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Degradation of thermal conductivity of the damaged layer of tungsten irradiated by helium-plasma

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ABSTRACT

Pure tungsten samples were irradiated by helium plasma in the linear plasma device PSI-2 with an ion energy of 40 eV and a flux of $1.1 \times 10^{22}\,\mathrm{m^{-2}s^{-1}}$. The irradiation temperature was from 523 K to 773 K and the fluence was from 1.0×10^{25} to $1.0 \times 10^{26}\,\mathrm{m^{-2}}$. A damaged layer of 10 nm thickness was formed on the sample surface with a destroyed crystalline structure. Helium-bubbles and surface modification in nanoscale were observed. Thermal conductivities of the ultra-thin damaged layers were measured by the transient thermoreflectance technique. Result shows that the thermal conductivity reduced two orders of magnitude compared to the bulk value and decreased with increasing irradiation temperature and fluence. Moreover, the helium-irradiated samples were exposed to ELM-like heat load produced by electron beam on EMS-60. The pulse length was 1 ms and each sample was exposed to 5 pulses. Melting occurred under power density of $1.7\,\mathrm{GW\,m^{-2}}$. As the thermal conductivity of the damaged layer decreased, the molten bath of the irradiated sample deepened. The degraded thermal conductivity led to a lower melting threshold. The characterization of the thermal conductivity of the damaged layer induced by the plasma irradiation is a promising way to estimate the damage level, as well as the failure threshold, of the plasma facing components.

1. Introduction

Tungsten (W) is the most promising candidate for the plasma facing materials (PFMs) of tokamak device, taking advantages of good thermal properties such as thermal conductivity (TC) and high melting point [1,2]. Recently, helium (He) discharge have been conducted on ASDEX [3] and radio-frequency heating have been carried out on JET and EAST [4,5]. The interaction of He-plasma and W surface has attracted great interest of research. The degradation of properties of W induced by He-plasma irradiation is one of the most concerned topics.

He-plasma exposure induces modification of W surface. Holes [6], surface modification [7,8] and fuzz-like structure [7,9] form under certain conditions. Point-defects and He-bubbles are introduced in the surface damaged layer [10–12]. These damages cause a severe degradation of W properties. Research found that nanostructure formed on the W surface leaded to a higher surface temperature when exposed to transient heat load with parameters as edge localized modes (ELMs) [13]. The ELMs produce extremely powerful heat loads by magnitude of $\mathrm{GW/m^2}$ in a duration of several milliseconds [14]. The heat penetration length is very short [15] and the energy therefore concentrates on the surface region during the ELM-pulses. Degradation of thermal properties [16] is supposed to decrease the melting threshold of W and cause more severely and easily melting during transient events [17].

Efforts have been made to quantify the modified thermal properties of damaged W surface irradiated by ions or plasma. 3-omega method was employed to test the Cu ions implanted W samples [15]. This method was improved and successfully applied on the He-plasma irradiated W samples recently [18]. The TC of the damaged layer decreased 1–2 orders of magnitude comparing to the bulk. The large reduction is caused by the scattering of the electrons, which is induced by the irradiation defects. Transient gating (TG) was used to measure the thermal diffusivity of He ions implanted W layer [19]. For rougher

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surface with more severe irradiation, transient thermoreflectance method (TTR) was employed. The TC of fuzz-like structure was gained by a back heating TTR method [20]. Result show the TC reduced to 2% of the bulk value. Moreover, a front heating TTR method was put forward to test He ions implanted W in different temperature range [21], taking advantage of easy preparation of tested sample and unstick requirement of flat surface. The irradiation of plasma or ions causes serious reduction of thermal properties of the damaged layer. The degradation by He-plasma irradiation need to be quantified. Moreover, a serious issue is put forward that whether the degradation of W surface layer, about tens of nanometers caused by plasma with low ion energy, would affect the melting behavior of W remarkably and induce failure of W material.

In the present study, W samples were exposed to He-plasma on the linear plasma device PSI-2 [22] with different irradiation temperature (T_{irr}) and fluence. Previous investigations in PSI-2 showed a well-developed morphology of the W surface after the exposure to pure He-plasma [23]. Mixed deuterium/helium plasmas resulted as well in the formation of a ≈ 20 nm layer of He nano-bubbles [24], which led to a significant reduction of the deuterium retention compared to a pure D exposure [25]. In our case, similar surface modifications were found, i.e. He-bubbles were observed in the cross-section. A front heating TTR method [26–28] was employed to test the TC of W damaged layer. Severe degradation of TC was analyzed. The effect of He-plasma fluence and T_{irr} on the TC reduction was studied. Furthermore, the irradiated samples were exposed to ELM-like heat load produced by EMS-60 [29]. The melting behaviors of samples with different TCs on the surface were studied. The sample and method details are described in Section 2. The testing result of TC value and the melting behavior of the irradiated samples are shown in Section 3. The discussion of the reduced TCs and effects on the melting behavior can be found in Section 4.

