4.7 NEUTRON IRRADIATION EFFECTS IN TUNGSTEN - L.M. Garrison, L.L. Snead, X. Hu, T. Koyanagi, N.A.P. Kiran Kumar (Oak Ridge National Laboratory), M. Fukuda (Tohoku University, Japan) and K. Yabuuchi (Tohoku University, Japan)

OBJECTIVE

The objective of this work is to evaluate the effect of neutron irradiation on the mechanical properties of tungsten with selected microstructures 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. 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. Each rabbit irradiation capsule also contained silicon carbide (SiC) samples to be used as temperature monitors. The post-irradiation analysis of the SiC samples has been completed, and the estimated tungsten irradiation temperatures were determined. A subset of single crystal [110] samples was selected to study the effects of annealing on recovering mechanical properties and defects through positron annihilation spectroscopy (PAS) and hardness testing.

PROGRESS AND STATUS

PAS and Hardness Tests

Samples 1W05 and 1W25 were selected for PAS and hardness testing. The samples were tested after irradiation, and then the tests were repeated after 1 hour anneals at 400, 500, and 650°C. Comparing the unirradiated to the as-irradiated state of 1W05 (Figure 1 and Table 1) and 1W25 (Figure 2 and Table 2), showed that each sample experienced a large increase in the mean positron lifetime. After each subsequent annealing step, the lifetime has continued to increase for each sample up to 322 ps in 1W05 and 339 ps in 1W25 after the 650°C anneal. At all measured points, sample 1W25, irradiated to the higher fluence, had a longer mean lifetime than sample 1W05.

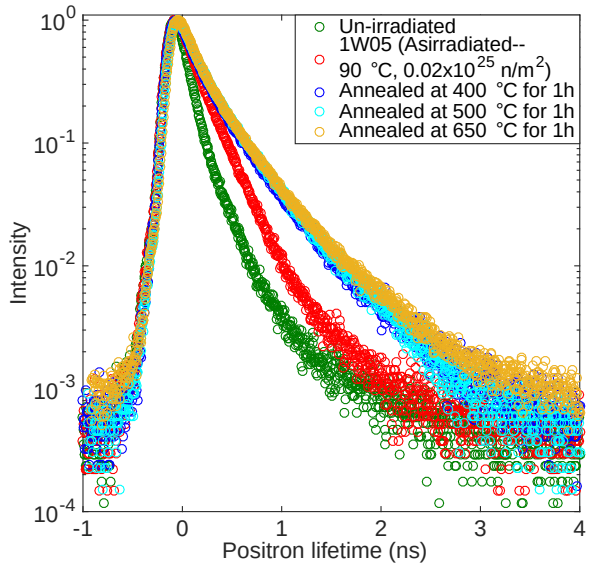

Figure 1. PAS results on 1W05 after irradiation and after three annealing stages.

Table 1. PAS data for sample 1W05.

Samples	τ_1 (ps)	τ_2 (ps)	τ_3 (ps)	I_1 (%)	I_2 (%)	I_3 (%)	Mean Lifetime (ps)
Unirradiated	91	184	489	70	23	7	140
1W05	124	231	516	26	69	5	218
Annealed at 400 °C	95	189	452	8	42	50	312
Annealed at 500 °C	108	269	510	20	46	34	318
Annealed at 650 °C	101	232	507	18	41	41	322

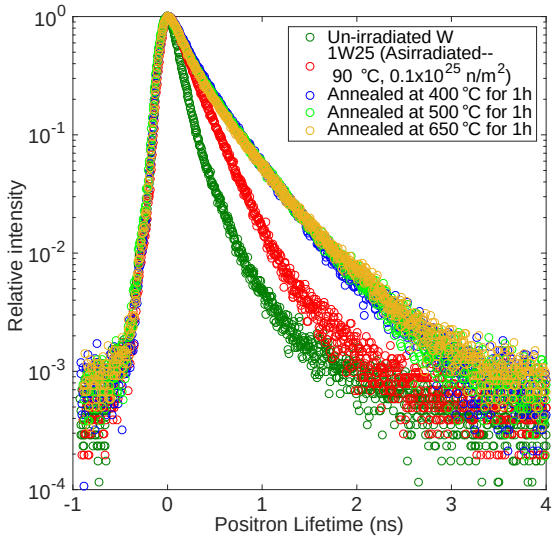

Figure 2. PAS results for sample 1W25.

Table 2. PAS data for sample 1W25.

