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

OBJECTIVE

The objective of this work is to evaluate the effects of neutron irradiation on the mechanical properties and microstructure of tungsten-based materials to aid in developing plasma-facing materials for fusion reactors.

SUMMARY

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.

PROGRESS AND STATUS

Detailed microstructural analysis was completed on selected irradiated single crystal and polycrystalline tungsten samples. Irradiated tungsten transmutes to rhenium and rhenium transmutes to osmium.The rhenium and osmium precipitate out of the tungsten matrix due to irradiation induced precipitation and form needle-shaped precipitates. TEM investigation of both single crystal and polycrystalline tungsten revealed an association between the needle-shaped precipitates and voids in irradiated tungsten (Figure 1).

The last two capsules from the TITAN campaign, TB-650-4 and T9G-13, were opened and the specimens cataloged at the hot cells. The target irradiation conditions for these capsules were TB-650-4: 20×10^{25} n/m^2 at 650°C and T9G-13: 12×10^{25} n/m^2 at 300°C. The preliminary analysis of the SiC temperature monitors from capsule T9G-13 revealed the irradiation temperature was between 400 and 500°C. Based on other capsules in this campaign, the irradiation temperature of TB-650-4 is expected to be in the range of 700-800°C. The SiC temperature monitors for TB-650-4 are planned to be tested.

Radioactivity of all specimens from T9G-13 were measured and specimens packaged in several lead pigs, as noted in Table 1, for shipment to LAMDA. Pigs CCC, III, JJJ, and HHH were shipped to LAMDA, and the samples have been inspected and cleaned.

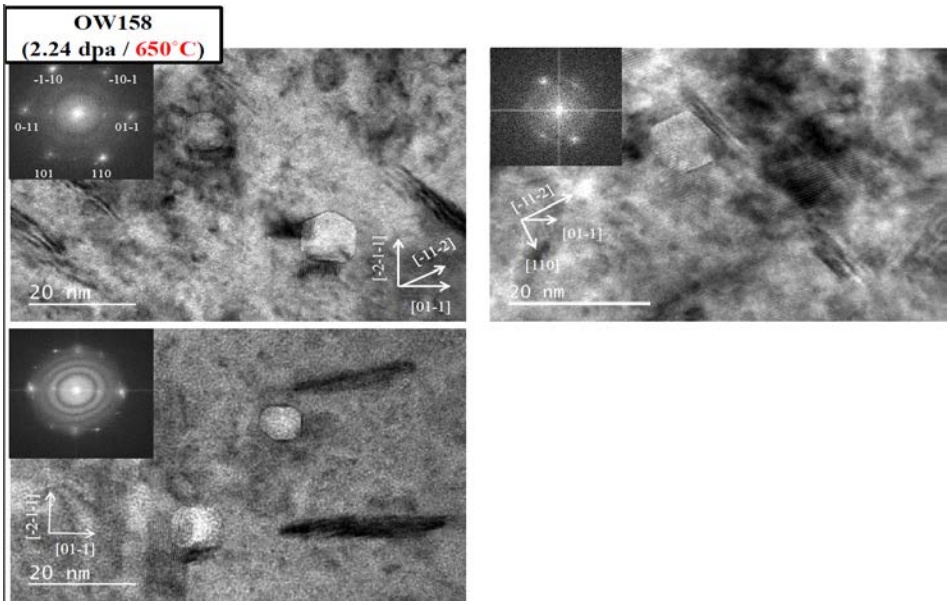

Figure 1. Polycrystalline wrought foil tungsten sample OW158 was imaged with TEM after irradiation to 2.24 dpa at an estimated 650°C irradiation temperature. The voids are faceted and appear associated with neighboring needle-shaped Re and Os rich precipitates in the tungsten matrix.

