Nuclear Materials and Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

Effects of helium on mechanical properties of tungsten for fusion applications

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ARTICLE INFO

Keywords:
Tungsten
Helium implantation
Tensile properties
Recrystallization

ABSTRACT

The effects of helium (He) on mechanical properties of hot-rolled pure W were investigated using a high-energy He-implantation technique and post-implantation tensile tests. After the He implantation, the tensile specimens were heat treated at 1100 °C for 100 h in order to recrystallize the pure W. The post-implantation tensile tests were conducted in vacuum at 400 and 700 °C. The post-implantation annealed specimens showed almost the same hardness as-received unimplanted specimens. Tensile properties of He-implanted specimens after the post-implantation annealing indicated almost the same trend as those of as-received specimens under these experimental conditions. Dimples were formed and ductile fracture was observed on the ruptured surface of all specimens. No grain-boundary fracture surface was observed under these experimental conditions. The results showed that He clusters would suppress the recrystallization of hot-rolled pure W because the He clusters might form on dislocations in low angle grain boundaries or in cell walls in the matrix. Because of the suppression of recrystallization by the He clusters, the tensile properties of He-implanted specimens after post-implantation annealing show almost the same trend as those of as-received specimens under the experimental conditions. The results indicate that 20 appm of He implantation is level enough to suppress the recrystallization of pure W.

1. Introduction

Tungsten (W) is the most promising material for use as the divertor material for fusion reactors because of its high melting temperature, high resistance for sputtering and low tritium inventory. During fusion reactor operation, the divertor will be exposed to high-flux neutron irradiation, which results in displacement damage and nuclear transmutation elements in the component materials of the divertor. Solid elements such as rhenium (Re) and osmium (Os), and gaseous elements such as helium (He) and hydrogen (H) will be produced in the W matrix by nuclear transmutation reactions. The effects of Re and Os on material properties have been studied for several years [1]. Helium-induced hardening effect in W has been studied [2], while fracture behavior on He-implanted W have not yet been studied.

Helium is insoluble in all metals and is easily precipitated on defects or interfaces in materials such as point defect clusters, dislocations, precipitates and grain boundaries [3]. It is well known that He precipitation on the grain boundary of metals causes grain-boundary embrittlement [4]. Helium production in W by the transmutation reaction is estimated to be approximately 20 appm for the operation of DEMO for 5 years [5]. In the case of austenitic stainless steels, it is known that just 5 appm He causes grain-boundary embrittlement at high temperatures [6,7]. The grain-boundary embrittlement caused by He strongly depends on the He concentration, test temperature, and material. In contrast, low-temperature embrittlement is a well-known characteristic property of W. The low ductile-brittle transition temperature of the matrix and the weak grain-boundary bonding strength of W are considered the main reasons for the embrittlement, but the effects of He on the mechanical properties of W at a lower temperature and at the temperature of reactor operation have not yet been clarified. The present study aimed to clarify the effects of He on mechanical properties of pure W using tensile tests.

2. Experimental

Examined material of this work is a powder metallurgical processed pure W followed by hot rolling and stress relieved at 900 °C for 20 min (supplied by A.L.M.T Ltd. Japan). Detailed material data such as the fabrication process and chemical composition are described in the literature [8]. A small tensile specimen (SS-J) with a thickness of 0.23 mm

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https://doi.org/10.1016/j.nme.2018.04.003
Received 15 December 2017; Received in revised form 21 February 2018; Accepted 6 April 2018

Please cite this article as: Miyazawa, T., Nuclear Materials and Energy (2018), https://doi.org/10.1016/j.nme.2018.04.003

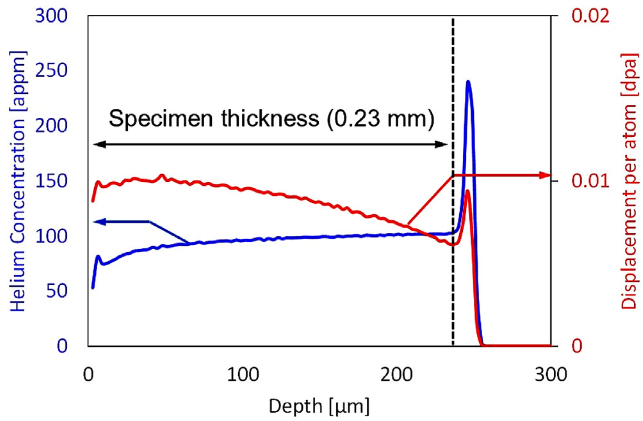

Fig. 1. Distribution of He and displacement damage in W calculated using the SRIM code [9] when the He concentration at the uniformly implanted region was 100 appm.

