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Effects of helium irradiation on high heat load properties of tungsten

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Abstract

He ion pre-implanted tungsten has been irradiated by electrons to examine synergistic effects of He implantation and high heat load. Depth profile measurements show that He distributes on the surface locally and most of He is distributed in the projected range, however, some of the helium atoms diffuse to deeper region. Blisters are observed on the sample irradiated to a fluence of 1×10^{22} He/m^2 at 300 K. However, at 1073 K, such blisters are not observed and no noticeable modification occurs. There is no large difference in surface modification by electron beam irradiation between the samples irradiated or not with He when the sample is at the high temperature (2773 K) for 6 s. Two large He release peaks are observed from the sample irradiated to a fluence of 1×10^{22} He/m^2 at 1073 K. It is thought that He release in the first peak is due to microcrack formation near the surface and that the second He release peak is due to the exfoliation or rupture of blisters.

1. Introduction

Although the utilization of low Z materials like carbon for plasma facing components has enabled an improvement in plasma confinement, high erosion rates at elevated temperatures create serious problems. Degradation of thermal conductivity by neutron damage and high tritium retention will be serious issues in the next generation of D–T fusion machines [1]. Tungsten seems to be a promising candidate material for plasma facing components in steady state plasma discharge devices because of its low sputtering yield and good thermal properties.

Plasma-facing materials of fusion reactors are subject to high flux particle (hydrogen isotopes, He and neutron) irradiation and high heat load. It is well known that He implanted in tungsten is not released up to high temperatures due to strong interaction with lattice defects [2]. He enhances the formation of bubbles drastically due to the strong binding to vacancies and their clusters [3]. As a result, local swelling and degradation of mechanical properties of bulk materials take place [4]. As a basic study of the He implantation effects, microstructure evolution during He implantation has been investigated in metals under various irradiation conditions. Post irradiation annealing experiments have also been carried out to elucidate thermal stability of defect clusters and their release behavior [5–7]. It is also anticipated that implanted He influences high heat load properties of tungsten. Very little information is available on the combined effects of He implantations and the high heat loading. This is the objective of the present paper.

2. Experimental

The sample used in the present experiment was powder metallurgy tungsten (PM-W). Its sizes and purity were $10 \times 10 \times 1$ mm^3 and 99.99%, respectively. The sample surface was mechanically and electrolitically polished. The samples were irradiated with 8 keV He to

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fluences of 1×10^{20}, 1×10^{21} and 1×10^{22} He/m^2 at 300 and 1073 K. After He irradiation, the samples were subjected to heat loading by electron beam irradiation. The facility used was an electron beam irradiation test simulator at the Research Institute for Applied Mechanics (RIAM) at Kyushu University [8]. The sample was placed on a Cu block, actively cooled with water. The electron beam energy used was 20 keV. Duration of electron beam exposure was 10 s. The surface temperature of the central region of the specimen 1 mm in diameter was measured with two-color optical pyrometers (450–1100, 1000–3100 °C). He emitted from the heated sample surface was detected with a quadrupole mass spectrometer (QMS). He detected was quantitatively evaluated using a standard helium leak. Heat flux was evaluated by the beam diameter and net electrical current. Before and after the He and electron beam irradiation, the sample surface was investigated with a scanning electron microscope (SEM). Microstructure of the sample after He irradiation was also investigated with a transmission electron microscope (TEM).

In addition, residual gas analysis (RGA) measurements of partial pressure of He was carried out during the course of sputtering of the surface with 10 keV Ga^+ in order to investigate the depth profile of helium in tungsten. The sputtering rate of tungsten was determined as a ratio of the depth to the sputtering time of a crater produced by sputtering on the surface. Displacement per atom (dpa) and atom per atom (apa) were calculated using TRIM code [9] and were compared with the results of the depth profile measurements.