Samples	τ_1 (ps)	τ_2 (ps)	τ_3 (ps)	I_1 (%)	I_2 (%)	I_3 (%)	Mean Lifetime (ps)
Unirradiated	91	184	489	70	23	7	140
1W25	125	220	525	15	78	7	228
Annealed at 400 °C	122	203	414	12	22	66	332
Annealed at 500 °C	118	314	574	18	56	26	345
Annealed at 650 °C	108	283	545	20	45	35	339

From the PAS data, information about the vacancy cluster size can be extracted (Figure 3). Five-component analysis is used, four of which have fixed lifetimes: 200, 260, 330, and 437 ps, equivalent to three-dimensional vacancy clusters of sizes of about 0.312 (1V), 0.49 (4V), 0.67 (10V) and >1.14 (50V) nm in diameter, respectively. For both samples, the vacancy clusters grew after each annealing step.

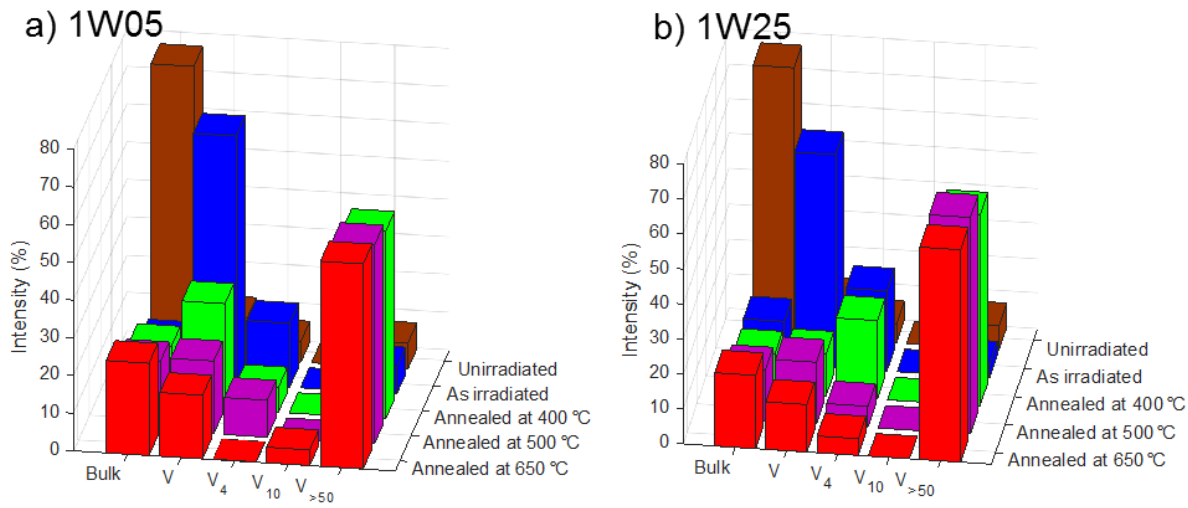

Figure 3. Vacancy cluster evolution in samples a) 1W05 and b) 1W25 after irradiation and annealing.

Hardness was measured on samples 1W05 and 1W25 after each annealing step (Figure 4). The hardness values increased after each annealing step. This is caused by the microstructural changes such as cluster growth in the materials during annealing. The experiment will continue with annealing at 800, 1000, and 1300°C. TEM analysis will also be conducted on the samples to aid in understanding the hardness changes.

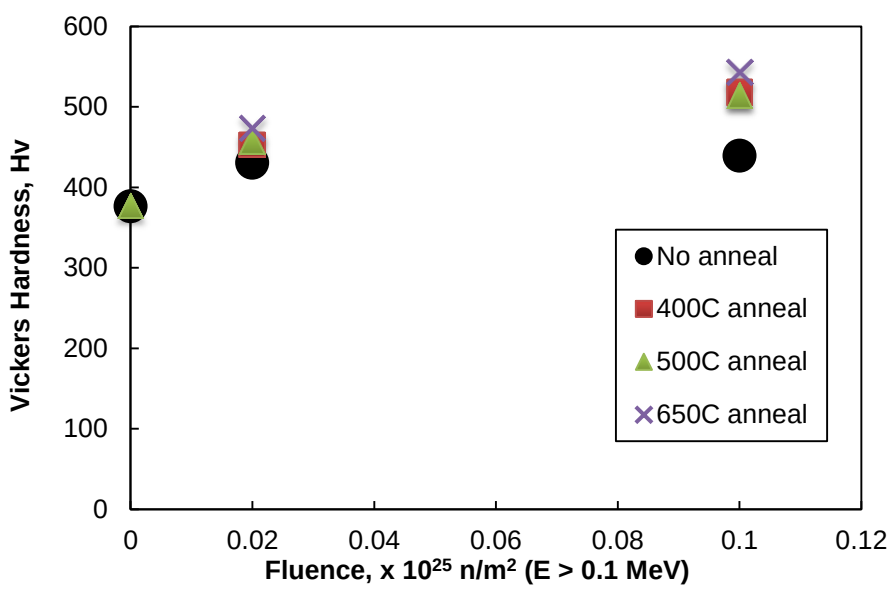

Figure 4. Hardness of 1W05 and 1W25 after annealing.

