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Synergistic effects of high heat loading and helium irradiation of tungsten

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Abstract

High heat flux experiments using a helium beam have been carried out on powder metallurgy tungsten. The energy of He is 19 keV. He beam flux and heat flux at the beam center is 2.0×10^{21} He/m^2 s and 6.0 MW/m^2, respectively. Beam duration is 3.0–3.9 s and interval of beam shot start is 30 s. The samples are irradiated up to a fluence of 10^{22}–10^{24} He/m^2 by the repeated irradiation pulses. In addition to the He beam irradiation, high heat flux experiments using hydrogen and electron beams have also been carried out on the samples. After the irradiation, surface modification by the irradiation has been investigated. Surface modification by helium and hydrogen beams is completely different from results of electron beam heating. In particular, helium beam heating causes remarkably surface modification such as a fine-scale rough surface at a peak temperature above 2400 °C.

1. Introduction

Tungsten is a candidate for the plasma facing armor of the next fusion devices due to the low erosion yield and high temperature properties. However, heat and particle loads (hydrogen isotopes, helium) from the plasma, which affect damage accumulation and mechanical properties, may degrade these superior properties. Heat loading tests using an electron beam have been performed to investigate material behavior under high heat flux; however, the armor materials are exposed to hydrogen isotopes and He as well as electrons. Very little information is available on the combined effects of the particle implantation and the high heat loading.

On the other hand, the behavior of implanted hydrogen isotopes and He in metals and their effects on material properties have been studied. In particular, it is well known that He implanted in tungsten does not release until high temperatures due to strong interaction with lattice defects [1]. He drastically enhances the formation of bubbles due to the strong bonding to vacancies and their clusters [2–7]. As a result, local swelling and degradation of mechanical properties of bulk materials takes place as well [8]. Therefore, it is also anticipated that implanted He influences high heat load properties of tungsten. In the present study, He beam irradiation experiments have been performed to investigate the synergistic effects between the heat loading and helium irradiation of tungsten.

2. Experimental

The samples used in the present experiment were powder metallurgy tungsten, with size 20 mm×20 mm×5 mm, 10 mm×10 mm×1 mm, 20 mm×20

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mm × 0.1 mm and 10 mm × 10 mm × 0.1 mm. The W purity was 99.99%, and the sample surfaces were electropolished.

Hydrogen and He beam irradiations were performed in an ion beam facility at JAERI, the Particle Beam Engineering Facility (PBEF). The samples were mechanically mounted on a Cu holder, actively water cooled. In the case of the He beam, the energy of He was 19 keV and its half-value width was 140 mm. He beam flux and heat flux at the beam center was 2.0×10^{21} He/m^2 s and 6.0 MW/m^2, respectively. Beam duration was 3.0–3.9 s. Interval of beam start was 30 s. The samples were irradiated up to a fluence of the orders between 10^{22} and 10^{24} He/m^2 by the repeated pulse irradiations of 7–170 cycles. In addition to the He beam irradiation, hydrogen irradiation experiments using PBEF and electron beam irradiation experiments using a JAERI Electron Beam Irradiation Stand (JEBIS) were carried out on the samples under almost the same heat flux and pulse length conditions.

The surface temperature of the sample was measured with a two-color optical pyrometer and two dimensional surface temperature distribution of the samples was also monitored with an IR camera. Temperatures of the samples are also measured on the side opposite the beam irradiation with thermocouples.

After repeated irradiation experiments, surface modifications were examined with a scanning electron microscope (SEM). In addition, light reflectivity of the surface of tungsten after the He irradiation was also measured.

3. Results

A temperature evolution during He beam irradiation is shown in Fig. 1. The surface temperatures gradually increase and reach a peak temperatures and starts to decrease after beam turn-off. Temperature changes also depend on the size of the samples.

Shown in Fig. 2 is an SEM image taken from the surface irradiated to 1.7×10^{22} He/m^2 at the peak temperature of 800 °C. Blisters with a diameter of 0.5–1.0 μm are formed and exfoliation of blister skin is observed for some blisters. However, surface modification was relatively small at a high peak temperature of 1900 °C for the same fluence. The reason why blister are not formed at a high temperature is believed to be the lack of pressure in the bubbles due to the coalescence of vacancies and helium bubbles, and the broad depth distribution of the bubbles by migration near the surface.

