatures from 300 to 900°C and fast neutron fluences of 0.01 to 20 $\times 10^{25}$ n/m^2 at E>0.1 MeV. One material was a tungsten-copper laminate composite composed of 0.1 mm alternating layers of tungsten and copper. Tensile tests have previously been completed on the tungsten-copper laminate and EDS and EBSD analysis of the material is underway. The other material was a tungsten-copper powder sintered composite, with 75% W and 25% Cu. Tensile tests of unirradiated and irradiated tungsten-copper sintered composite have been completed and are being analyzed.

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4.8 **HIGH-HEAT FLUX TESTING OF LOW-LEVEL IRRADIATED MATERIALS USING PLASMA ARC LAMPS**—A.S. Sabau, Y. Katoh (Oak Ridge National Laboratory) and K. Ibano (Osaka University) **134**

A review was conducted of relevant physical phenomena that take place during high-heat flux testing (HHFT) in order to identify areas of concentration in the ORNL program for materials characterization. Planning of activities for handling the irradiated specimens in FY17 was started in order to ensure a close coordination between the multidisciplinary efforts needed for a comprehensive material science study of irradiated effects during HHFT. Temperature-dependent physical and mechanical properties for the SiC were obtained for use as input in the numerical simulations of the HHFT to reveal insight on the temperature and stress conditions for the four W/SiC specimens. The setup of thermo-mechanical model simulations for the high-heat flux testing of W/SiC specimens was completed.

5 **MAGNETIC AND DIAGNOSTIC SYSTEM MATERIALS**
No contributions this reporting period.

6 **FUSION CORROSION AND COMPATIBILITY SCIENCE**

6.1 **COMPATIBILITY OF FeCrAl IN FLOWING Pb-LI AT 550°-600°C**– B. A. Pint and S. J. Pawel (Oak Ridge National Laboratory, USA) **137**

The second monometallic thermal convection loop (TCL) using Kathal FeCrAlMo alloy APMT tubing and specimens has completed 1000 h in commercial purity eutectic Pb-Li with a peak temperature of 600°C. After cleaning, the mass change data showed small mass losses for all of the specimens preoxidized at 1000°-1100°C to form an alumina scale prior to exposure in the loop. Larger mass losses were noted for specimens that were not pre-oxidized, especially at the lower temperatures. Characterization of the specimens is in progress.

7 **MECHANISMS AND ANALYSIS**

7.1 **QUALITATIVE ANALYSIS OF COMMERCIAL $M_{n+1}AX_n$ PHASES UNDER NEUTRON IRRADIATION**—C. Ang*, C. Shih, S.J. Zinkle, C. Silva, C. Parish, N. Cetiner, P. Edmondson, and Y. Katoh (Oak Ridge National Laboratory, USA) **141**

Mn+1AXn (MAX) phases are ternary nitrides and carbides. The materials studied were purchased from 3-ONE-2, LLC, and were previously characterized (see DOE/ER-0313/58). These were nominally "Ti_3SiC_2" and "Ti_2AlC" compositions irradiated to 2 x 10^{25} n/m^2 (E > 0.1 MeV) or ~ 2 dpa (based on the SiC displacement cross-section). After extensive characterization, weighted compositions were determined to be ~80% MAX phase. Irradiation temperatures were determined by passive dilatometry to have reached ~400, 630 and 700°C. After irradiation at ~400°C, swelling of Ti_3AlC_2-$Ti_5Al_2C_3$ material was 50% higher than Ti_3SiC_2, and this was reflected in the loss of room temperature equibiaxial fracture strength. The Si-containing MAX phase was more radiation resistant than the Al-containing material at lower temperatures. After irradiation at 630°C, electrical, thermal, and mechanical properties were unaffected. Lattice parameter swelling was mitigated at high temperature, but ~0.5-1% volumetric swelling was observed.

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7.2 **DAMAGE MECHANISM INTERACTIONS AT THE PLASMA-MATERIALS INTERFACE (Early Career Award)**—C. M. Parish, K. Wang (Oak Ridge National Laboratory) **146**

This reporting period has emphasized experimental technique developments as the necessary foundation for all later work, continued collaborations with other institutions, and has begun exploration of defect-defect interactions within plasma-exposed and neutron-irradiated tungsten.

7.3 **THERMOMECHANICS OF RESILIENT MICRO-ENGINEERED PLASMA FACING MATERIALS**—David Rivera, Richard Wirz, Nasr M. Ghoniem (University of California, Los Angeles) **152**

Extended abstract of a paper to be submitted to the International Journal of Plasticity in 2016.