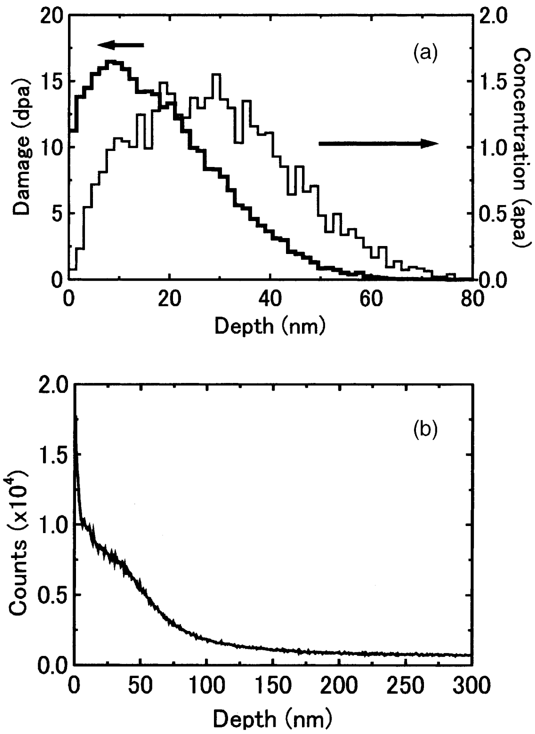

Fig. 1. (a) dpa and apa in tungsten irradiated with 8 keV He ions to a fluence of 5×10^{21} He/m^2 calculated by the TRIM-code and (b) RGA depth profile of He in tungsten irradiated with 8 keV He ions at 300 K to a fluence of 5×10^{21} He/m^2.

3. Results

3.1. Depth profile of implanted He

Fig. 1(a) shows dpa and apa in tungsten irradiated with 8 keV He ions to a fluence of 5×10^{21} He/m^2 calculated by the TRIM-code. It can be seen that primary damage and implanted He distributes near the surface region. Fig. 1(b) shows RGA depth profile of He in tungsten irradiated with 8 keV He ions at 300 K to a fluence of 5×10^{21} He/m^2. It is possible to detect He in bubbles as well as atomic He by the RGA measurement. The depth profile shows that He is distributed on the surface locally and most of helium is distributed in the projected range, however, some of He diffuses to deeper regions.

3.2. Surface modification after He irradiation

No modification was observed on the samples irradiated to fluences of 1×10^{20}, 1×10^{21} He/m^2 at 300 and 1073 K. On the contrary, blisters with a diameter of about 0.3 μm were observed on the sample irradiated to a fluence of 1×10^{22} He/m^2 at 300 K as shown in Fig. 2(a). However, at 1073 K, such blisters are not observed and no noticeable modification occurred as shown in Fig. 2(b). The TEM investigation shows that bubbles were formed in tungsten irradiated with He to a fluence of 1×10^{22} He/m^2. Diameters of He bubbles in tungsten samples irradiated at 300 and 1073 K were a few nm and 30 nm, respectively. These results indicate that the reason why blisters were not formed at 1073 K may be the lack of pressure in the bubbles at 1073 K, because bubbles grow by absorption of vacancies when the vacancies become mobile at high temperature.

3.3. Time evolution during electron beam irradiation

Fig. 3 shows the time evolution of (a) the electric current in the sample, pressure in the vacuum chamber and (b) the surface temperature and QMS signal intensity for He during the electron beam irradiation. The sample used was irradiated with 8 keV He to a fluence of 1.0×10^{22} He/m^2 at 300 K. The electric current started to increase at the same time as the irradiation started and was almost constant during the irradiation. The surface temperature gradually increased and reached about 2773 K and started to decrease when the irradiation

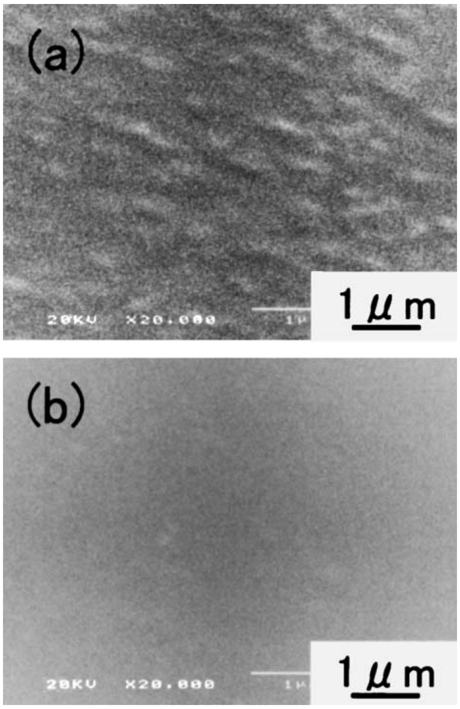

Fig. 2. SEM images after He irradiation: (a) sample irradiated with 8 keV He to a fluence of 1×10^{22} He/m^2 at 300 K, (b) sample irradiated with 8 keV He to a fluence of 1×10^{22} He/m^2 at 1073 K.