2. Method principle and experimental details

2.1. Sample preparation and He-plasma irradiation details

Samples prepared for irradiation were W with purity of higher than 99.99%, provided by Advanced Technology & Materials Co., Ltd. It was produced by powder sintering followed by warm rolling to a final thickness of 3 mm. The initial microstructure is shown in Fig. 1. The sample surfaces were electropolished to a mirror-finish. The He-plasma exposure was performed on the linear plasma device PSI-2 in Jülich, Germany [22]. The ion energy was about 40 eV. The irradiation was conducted under surface temperature of 523 K and 773 K. The temperature of one of the samples was measured by a thermocouple against the back of the sample, while the front surface temperatures of all samples were simultaneously recorded by an infrared (IR) camera. In the present study, T_{irr} represents the surface temperature during the irradiation. The samples under 523 K were heated solely by the He-plasma whereas the samples under 773 K were additionally heated by a resistive heater incorporated in the sample holder. The ion flux, which was monitored by a Langmuir probe, was $1.1 \times 10^{22}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$. The fluence was varied between $1.0 \times 10^{25}\,\mathrm{m}^{-2}$ and $1.0 \times 10^{26}\,\mathrm{m}^{-2}$ to investigate its effect on the degradation of TC.

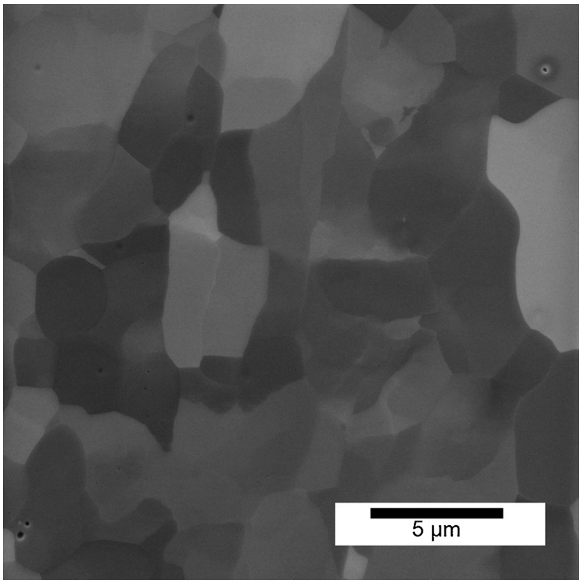

Fig. 1. The initial microstructure of W.

2.2. Transient thermoreflectance technique

A front heating TTR was employed [21,28] to test the TC value of the He irradiated layer. The sketch is shown in Fig. 2. A pulse laser was loaded on the surface as transient heating source, with pulse width of 8 ns and energy of 50 mJ. The diameter of the spot was 3 mm. A continuous probe-laser with power of 1.8 W was loaded simultaneously on the metal film which was coated on the damaged layer by magneto-sputtering. Samples were coated by gold (Au) with thickness of 150 nm. The intensity of the reflected laser was recorded by the photodetector. The temperature delay curve of the surface could be deduced by the intensity profile because the proportional correlation between the temperature and the reflectivity [30]. The heat transfer process was simulated by a transmission-line theory [31]. A two-layer model was employed [28,32], assuming that the depth and the heat capacity of the damaged layer were negligible. The damaged layer was considered as thermal resistance r, which was fitted by genetic algorithm [33] from the temperature delay curve. The TC, κ, was deduced by $\kappa = r/d$, where d was the thickness of the damaged layer. The samples were installed in a vacuum furnace with 3D-adjustable stage. The testing temperature (T_{test}) was from room temperature to 473 K.

2.3. Transient heat load experiment

The irradiated samples were loaded by ELM-like heat load, produced by scanning electron beam on EMS-60, in Chengdu, China. The electron beam frequency was 40 kHz. The scanning area was $2.6 \times 2.6\,\mathrm{mm}^2$. The pulse width was 1 ms and the frequency was 1 Hz. The absorption coefficient was assumed to be 0.46 [34]. The peak power density was $1.7\,\mathrm{GWm}^{-2}$. Five pulses were loaded on each sample.

2.4. Characterization

The surface modification after the irradiation was observed by scanning electron microscopy (SEM). The images were taken by the second electron mode with accelerating voltage of 10 keV. Focus ion beam (FIB) cutting was performed to obtain the cross-section of the damaged layer, which was subsequently observed by transmission electron microscopy (TEM) with accelerating voltage of 200 keV. The TEM images were taken under bright field mode. Thermal desorption spectroscopy (TDS) [35] was employed to test the retention of He atoms. The samples were heated up to 1423 K in a chamber with base pressure better than 5×10^{-5} Pa.

Since the duration of the pulse was very short, the temperature of the surface was hardly detected by an IR-camera with limited resolution in time domain. The melting behaviour was therefore investigated by observing the re-solidified structures by SEM and laser scanning confocal microscopy (LSCM).