7.4 **A VARIATIONAL FORMULATION OF THE VOLTERRA DISLOCATION RECONSTRUCTION OF 3-D MOVING CRACKS**—A. Sheng, G. Po, N.M. Ghoniem (University of California, Los Angeles) **156**

Modeling crack growth in three-dimensional geometries poses a challenging problem especially for FEM-based techniques such as EFEM or XFEM, which display some degree of mesh dependence. Additionally, existing methods are unable to investigate the interaction between cracks and other defects present in real materials. An alternative method developed in the framework of discrete Dislocation Dynamics is presented which provides a solution to these challenges by being completely mesh-independent and capable of coupling cracking with crystal plasticity. The Discrete Crack Mechanics method is a dislocation-based fracture mechanics technique that represents cracks using arrays of Volterra dislocations. In this report, a variational formulation based on the Principle of Maximum Entropy Production rate is given of the evolution equations for cracks coupled with crystal dislocations along with examples of its implementation.

7.5 **LOADING CONTROLLED TRANSITION OF PLASTIC FLOW FROM DISLOCATION AVALANCHE TO QUASI-PERIODIC STRAIN BURST BEHAVIOR**—Y.N. Cui, G. Po, N.M. Ghoniem (University of California, Los Angeles) **163**

Extended abstract of paper to be submitted for publication.

8 **MODELING PROCESSES IN FUSION SYSTEM MATERIALS**

8.1 **DEVELOPMENT OF INTERATOMIC POTENTIALS IN TUNGSTEN-RHENIUM SYSTEMS**—W. Setyawan, G. Nandipati, and R. J. Kurtz (Pacific Northwest National Laboratory) **165**

Reference data are generated using the ab initio method to fit interatomic potentials for the W-Re system. The reference data include single phases of W and Re, strained structures, slabs, systems containing several concentrations of vacancies, systems containing various types of interstitial defects, melt structures, structures in the σ and χ phases, and structures containing several concentrations of solid solutions of Re in bcc W and W in hcp Re. Future work will start the fitting iterations.

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8.2 **STRUCTURE AND MOBILITIES OF TUNGSTEN GRAIN BOUNDARIES CALCULATED FROM ATOMISTIC SIMULATIONS**—Timofey Frolov and Robert E. Rudd (Lawrence Livermore National Laboratory) **172**

Recrystallization determines the upper extent of the operating temperature of tungsten as a divertor or first-wall material. At temperatures above the onset of recrystallization, migrating grain boundaries sweep out defects that contribute to hardening. These processes make the recrystallized material unsuitable because of its brittleness. Thermomechanical models to predict recrystallization and its effect on mechanical properties have to be informed of the mechanisms of grain boundary migration under stress and other driving forces at tokamak operating temperatures. Recent experimental and computational studies suggest that addition of impurities and elevated temperatures can trigger structural transformations at grain boundaries that result in orders of magnitude increase in mobility. Here we present preliminary results demonstrating that tungsten grain boundaries do exhibit phase transformations and calculate the mobilities needed for thermomechanical models of recrystallization.

8.3 **OBJECT KINETIC MONTE CARLO SIMULATIONS OF RADIATION DAMAGE ACCUMULATION IN TUNGSTEN**—G. Nandipati, W. Setyawan, K. J. Roche, R. J. Kurtz (Pacific Northwest National Laboratory) and B. D. Wirth (University of Tennessee) **178**

We used the lattice-based object kinetic Monte Carlo code; *KSOME* [1] to perform simulations of radiation damage accumulation in bulk tungsten at 300 K and for a dose rate of 10-4 dpa/s, up to a dose of 1.0 dpa. These are ad-hoc irradiation simulations performed using a set of cascades with the same PKA energies. In this study, eight different irradiation simulations were performed using eight sets of cascades with PKA energies of 10, 20, 30, 40, 50, 60, 75 and 100 keV. Both the number density of vacancies and vacancy clusters in the simulation box appears to saturate with increasing dose in the simulation using cascades with PKA energies of 40, 50, 60, 75, 100 keV, while the same parameters increase linearly with dose in the simulations using cascades with PKA energies of 10, 20 and 30 keV. In all simulations the average vacancy cluster size remained constant with dose. However, the vacancy cluster size increases with cascade PKA energy.

8.4 **INTERACTION OF INTERSTITIAL CLUSTERS WITH RHENIUM, OSMIUM, AND TANTALUM IN TUNGSTEN**—W. Setyawan, G. Nandipati, and R. J. Kurtz (Pacific Northwest National Laboratory) **183**

In the previous semi-annual report [1], we explored the stability of interstitial clusters in W up to size seven. In this report, we study the binding of those clusters to Re, Os, and Ta atoms. For each cluster size, the three most stable configurations are considered to average the binding property. The average binding energy to a Re decreases from 0.79 eV for a size-1 cluster (a [111] dumbbell) to 0.65 eV for a size-7 cluster. For Os, the binding decreases from 1.61 eV for a [111] dumbbell to 1.34 eV for a size-7 cluster. Tantalum is repulsive to interstitial clusters with binding energy ranges from -0.61 eV for a [111] dumbbell to -0.5 eV for a size-7 cluster.

