4.5 MECHANICAL PROPERTIES OF NEUTRON IRRADIATED TUNGSTEN —L. L. Snead, L. M. Garrison, N.A.P. Kiran Kumar, T. S. Byun, M. R. McAlister, and W. D. Lewis (Oak Ridge National Lab)

OBJECTIVE

The objective of this work is to inform plasma-facing component development by creating a basic understanding of the effect of neutron irradiation on the mechanical properties and microstructure of tungsten.

SUMMARY

Tungsten samples of types [110] single crystal tungsten (SCW), [100] SCW, wrought tungsten foils, and annealed tungsten foils were irradiated in HFIR at temperatures from 70 to 900°C and fast neutron fluences of 0.01 to 20 ×10^{25} n/m^{2} at E>0.1 MeV. Samples that were irradiated at 2×10^{25} n/m^{2} and below were previously tensile and hardness tested at 300°C and below [1]. In this period samples irradiated at 2×10^{25} n/m^{2} and below at temperatures between 300 and 650°C were tensile tested at high temperatures. Annealed and wrought tungsten foils were hardness tested. A sample irradiated to a dose of 2.2dpa at 725°C was analyzed in the TEM.

PROGRESS AND STATUS

Introduction

Tungsten is a material of interest for high heat flux applications such as the divertor of fusion tokamaks. In this position in a fusion device, the material will be exposed to neutron irradiation at high temperatures. While tungsten has several beneficial properties such as a low sputtering yield, it has a small temperature operating window bounded by the ductile to brittle transition temperature on the low end and the recrystallization temperature on the high end. The behavior of tungsten under neutron irradiation needs to be better understood, especially the property changes with temperature. In this study, samples of single crystal tungsten and tungsten foils that had been irradiated in HFIR were analyzed in the LAMDA laboratory. Transmission electron microscopy was utilized to analyze the defect structure and phases. Hardness testing was performed using a microhardness indenter. Tensile test were performed in a vacuum furnace at 300, 500, and 650°C.

Results and Discussion

<u>TEM observation of tungsten single crystal samples</u>

Microstructural analysis on the high dose, high temperature irradiated specimens showed voids with diameter ranging from 3 to 9 nm (Figure 1). The size of voids increases with the irradiation dose and temperature. Figure 2 shows the voids in the 2.2 dpa sample. Fine needle or platelet-like precipitates were observed in specimen irradiated to a dose of 2.2 dpa at 725°C. Scanning mode TEM with energy dispersive spectroscopy (EDS) analysis showed that the precipitates are rhenium rich (χ phase) platelets formed due to transmutation of tungsten to rhenium during irradiation (Figure 3). The length of the transmuted χ phase precipitates ranged from 2 to 28 nm with an average length of 20 nm in material irradiated to 2.2 dpa at 725°C. Based on the transmutation calculations, the predicted amount of tungsten to rhenium transmutation after irradiation in HFIR to a fluence of 7 × 10^{25} n/m^{2} (E>0.1 MeV) is ≈3 at% [2]. The amount of rhenium in the sample is being calculated to compare with that prediction.

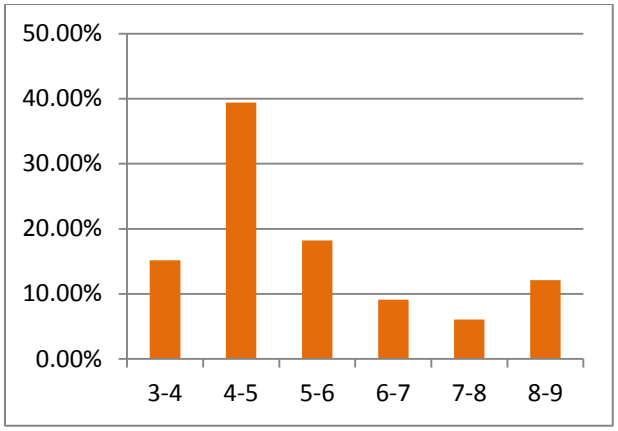

Figure 1. Void size distribution plot for sample irradiated to 2.2 dpa at 725°C.