Fig. 3 shows an SEM image taken from the surface irradiated to a fluence of 3.3×10^{23} He/m^2 at the peak temperature of 800 °C. As shown in Fig. 3, holes with a diameter of 1.5 μm are observed. In addition, fine

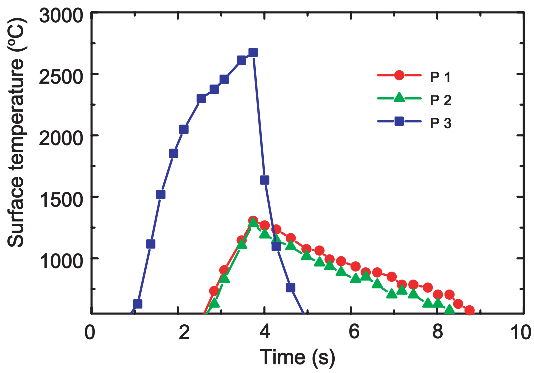

Fig. 1. Time evolution of surface temperatures measured by IR camera. Beam duration is 3.5 s. P-1: 6 MW/m^2, 20 mm × 20 mm × 5 mm, P-2: 4 M/W/m^2, 10 mm × 10 mm × 1 mm, P-3: 2 MW/m^2, 20 mm × 20 mm × 0.1 mm.

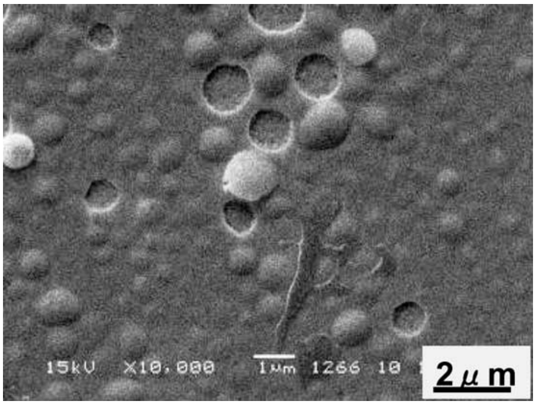

Fig. 2. SEM image taken from the surface irradiated to 1.7×10^{22} He/m^2 at the peak temperature of 800 °C.

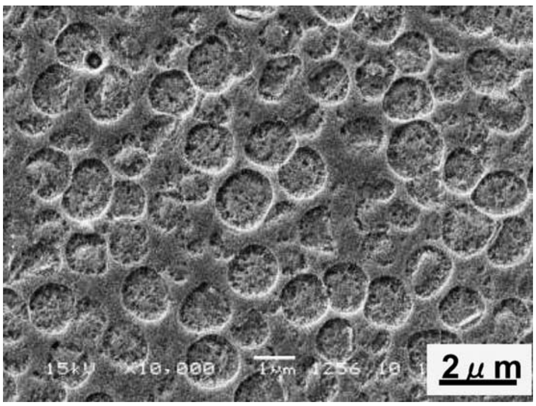

Fig. 3. SEM image taken from the surface irradiated to 3.3×10^{23} He/m^2 at the peak temperature of 800 °C.

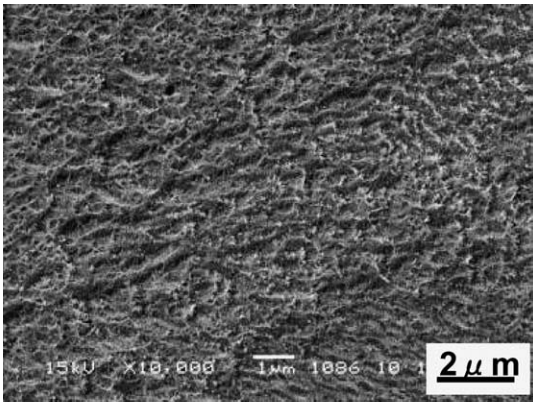

Fig. 4. SEM image taken from the surface irradiated 5.0×10^{23} He/m^2 to at the peak temperature of 1400 °C.

modification on the bottom of the holes are also observed. Shown in Fig. 4 is an SEM image taken from the surface irradiated up to 5.0×10^{23} He/m^2 at the peak temperature of 1400 °C. In this case, the fluence is almost the same as the previous one; however, the surface is finely modified into the wavy structure as shown in Fig. 4. This is considered to be the result of erosion due to sputtering caused by the He irradiation.