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9 FUSION SYSTEM DESIGN

9.1 MULTI-PHYSICS DESIGN OF THE FIRST WALL AND BLANKET SYSTEM IN THE FUSION NUCLEAR SCIENCE FACILITY (FNSF)—Yue Huang, Nasr Ghoniem, Mark Tillack, Jake Blanchard, Laila El-Guebaly, Chuck Kessel **188**

The dual coolant lead-lithium (DCLL) blanket concept is based on a helium-cooled first wall and blanket structure with RAFS (Reduced Activation Ferritic Steel) and a self-cooled LiPb breeding zone. 3D finite element multiphysics modeling of the DCLL first wall and blanket has been performed using *COMSOL 5.0.* The multiphysics aspect of the design is demonstrated via coupling of fluid dynamics, conjugate heat transfer and solid mechanics modules within the COMSOL. The results of primary and thermal stress of the structure were obtained. This was followed by determination of the factors of safety along three critical paths based on the ITER Structural Design Criteria for In-vessel Components (ISDC-IC). We show that the structural design meets the design rules under both normal and off-normal operating conditions, though the safety factors under off-normal condition are marginal. Thus simple design optimization was conducted based on a parametric study on first wall dimensions to improve the design.

10 IRRADIATION METHODS, EXPERIMENTS AND SCHEDULES

10.1 MINIATURE MECHANICAL TEST DEVELOPMENT FOR TUNGSTEN-BASED MATERIALS—L. M. Garrison (Oak Ridge National Laboratory), Jeremy Moon (University of Nevada-Reno), Joseph Willenborg (University of Tennessee-Knoxville) **195**

Many tungsten based composites employ tungsten foils or tungsten fibers. Understanding the mechanical properties of the composite also requires understanding the mechanical properties of the constituent elements of the composite. While certain miniaturized mechanical tests, such as tensile testing SSJ size samples, is routinely accomplished in LAMDA, the requirements for testing foils and fibers is beyond the current capabilities in the laboratory. Three mechanical tests are being developed for the foils and fibers: a) shear punch test for foils, b) 3-point bend test for foils, and c) tensile test for fibers.

10.2 DEVELOPMENT OF A NON-CONTACT STRAIN MEASUREMENT SYSTEM FOR POST IRRADIATED TENSILE TESTS AT HIGH TEMPERATURES—H. Sakasegawa, T. Kato, H. Tanigawa (National Institutes for Quantum and Radiological Science and Technology), and Y. Katoh (Oak Ridge National Laboratory) **201**

Appropriate stress strain curves were obtained applying the non-contact strain measurement system developed in this work and the system specifications were selected. Two marks were painted on the specimen gage using a mixture of paste and fluorescent powder which can be used in high vacuum at high temperatures. UV light illuminated these two marks and clear contrast was obtained to measure the distance between marks using a video camera. This system can be used for post irradiated tensile tests at high temperatures in hot cells.

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The HFIR RB-19J irradiation experiment contains six cylindrical holders (four temperature zones) which house ~1300 tungsten and steel specimens. The capsule and shield is design to be centered about the HFIR mid-plane, but the holders are slightly shifted toward the positive axial direction from the mid-plane. The assembly of the RB19J capsule was completed in May 2016 and installed in HFIR in June 2016. The first irradiation cycle, 466, started June 14, 2016. Starting temperatures stabilized within design range for the 500°C and the 800°C holders. The 1200°C and the 300°C were lower and higher than designed by about 50°C to 100°C respectively.

10.4 **HFIR-MFE-RB-19J SPECIMEN LOADING LISTING**—J.W. Geringer, J.L. McDuffee, C.M. Petrie, L.M. Garrison, R.H. Howard, N.O. Cetiner, D.A. Stringfield, R.G. Sitterson (Oak Ridge National Laboratory) **215**

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10.5 **HFIR IRRADIATION EXPERIMENTS**—J.P. Robertson, Y. Katoh and J. McDuffee (Oak Ridge National Laboratory) **234**

HFIR completed 2.7 cycles during the first half of 2016. Cycle 464 operated from January 1, until February 6, 2016, for 2101 MWdays. Cycle 465 started on February 23, and ran for 2093 MWdays, shutting down on March 18. Cycle 466 began on June 14, 2016.