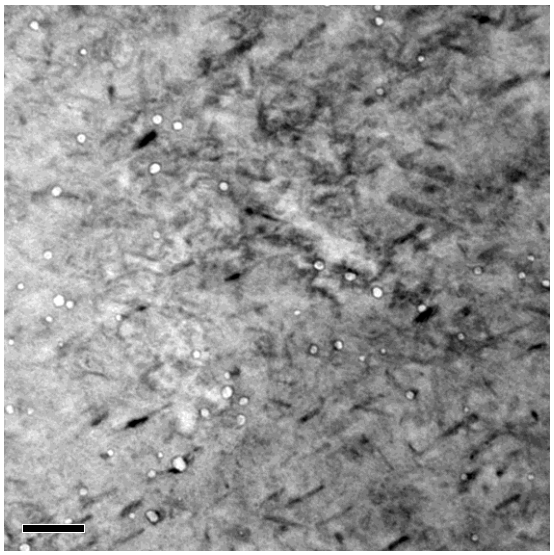

Figure 2. Under-focused TEM image showing the voids in a sample irradiated to 2.2 dpa at 725°C.

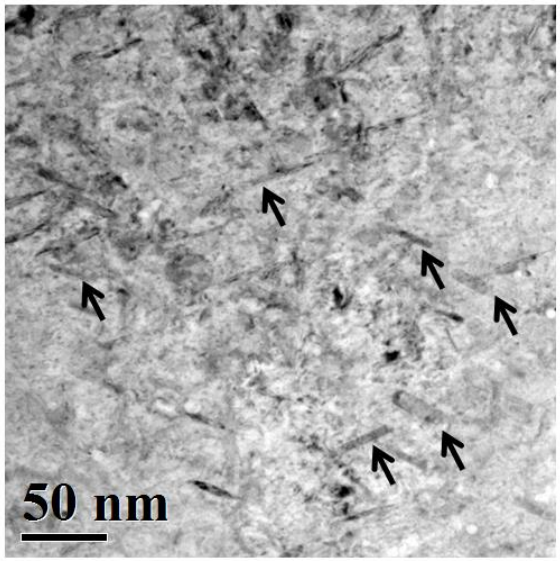

Figure 3. TEM micrograph of single crystal tungsten specimen irradiated to a dose of 2.2 dpa at 725°C. The χ-phase platelets, indicated by arrows, formed due to transmutation of tungsten to rhenium during neutron irradiation.

Hardness testing of irradiated foils

Wrought foil and annealed foils were hardness tested after irradiation to 0.02×10^{25} n/m^2 (E>0.1 MeV) and 0.1×10^{25} n/m^2 (E>0.1 MeV) at 90°C. For both irradiation doses, the wrought foil has a higher hardness than the annealed foil (Figure 4). The annealed foil is insensitive to the irradiation dose with both hardness values being approximately 400. The wrought foil showed a significant increase in hardness from 470 at 0.02×10^{25} n/m^2 to 610 at 0.1×10^{25} n/m^2.

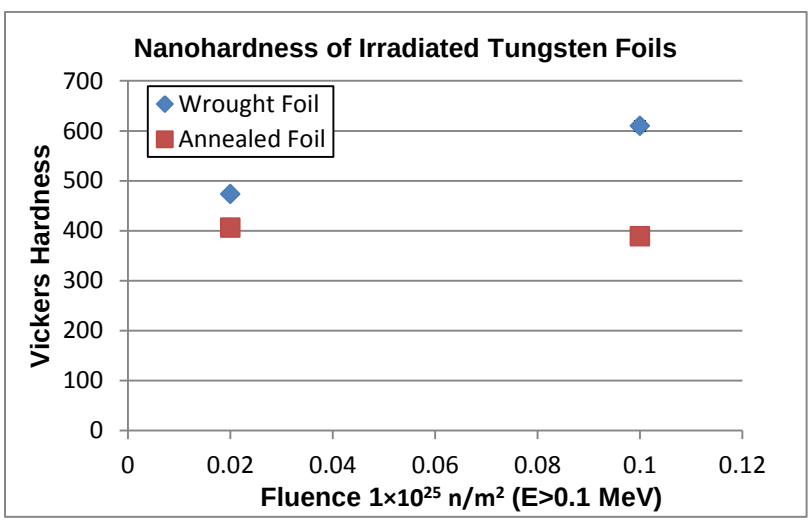

Figure 4. Hardness values for wrought and annealed foil samples after irradiation.