<u>Sample Temperatures during Irradiation</u>

The length changes of the SiC temperature monitors from each rabbit capsule were measured during heating and cooling. A program in the software R, written by Anne Campbell, was used to analyze the SiC data to extract the irradiation temperatures. The program allows the analysis of SiC data to be more repeatable and reduces the operator bias in analyzing the data. There is still an element of human

interpretation for the more difficult data sets, so the values obtained should be considered within an uncertainty on the order of 10°C. The version "TM_Analysis 20141017 new first guess.R" was used to analyze these data. The results of the SiC data fitting are reported in Table 3 under the heading "Values from curve fitting measured SiC data."

To relate the SiC irradiation temperatures to the W sample temperatures, an Ansys model by Nesrin Cetiner was used. In the Ansys model, the Top and Bottom sections of each rabbit are assumed to be identical, so are not independently modeled. To obtain the estimated W sample temperatures during irradiation, the difference between the SiC and W sample temperature in the Ansys model is added to the temperature obtained from the curve fitting of the SiC data. The final result is listed in the far right column in Table 3. All the W sample irradiation temperatures are higher than the target temperatures for which the capsules were designed.

Table 3. Measured and modeled temperature values for the irradiation capsules.

				Values from curve fitting measured SiC data			Values from Ansys thermal model			Result
	Rabbit Capsule	SiC sample ID	Target temp (°C)	Max (°C)	Median (°C)	Min (°C)	SiC (°C)	W (°C)	Dif. SiC to W (°C)	W sample temperature (°C)
Top	TB-300-1	658	300	333.8	318	NaN	268	320	52	370
	TB-300-2	675	300	427.9	409	393.4	268	320	52	461
	TB-300-3	686	300	343.1	311.4	291.4	268	320	52	363.4
	T9G-11	603	300	393	376.7	356.3	269	319	50	426.7
	TB-500-1	699	500	743.4	728.6	708.1	457	526	69	797.6
	TB-500-2	709	500	663.5	620	590.8	457	526	69	689
	TB-500-3	582	500	712.9	704.2	673.2	459	524	65	769.2
	T9C-14	644	500	668.2	638.6	615.1	458	524	66	704.6
	TB-650-1	646	650	746.7	724	697.6	585	695	110	834
	TB-650-2	723	650	703.9	686.9	646.6	585	695	110	796.9
Middle	TB-300-1	664	300	370	360.3	349.9	278	325	47	407.3
	TB-300-2	670	300	428.3	414.3	399.4	278	325	47	461.3
	TB-300-3	690	300	384.6	365	351.8	278	325	47	412
	T9G-11	601	300	422.2	393.5	373.7	279	325	46	439.5
	TB-500-1	695	500	776.6	737.7	720.9	472	533	61	798.7
	TB-500-2	712	500	744.4	722.3	715.3	472	533	61	783.3
	TB-500-3	581	500	741.1	733.8	710.6	473	530	57	790.8
	T9C-14	638	500	690.7	667.4	669.1	474	531	57	724.4
	TB-650-1	649	650	685.7	681.7	661.5	613	712	99	780.7
	TB-650-2	718	650	682.6	646.3	576.6	613	712	99	745.3

Continued

				Values from curve fitting measured SiC data			Values from Ansys thermal model			Result
	Rabbit Capsule	SiC sample ID	Target temp (°C)	Max (°C)	Median (°C)	Min (°C)	SiC (°C)	W (°C)	Dif. SiC to W (°C)	W sample temperature (°C)
Bottom	TB-300-1	665	300	382.7	362.1	345.7	268	320	52	414.1
	TB-300-2	679	300	412.4	396	377.4	268	320	52	448
	TB-300-3	682	300	386.2	368	347.6	268	320	52	420
	T9G-11	597	300	424.3	401.5	387.2	269	319	50	451.5
	TB-500-1	703	500	696.2	681.5	645.4	457	526	69	750.5
	TB-500-2	710	500	615.1	598.4	582.1	457	526	69	667.4
	TB-500-3	583	500	609.2	567.8	535.3	459	524	65	632.8
	T9C-14	642	500	659.2	640	613.7	458	524	66	706
	TB-650-1	656	650	692.9	666.1	637.4	585	695	110	776.1
	TB-650-2	588	650	670.1	649.4	627.8	585	695	110	759.4