Table 1. Dose measurements for samples from rabbit capsule T9G-13

Specimen	**Open Contact**	**Closed 1 Ft DR**	**Smear #**	**Smear B/G**	**Smear Alpha**	**PIG**	DR @ a ft OT/@ 5" on side
W11	7 R/hr	7.2 mr/hr	4	6952	<Lc	FY16-CCC	128 mr/hr / 142 mr/hr
T9G-13 Foils	>10 R/hr	64 mr/hr	4	6952	<Lc	FY16-CCC	128 mr/hr / 142 mr/hr
HK40 (4X16X0.5)	>10 R/hr	187 mr/hr	4	6952	<Lc	FY16-CCC	128 mr/hr / 142 mr/hr
P13	>10 R/hr	155 mr/hr	4	6952	<Lc	FY16-EEE	110 mr/hr / 155 mr/hr
AW013 Foil	5 R/hr	10 mr/hr	4	6952	<Lc	FY16-EEE	110 mr/hr / 155 mr/hr
OW011 Foil	7.6 R/hr	9.2 mr/hr	4	6952	<Lc	FY16-DDD	105 mr/hr / 155 mr/hr
S9902	7.8 R/hr	71 mr/hr	4	6952	<Lc	FY16-DDD	105 mr/hr / 155 mr/hr
SOO02	8.7 R/hr	69 mr/hr	4	6952	<Lc	FY16-DDD	105 mr/hr / 155 mr/hr
T0015	8.5 R/hr	72 mr/hr	4	6952	<Lc	FY16-FFF	108 mr/hr / 115 mr/hr
T9915	>10 R/hr	100 mr/hr	4	6952	<Lc	FY16-FFF	108 mr/hr / 115 mr/hr
April 13th							
9BA24	>10 R/hr	130 mr/hr	4	6952	<Lc	FY16-GGG	100 mr/hr / 125 mr/hr
SW10	>10 R/hr	47 mr/hr	4	6952	<Lc	FY16-	100 mr/hr / 125

						GGG	mr/hr
1W12	>10 R/hr	6 mr/hr	4	6952	<Lc	FY16-GGG	100 mr/hr / 125 mr/hr
SW09	>10 R/hr	30 mr/hr	4	6952	<Lc	FY16-HHH	125 mr/hr / 120 mr/hr
T9G-13 Bar ID # ?	>10 R/hr	80 mr/hr	4	6952	<Lc	FY16-HHH	125 mr/hr / 120 mr/hr
OBA02	>10 R/hr	90 mr/hr	4	6952	<Lc	FY16-HHH	125 mr/hr / 120 mr/hr
Tem Monitors	55 mr/hr	1 mr/hr	4	6952	<Lc	FY16-III	95 mr/hr / 110 mr/hr
LW917	>10 R/hr	70 mr/hr	4	6952	<Lc	FY16-III	95 mr/hr / 110 mr/hr
GB05	>10 R/hr	93 mr/hr	4	6952	<Lc	FY16-III	95 mr/hr / 110 mr/hr
1W11	>10 R/hr	6.5 mr/hr	4	6952	<Lc	FY16-III	95 mr/hr / 110 mr/hr
W12	9.8 R/hr	6 mr/hr	4	6952	<Lc	FY16-JJJ	150 mr/hr / 175 mr/hr
9BA23	>10 R/hr	130 mr/hr	4	6952	<Lc	FY16-JJJ	150 mr/hr / 175 mr/hr
9BA15	>10 r/hr	130 mr/hr	4	6952	<Lc	FY16-JJJ	150 mr/hr / 175 mr/hr
A7/B2 (4X4X0.5)			4	6952	<Lc		
LW918	>10 R/hr	68 mr/hr	4	6952	<Lc	FY16-KKK	Partial
FD01			4	6952	<Lc		High Dose In Cell 6
FD02			4	6952	<Lc		High Dose In Cell 6

Previously, microhardness was measured on single crystal tungsten samples that had been irradiated up to approximately 1 dpa. The hardness was not sensitive to irradiation temperature and was increasing rapidly with increasing dose. To test if the hardness saturated, three higher dose samples were hardness tested (Figure 2). Now, it is seen that up to a dpa of 4.5 the hardness has not yet saturated.