Comparing the hardness values of the foils with the SCW [100] and [110] values reported previously [1], the annealed foil hardness at 0.02×10^{25} n/m^2 is very close to the hardness values for both orientations of SCW irradiated to the same fluence. The annealed foil irradiated to 0.02×10^{25} n/m^2 has a slightly lower

hardness value than the SCW samples at that fluence (Figure 5). The wrought foil has a higher hardness value than the SCW samples of both orientations at both fluences tested.

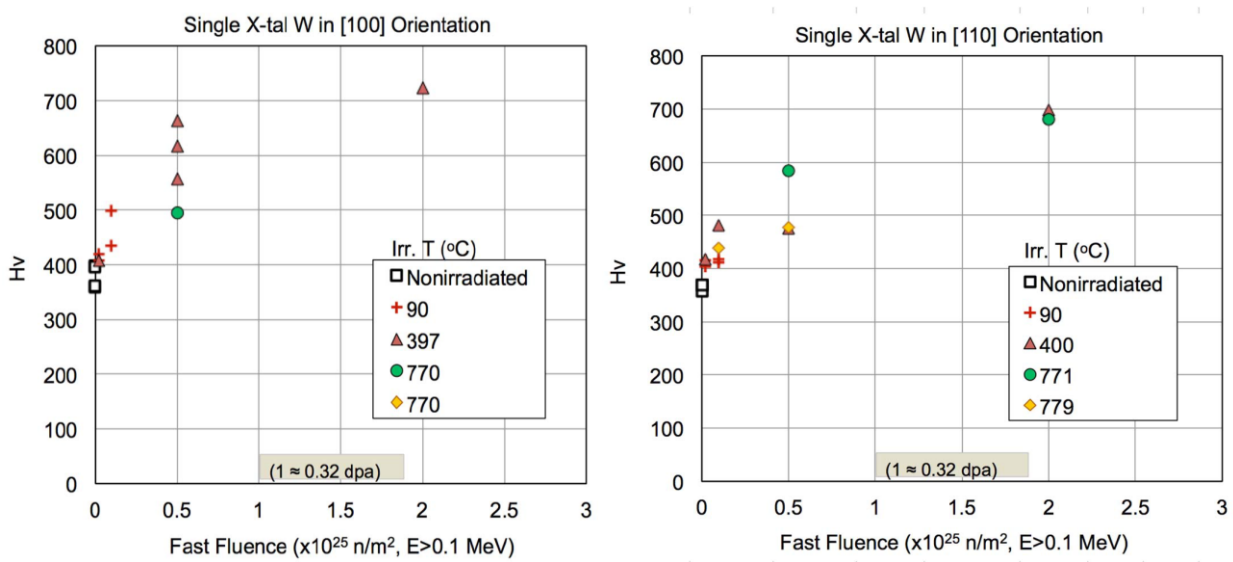

Figure 5. Hardness values of irradiated single crystal tungsten samples in orientations [110] and [100], for a range of neutron fluences and temperatures. Reprinted from Reference [1].

<u>Tensile properties at high temperatures</u>

Samples of SCW with orientation <110> along the axis of the tensile bars were tested at high temperatures. The irradiation temperatures of all irradiated tungsten samples were calculated from dialometry of silicon carbide (SiC) temperature monitors present in each irradiation rabbit capsule. Each temperature determined has a spread on the order of 50°C due to the temperature profile inside the rabbit capsule. The average temperature from the SiC monitors are used here as the temperature of the samples.

