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The effect of 800 MeV proton irradiation on the mechanical properties of tungsten at room temperature and at 475 °C

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Abstract

For the accelerator production of tritium (APT), the accelerator driven transmutation facility (ADTF), and the advanced fuel cycle initiative (AFCI), tungsten is being proposed as a target material to produce neutrons. In this study, tungsten rods were irradiated at the 800 MeV Los Alamos Neutron Science Center (LANSCE) proton accelerator for six months. After irradiation to a maximum dose in the tungsten of 23.3 dpa at T_{irr} = 50–270 °C, the rods were sliced into sections, hardness tests were performed at room temperature, and compression tests were performed at room temperature and at 475 °C to assess the effect of irradiation on the mechanical properties of tungsten. The results show an increase in strength and a decrease in ductility with dose. Specimens tested at 475 °C had lower yield strength and reduced work hardening capability compared to specimens tested at room temperature.
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1. Introduction

Tungsten is being considered for use as a primary or backup neutron source in many spallation neutron source applications such as the APT [1], ADTF [2], the spallation neutron source (SNS) [3], KENS (the spallation neutron source at the High Energy Accelerator Research organization, KEK) [4] and the accelerator transmutation of waste (ATW) projects [2]. For such applications the irradiation temperature is close to the ductile-to-brittle transition temperature (DBTT) for unirradiated tungsten, which ranges from 65 to 700 °C depending on the impurity content, grain size and heat treatment of the tungsten [5–7]. Therefore, tungsten is quite notch sensitive in this temperature regime, making it difficult to measure its true tensile properties. Very often, the tungsten specimens break in the elastic region before reaching yield [8,9]. Therefore to avoid brittle fracture, the mechanical properties of tungsten in this study have been measured in compression after irradiation in a proton beam.

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2. Background

The effects of irradiation on tungsten have been studied previously but have mainly concentrated on the recovery of defects in irradiated tungsten [10–16]. The irradiation temperature of the tungsten in this paper is between 50 and 270 °C. These temperatures are in the stage III recovery range for tungsten. Much debate has centered on the defects responsible for recovery in stage III. Kim and Galligan [12], present strong arguments that the irradiation-produced interstitials must be the mobile defects responsible for recovery during this stage because the measured activation energy, 1.7 eV, is too low to support vacancy migration and single vacancies are always observed after stage III recovery.

A few papers have been written on the mechanical properties of tungsten after irradiation [6,7,9,17]. In these studies, the mechanical properties were either measured in bending or in tension or inferred through hardness measurements. When the properties were measured in bending or tension (at 300 °C or below), the specimens broke in the elastic regime or fractured after very low strains at 200 °C (less than 1% uniform elongation at 200 °C [6]). In one study, the Vickers micro-hardness was measured after irradiation in a proton beam [17]. These results showed an increase in hardness from 489 to 563–583 kg/mm^2 after irradiation to a dose of 3.7×10^{20} protons (∼2.4 dpa). The calculated irradiation temperature was 120–300 °C.

In this paper, the mechanical properties of tungsten are presented after irradiation in an 800 MeV, 1 mA proton beam to a maximum dose of 23 dpa. The properties were measured by means of compression testing and hardness testing performed either at room temperature or at 475 °C.

3. Experimental

High purity tungsten (99.95%) was obtained from Plansee Corporation [18] in the form of ∼3 mm diameter wrought rods, hot pressed, sintered and forged from powder metallurgical material. Two different rod sizes of tungsten were irradiated. One was 2.6 mm in diameter and a second was 3.2 mm in diameter. The grain size of both unirradiated materials ranged from 20 μm to 40 μm. These rods were slip clad with either 0.25 mm thick 304 L SS tubing (for the 2.6 mm diameter rods) or 0.125 mm-thick Alloy 718 tubing (for the 3.2 mm diameter rods) and backfilled with helium. The clearance between the rod and the cladding was 0.013 mm on the radius. Bundles containing 19 rods each were held in tubes and cooled with flowing water [19]. The 2.6 mm diameter rods were irradiated for six months and the 3.2 mm diameter rods for two months with an 800 MeV, 1 mA proton beam with a Gaussian distribution (two sigma = 3.2 cm). Each tungsten rod was 10 cm long allowing the accumulation of a range of doses on each rod from the center of the rod to the ends.

The fluence determination (see results in Table 1) for the irradiated samples was performed through analysis of an activation foil package that was irradiated in the center of each clad rod. The activation foil packages

Table 1
Irradiation conditions and testing conditions for tungsten specimens

Sample no.	Dose (dpa)	Tirr (°C)	Calculated H (appm)	Calculated He (appm)	Usage	Test temperature (°C)
W1-3	21.9	250	10 300	1900	Hardness	RT
W1-5	17.6	190	8300	1500	Compression	RT
W1-6	14.9	160	7000	1300	Compression	RT
W1-7	2.8	50	1300	250	Compression	RT
W1-8	3.2	50	1500	270	Compression	RT
W1-9	3.7	50	1800	320	Hardness	RT
W1-10	4.6	60	2100	400	Compression	RT
W1-12	4.0	160	1600	290	Compression	RT
W1-13	3.8	160	1600	280	Hardness	RT
W1-16	2.8	120	1100	200	Compression	RT
W1-17	0.6	60	200	40	Compression	RT
W1-18	0.7	60	300	50	Hardness	RT
W1-19	0.9	60	400	70	Compression	RT
W1-21	1.5	80	600	110	Compression	RT
W1-22	23.3	270	11 000	2020	Compression	RT
W1-23	22.5	222	10 100	1900	Compression	475
W1-24	20.3	188	9100	1700	Compression	475
W1-25	3.0	45	1300	250	Compression	475
W1-26	4.0	50	1800	330	Compression	475