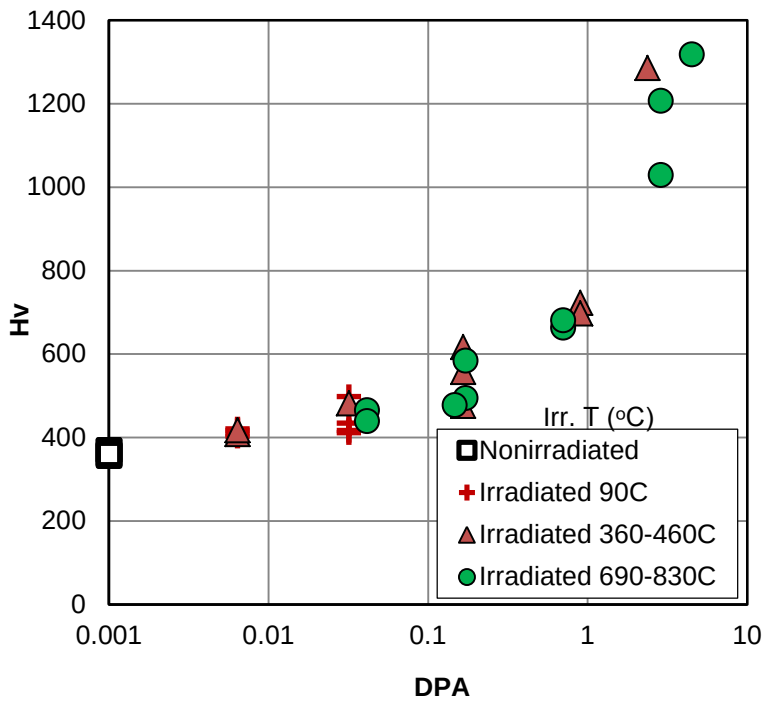

Figure 2. Microhardness on irradiated single crystal tungsten before and after HFIR irradiation.

Many of the lower dose tensile tests on the single crystal tungsten have been completed and the results are summarized in Table 2. Samples with an ID that begins with "1W" are single crystal tungsten with <110> crystal direction along the tensile direction. Those samples whose IDs begin with "W" are single crystal tungsten with <100> crystal direction along the tensile direction.

Table 2. Tensile properties of single crystal tungsten samples

ID	Irradiation T (°C)	Fast Fluence ($\times 10^{25}$ n/m^2, E>0.1 MeV)	DPA	Test T (°C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
1W24	830	0.13	0.042	650	261	278	0.96	13.7
1W02	370	0.02	0.0064	300	376	440	1.8	18.7
W02	370	0.02	0.0064	300	472	476	0.18	5.1
1W49	360	0.52	0.17	300	471	471	0.23	35.0
1W14	800	0.08	0.026	500	206	238	4.0	20.6
W25	830	0.13	0.042	650	241	286	4.4	19.7
1W18	700	2.2	0.70	500	1176	1214	0.35	0.51
1W54	800	0.46	0.15	650	407	424	1.5	21.1
1W08	430	2.82	0.90	300	brittle failure	683	0	0
1W52	690	0.54	0.17	500	518	530	0.02	12
1W01	370	0.02	0.0064	22	brittle failure	756	0	0

1W05	90	0.02	0.0064	22	654	671	0.45	0.49
1W13	800	0.08	0.026	22	brittle failure	627	0	0
1W17	700	2.2	0.70	22	brittle failure	359	0	0
1W23	830	0.13	0.042	22	brittle failure	813	0	0
1W25	90	0.1	0.032	22	674	674	0.2	0.2
1W47	460	0.1	0.032	22	brittle failure	844	0	0
1W50	360	0.52	0.17	22	brittle failure	507	0	0
1W51	690	0.54	0.17	22	brittle failure	393	0	0
1W53	800	0.46	0.15	22	brittle failure	592	0	0
W01	370	0.02	0.0064	22	brittle failure	776	0	0
W08	430	2.82	0.90	22	brittle failure	225	0	0
W13	800	0.08	0.026	22	brittle failure	460	0	0
W24	830	0.13	0.042	22	brittle failure	416	0	0
W27	800	0.46	0.15	22	brittle failure	385	0	0
W52	360	0.52	0.17	22	brittle failure	716	0	0
W54	690	0.54	0.17	22	brittle failure	286	0	0
W03	460	0.1	0.032	22	brittle failure	742	0	0
W56	N/A	N/A	N/A	22	brittle failure	322	0	0
W57	N/A	N/A	N/A	90	brittle failure	298	0	0
W58	N/A	N/A	N/A	300	222	507	3.3	3.3
W59	N/A	N/A	N/A	500	66	204	30	45
W60	N/A	N/A	N/A	650	60	188	73	94

For tungsten samples that were part of the TITAN program, the conversion of 0.32 dpa=1E25 n/m^2 (E>0.1 MeV) has been used in all reports so far. Upon recent analysis, it was determined that a lower dpa conversion rate may be more accurate for these samples, but there is not a consensus in the literature. For example, M. E. Sawan, Fusion Eng. Des., 87(5-6), 551-555 (2012) uses the conversion 0.195 dpa=1E25 n/m^2 (E>0.1 MeV), but M. Fukuda, K. Yabuuchi, S. Nogami, A. Hasegawa, and T. Tanaka, J. Nucl. Mater., 455(1-3), 460-463 (2014) uses the conversion 0.167 dpa=1E25 n/m^2 (E>0.1 MeV). This issue of calculating the dpa in tungsten in the flux trap of HFIR is being further investigated.