Figure 6 compares the results for samples tested at 300°C. The samples were irradiated to fluences from 0.02 to 2×10^{25} n/m^2 at temperatures from 337 to 408°C. Results for an unirradiated sample are included for comparison. The unirradiated sample had significant elongation, at least 50% before failure. As the irradiation fluence was increased, the yield stress also increased. However the elongation did not follow a simple trend with increasing fluence. The sample 1W02, irradiated to 0.02×10^{25} n/m^2, had less elongation than the sample 1W49, irradiated to 0.5×10^{25} n/m^2. The sample 1W08 irradiated to the highest fluence of 2×10^{25} n/m^2 was fully brittle and fractured at the yield strength.

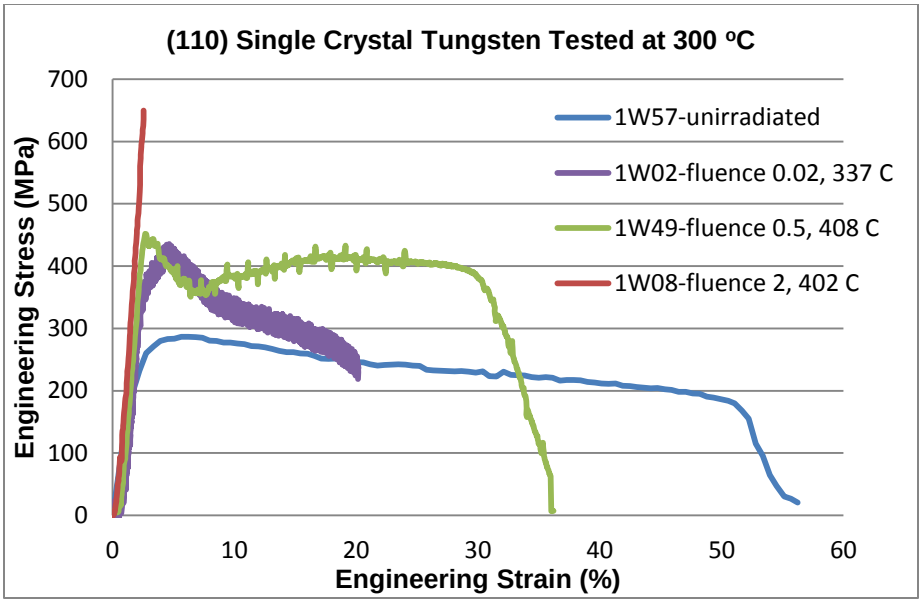

Figure 6. Samples tensile tested at 300°C after irradiation. Fluences are in units 1×10^{25} n/m^2 (E>0.1MeV). Irradiation temperatures of the samples are indicated in the figure legend.

The samples tested at 500°C show a clear trend of increasing yield stress and decreasing total elongation with increasing fluence (Figure 7). These samples were irradiated to fluences of 0.1 to 2×10^{25} n/m^2 at temperatures from 616 to 740°C. Sample 1W18 irradiated to 2×10^{25} n/m^2 at 634°C had the highest ultimate tensile strength of all of the samples tested at 300, 500, and 650°C. Comparing sample 1W52 tested at 500°C to 1W49 tested at 300°C after both were irradiated to 0.5×10^{25} n/m^2, sample 1W52 had a yield stress higher by about 50 MPa but also had significantly less elongation, only around 13% compared to at least 30% in sample 1W49.