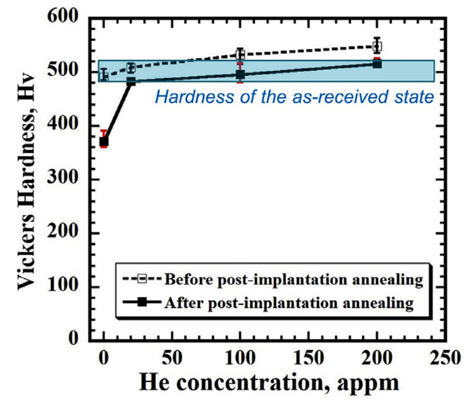

Fig. 2. Dependence of Vickers hardness on He concentration before and after post-implantation annealing.

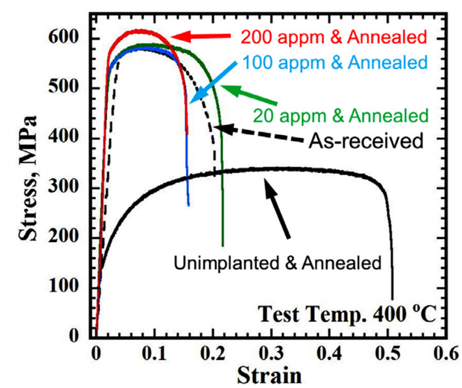

Fig. 3. Tensile stress–strain curves at 400 °C.

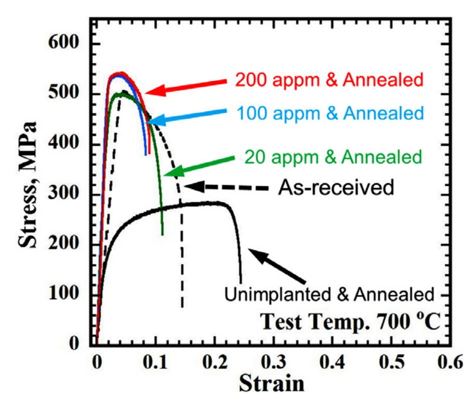

Fig. 4. Tensile stress–strain curves at 700 °C.

was fabricated by electric discharge machining (EDM). The gauge section of the tensile specimens was 5 mm long and 1.2 mm wide. The surface was mechanically polished by the emery paper with the roughness of #1500.

Helium implantation was performed using the 50 MeV α-particle (He^{2+}-ion) beam of the cyclotron accelerator at Tohoku University. A tandem-type energy degrader system was used to obtain a uniform He distribution along the implanted direction. The specimen temperature during the implantation process was kept below 100 °C. Fig. 1 shows the distribution of He and displacement damage in W calculated using the SRIM code [9] with a displacement threshold energy of 90 eV [10], when the He concentration at the uniformly implanted region was 100 appm. A calculated projected range of the 50 MeV He-ions in W was 0.26 mm. A uniform depth distribution of He was obtained along the specimen thickness direction. Three levels of He implantation (20, 100, and 200 appm) were conducted using the same irradiation conditions. Displacement damage by the He implantation were approximately 0.002, 0.01, and 0.02 dpa. After the He implantation, the tensile specimens were heat treated at 1100 °C for 100 h in a vacuum-sealed quartz tube with zirconium foils in order to recrystallize pure W [11].

Vickers microhardness testing was performed on the tab of the tensile specimens at room temperature, with an indentation load of 1.96 N (200 gf) and a dwell time of 15 s. Tensile tests were conducted in vacuum at 400 and 700 °C at a strain rate of 1.0×10^{-3}/s by using an Instron-type testing machine. After the tensile test, fracture surfaces of the ruptured specimens were observed by a TM-1000 scanning electron microscope (SEM).

3. Results

Fig. 2 shows the dependence of Vickers hardness on the He concentration before and after the post-implantation annealing. Softening occurred for unimplanted specimens by the annealing because of recrystallization, while slight decreases of hardness were observed for He-implanted specimens after the post-implantation annealing. Post-implantation annealed specimens showed almost the same hardness as-received unimplanted specimens.

Figs. 3 and 4 show tensile stress-strain curves obtained at 400 and 700 °C, respectively. In the case of unimplanted specimens, the tensile strength decreased and total elongation increased after the annealing, which are typical changes of tensile properties for recrystallized materials. However, the tensile stress-strain curves for He-implanted specimens have almost the same shape as-received specimens. The changes of tensile properties for post-implantation annealed specimens with respect to He concentration are not significant.

Figs. 5 and 6 show SEM images of the fracture surfaces after the tensile tests. The reduction in area at 400 and 700 °C is also shown in Figs. 5 and 6, respectively. Large reduction in area with dimples were formed and ductile fracture was observed on the surface of all the ruptured specimens. No grain-boundary fracture surface was observed under the experimental conditions. Overall, the reduction in area at 700 °C was higher than that at 400 °C. The amount of plastic deformation in areas other than the necked region of specimens tested at 400 °C would be larger than that of specimens tested at 700 °C [12]. The delamination of the layered structure, which was typically observed in rolled W plates [12,13], was observed in the fracture surfaces except for unimplanted specimens tested at 400 °C.

4. Discussion

In thermal treatment conditions (1100 °C × 100 h) in this study, it