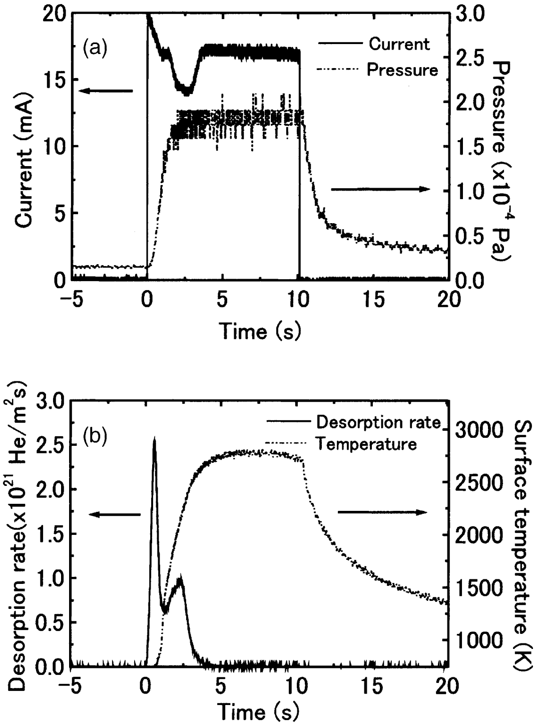

Fig. 3. Time evolution of (a) the electric current of the sample and the pressure of vacuum chamber and (b) surface temperature and QMS signal intensity for He during electron beam irradiation. The sample was irradiated with 8 keV He to a fluence of 1.0×10^{22} He/m^2 at 300 K.

ended. The pressure of vacuum chamber gradually increased and reached about 1.8×10^{-4} Pa and decreased after the irradiation. It can be seen that two large He peaks appeared. The temperature increases due to the electron beam irradiation were almost the same irrespective of the He irradiation condition but behavior of He release depended on the He irradiation condition.

3.4. Surface modification after electron beam irradiation

SEM observation after the electron beam irradiation of the sample surface irradiated showed that the grain grew by recrystallization. This is expected to be caused by the surface diffusion at 2773 K for about 6 s. There was no large difference between surface modification of the samples irradiated or not with He.

3.5. Implantation temperature dependence of He release

Fig. 4 shows the time evolution of the surface temperature and QMS signal intensity for He during electron beam irradiation. The sample was irradiated with 8 keV He to a fluence of 1×10^{22} He/m^2 at 1073 K. The profile of He release is similar to the sample irradiated at 300 K as shown in Fig. 3(b). Two large He release peaks appeared below 773 and at 2173 K from the sample irradiated with He at 300 K. On the other hand, He release appeared below 1073 K from the sample irradiated with He at 1073 K. This behavior is different from that of thermal desorption spectroscopy (TDS) experiments using a relatively slow ramping rate.

3.6. Relation of surface modification and He release

To investigate the relation between the surface modification and He release, the irradiation with the electron beam was stopped after the first peak and the second peak, respectively. After the electron beam irradiation, the samples were removed and the sample surface was investigated. Fig. 5(a) shows the time evolution of the surface temperature and QMS signal for He where the electron beam irradiation was stopped after the first peak. Blisters with a diameter of 0.3 μm were formed as shown in Fig. 5(b) after the first He release peak appeared. One possible reason of the blister formation is plastic deformation in the surface region caused by coalescence and growth of bubbles due to rapid temperature increase under electron beam irradiation. It seems that the He release in the first peaks is closely related to

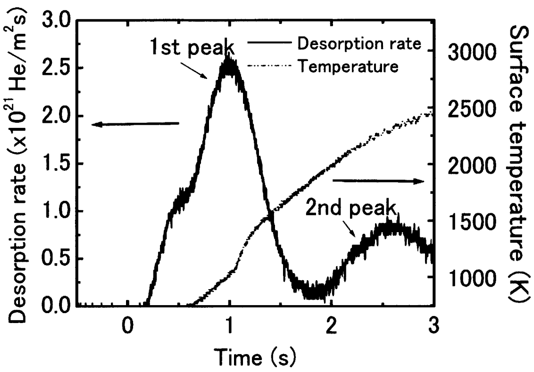

Fig. 4. Time evolution of the surface temperature and QMS signal intensity for He during electron beam irradiation. The sample was irradiated with 8 keV He to a fluence of 1×10^{22} He/m^2 at 1073 K.