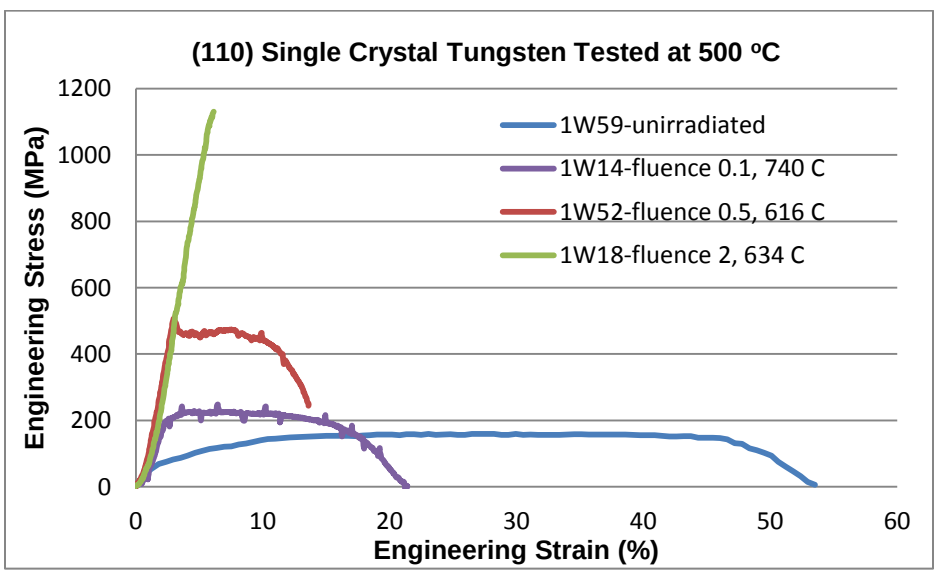

Figure 7. Samples tensile tested at 500°C after irradiation. Fluences in the figure legend are in units 1×10^{25} n/m^2 (E>0.1MeV). Irradiation temperatures are indicated in the figure legend.

The samples irradiated to fluences of 0.1 and 0.5×10^{25} n/m^2 at 710 and 675°C, respectively, and tensile tested at 650°C showed a similar trend to the samples tested at 300°C, in that the sample irradiated to 0.5×10^{25} n/m^2 had a higher yield stress than the sample irradiated to 0.1×10^{25} n/m^2 but the higher fluence sample had greater elongation. Sample 1W24 irradiated to 0.1×10^{25} n/m^2 and tested at 650°C exhibited only around 13% elongation and an ultimate strength of approximately 280 MPa, while sample 1W14 irradiated to the same fluence but tested at 500°C had close to 20% elongation and an ultimate strength of nearly 220 MPa. The samples irradiated to 0.5×10^{25} n/m^2 showed the opposite relationship with test temperature; sample 1W54 has a lower ultimate strength and the greater total elongation than 1W52.

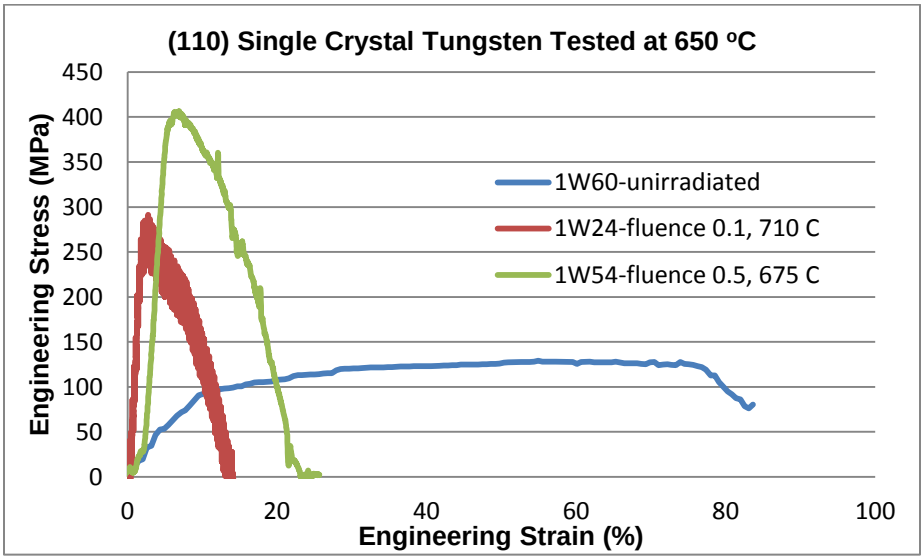

Figure 8. Samples tensile tested at 650°C after irradiation. Fluences in the figure legend are in units 1×10^{25} n/m^2 (E>0.1MeV). Irradiation temperatures are indicated in the figure legend.

REFERENCES

[1] L.L. Snead, L.M. Garrison, T.S. Byun, N.A.P. Kiran Kumar, W.D. Lewis, Fusion Materials Semiannual Progress Report for Period Ending December 31, 2013, DOE/ER-0313/55, 40-47.
[2] L.R. Greenwood, F.A. Garner, J. Nucl. Mater., 212-215 (1994) 635-639.