In the case of at a high temperature of 2000 °C, the color of the surface changed from metallic sliver color to white by the irradiation to $\sim10^{22}$ He/m^2. Furthermore, when the fluence exceeded $\sim10^{23}$ He/m^2, the color of the surface became black. Shown in Fig. 5 are SEM images of the surface (a) and cross section near the surface (b) of the sample irradiated to 3.3×10^{23} He/m^2 at the peak temperature of 2600 °C. The surface is modified resulting in a fine, uneven morphology and holes with diameter of about 50 nm are observed on the surface. Many horn-like protuberances with a width of about 300 nm and a length of about 1 μm are observed at the surface as shown in Fig. 5(b). In addition, He bubbles with a diameter of about 50–500 nm are observed near the surface. The surface modification is formed by the He bubbles, their coalescence and the migration of He bubbles near the surface.

Fig. 6 shows the surface light reflectivity from the visible range through the infrared range, after the surface color of surface had become black. The reflectivity from pure tungsten is also shown in Fig. 6. In the case of pure tungsten, reflectivity in the visible range is about 20% and increases with increasing wavelength. On the other hand, in the case of the He irradiated W which had become black, reflectivity is below a few %. This is believed to be due to oxidization or to the increase of the surface area by the fine surface modification. Fig. 7 shows a schematic diagram of the relation between the surface modification, fluence and peak surface temperature.

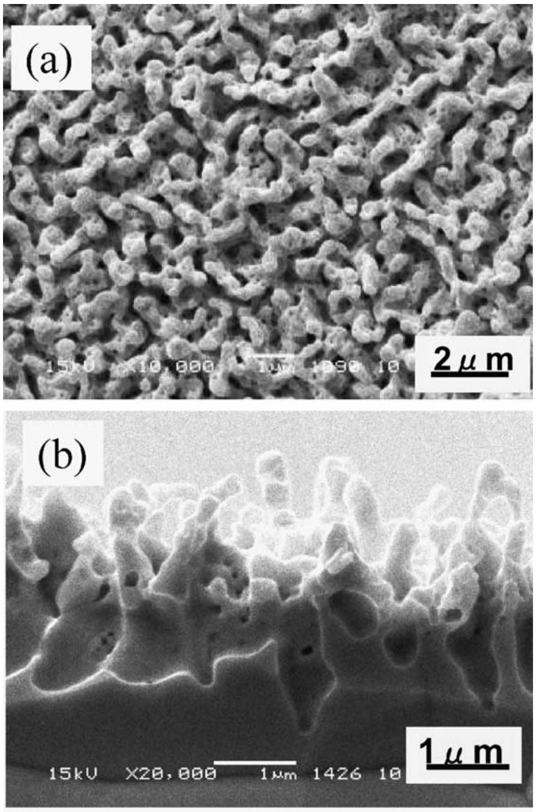

Fig. 5. SEM images of surface (a) and cross section (b) taken from the sample irradiated to 3.3×10^{23} He/m^2 at the peak temperature of 2600 °C.

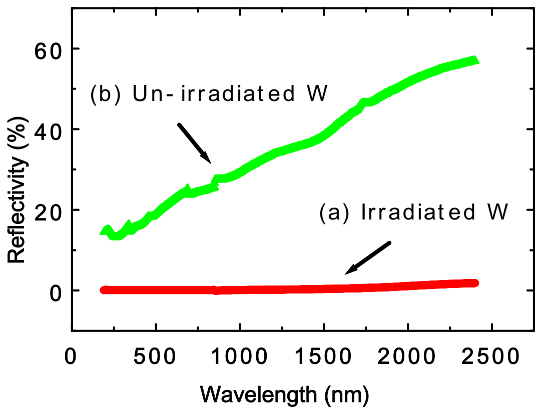

Fig. 6. Reflectivity of surface irradiated to 3.3×10^{23} He/m^2 at the peak temperature of 2600 °C (a). Reflectivity from pure tungsten is also shown (b).

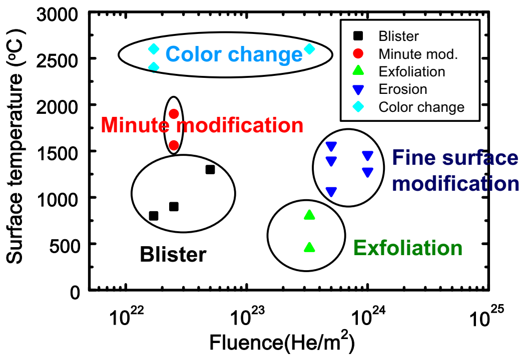

Fig. 7. Schematic diagram of the relation of surface modifications to fluence and peak temperature.