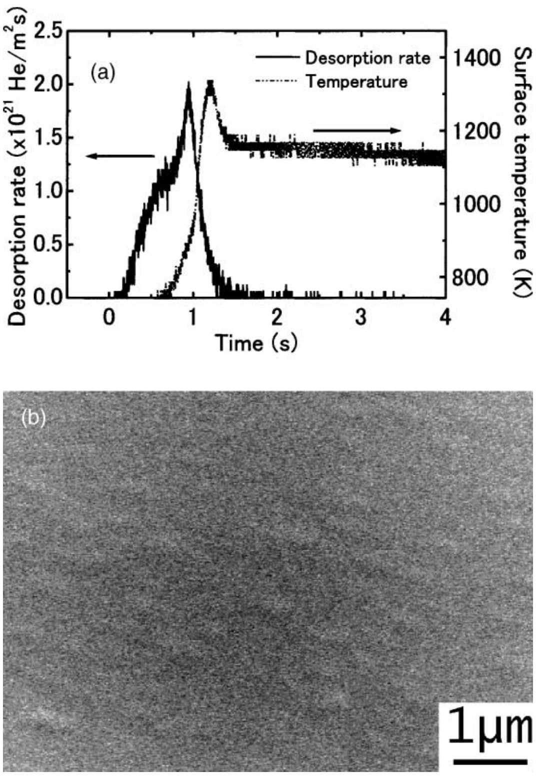

Fig. 5. Time evolution (a) of the surface temperature and QMS signal for He and (b) SEM image where the electron beam irradiation was stopped after the first peak appeared.

the blister formation. Probably, He is released through microcracks near the surface caused by the blister formation. Detailed investigations of the surface with high resolution are required.

Fig. 6 shows the time evolution and SEM image where the electron beam irradiation was stopped after

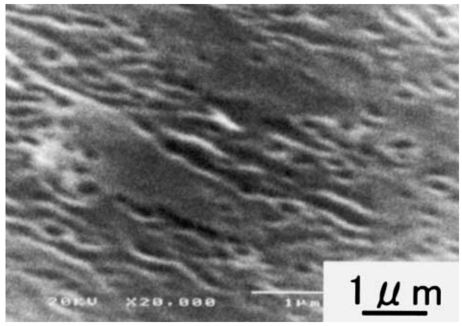

Fig. 6. SEM image where the electron beam irradiation was stopped after the second He release peak. The sample was irradiated with 8 keV He to a fluence of 1×10^{22} He/m^2 at 1073 K.

the second He release peak occurred. Holes with a diameter of 0.1–0.5 μm and exfoliation were observed. Therefore, it is concluded that the second He release peak is due to the exfoliation or rupture of the blisters.

4. Discussion

4.1. Surface modification and He release by rapid heating

He release from tungsten has been investigated by TDS [10]. These experiments derive the kinetics of He desorption in ramp heating or isothermal heating condition under quasi-steady state conditions. In addition, surface modification after He irradiation and He release during He irradiation were investigated [11–13]. However, in the plasma confinement devices, plasma facing materials will be subjected to pulsed high heat loads due to disruption, startup of plasma discharge and shift of plasma during long duration discharge. Therefore, it is necessary to investigate behavior under non-steady state condition. In the present experiments, He release and surface modification, which have not been observed in the conventional TDS, occurred. Detailed investigations are required, because the plasma facing materials in plasma devices will be subjected to heat load with different time evolution.

4.2. He irradiation effects on thermal properties

A dependence of He irradiation condition on temperature increase is not seen in the present experiment. Since the sample was only placed on a Cu block, actively cooled by water and its thickness was 1 mm, the temperature increase due to the electron beam irradiation was mainly determined by specific heat, density and radiation. These physical parameters do not seem to depend on He implantation condition. On the other hand, it is thought that changes of other thermal property, for example, degradation of thermal conductivity due to bubble formation and He emblittement by He irradiation may occur. Since degradation of thermal conductivity influences temperature increase under steady state, heat load experiments under steady state condition by actively cooling [14] are required to confirm this.

5. Conclusion

He ion pre-implanted tungsten has been irradiated by electron beam to examine synergistic effects of He implantation and high heat load.

(1) Depth profile measurement shows that He distributes on the surface locally and most of He is distributed in the projected range, however, some of helium diffuses to deeper region.
(2) Blisters are observed on the sample irradiated to a fluence of 1×10^{22} He/m^2 at 300 K. However, at 1073 K, such blisters are not observed and no noticeable modification occurs.
(3) There is no large difference in surface modification by electron beam irradiation between the samples irradiated or not with He. This is expected to be caused by surface diffusion due to the high temperature (2773 K) for 6 s.
(4) Two large He release peaks are observed from the sample irradiated to a fluence of 1×10^{22} He/m^2 at 1073 K. It is thought that He releases in the first peak is due to microcrack formation near the surface and that the second He release peak is due to the exfoliation or rupture of blisters.
(5) In the present experiments, He release and surface modification occurred, which have not been observed by conventional TDS. More detailed investigations are required because in plasma devices the plasma facing materials will be subjected to heat load with different time evolution and heat load.

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