4. Discussion

In the case of hydrogen beam irradiation, blisters with a diameter of about 1 μm were formed on the surface irradiated to 5×10^{22} H/m^2 at peak temperatures of 730 and 900 °C [11]. Wang et al. reported that no blisters were observed on tungsten irradiated with 1 keV D^+ at 600 °C up to the fluence of 1×10^{24} D^+/m^2 [9]. Therefore, these temperatures are higher than that of the blister formation temperature reported by Wang et al. This is believed to be due to the temperature increase during the pulse. Modification due to sputtering as well as blistering was observed on the surface irradiated to 1×10^{24} H/m^2 at the peak temperature of 980 °C. Surface modification due to sputtering was observed, however, blisters were not observed on the surface irradiated at the peak temperature of 1600 °C. The reason for this is that hydrogen was not retained at the high temperature. Furthermore, surfaces became smooth at the temperature of 2630 °C, due to the migration of atoms near the surface in addition to sputtering. In the case of electron beam heating, sputtering and blister formation were not observed. However, smoothing of surface occurred by the migration of atoms near surface [11].

The armor of the plasma facing materials in components such as the divertor will be subjected to electron, hydrogen isotope, helium and neutron bombardment. In our research group, surface modification of tungsten irradiated by electrons, hydrogen and helium, has been investigated. In the case of electron irradiation, heating is the main process so that grain growth by re-crystallization occurs above 1300 °C and additionally, smoothing of surface by the migration of surface atoms occurred above 2000 °C. In the case of hydrogen irradiation, blistering and sputtering as effects of radiation damage and implantation occurred. However, at high temperature, hydrogen re-emits from tungsten so that blisters are not formed and surface modification by sputtering was observed. At a higher temperature of more than 2000 °C, smoothing of surface occurs by the atom migration.

On the other hand, in the case of He irradiation, the principal difference in the behavior of implanted hydrogen and helium is that the high binding energy of helium at damages sites prevents diffusion to the surface [10]. In the present experiments, synergistic effects of heating and implanted He causes remarkably surface modification such as the fine-scale, rough surface at high temperatures. These modification may influence thermal properties such as thermal conductivity, mechanical properties and tritium retention of the surface. In the present work, single beams were used to investigate fundamental processes of heat load and hydrogen or He. However, in the fusion devices, synergistic effects of these processes including neutron irradiation will occur. Therefore, it is necessary to take account of these processes in evaluation of damage in armor materials.

5. Conclusion

He beam irradiation experiments have been performed to investigate the synergistic effects of the heat loading and the particle loads (helium) on modification of tungsten. Surface modification by helium and hydrogen beam heating is completely different from results of electron beam heating. In particular, helium beam heating causes remarkable surface modification such as the fine-scale, rough surface at high temperatures. This modification may influence thermal properties such as thermal conductivity, mechanical properties and tritium retention of the material.

References

[1] V.N. Chernikov, A.P. Zakharov, J. Nucl. Mater. 165 (1989) 89.
[2] M. Kaminsky (Ed.), Radiation Effects on Solid Surface, American Chemical Society, 1976, p. 112.
[3] H. Ullmaier, Radiat. Eff. 78 (1983) 1.
[4] B. Emmoth, Radiat. Eff. 78 (1983) 365.
[5] R. Behrisch, B.M.U. Scherzer, Radiat. Eff. 78 (1983) 393.
[6] V.N. Chernikov, Ju.V. Lakhotkin, H. Ullmaier, H. Trinkaus, P. Jung, H.J. Bierfeld, J. Nucl. Mater. 212–215 (1994) 375.
[7] P.B. Johnson, D.J. Mazey, J. Nucl. Mater. 218 (1995) 273.
[8] K. Shinohara, A. Kawakami, S. Kitajima, Y. Nakamura, M. Kutsuwada, J. Nucl. Mater. 179–181 (1991) 246.
[9] W. Wang, J. Roth, S. Lindig, C.H. Wu, J. Nucl. Mater. 299 (2001) 124.
[10] W.D. Wilson, Radiat. Eff. 78 (1983) 11.
[11] K. Tokunaga, K. Ezato, et al., in preparation.