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High-flux He^{+} irradiation effects on surface damages of tungsten under ITER relevant conditions

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ABSTRACT

A large-power inductively coupled plasma source was designed to perform the continuous helium ions (He^{+}) irradiations of polycrystalline tungsten (W) under International Thermonuclear Experimental Reactor (ITER) relevant conditions. He^{+} irradiations were performed at He^{+} fluxes of 2.3×10^{21} $-1.6 \times 10^{22}/m^2$ s and He^{+} energies of 12–220 eV. Surface damages and microstructures of irradiated W were observed by scanning electron microscopy. This study showed the growth of nano-fuzzes with their lengths of 1.3–2.0 μm at He^{+} energies of >70 eV or He^{+} fluxes of $>1.3 \times 10^{22}/m^2$ s. Nanometer-sized defects or columnar microstructures were formed in W surface layer due to low-energy He^{+} irradiations at an elevated temperature (>1300 K). The diffusion and coalescence of He atoms in W surface layers led to the growth and structures of nano-fuzzes. This study indicated that a reduction of He^{+} energy below 12–30 eV may greatly decrease the surface damage of tungsten diverter in the fusion reactor.

1. Introduction

Currently, W has been selected as one of the best plasma-facing materials for ITER due to its low hydrogen solubility, low sputtering yield, and good thermal properties. The W diverter of fusion reactor will suffer from a large flux ($>10^{22}$–$10^{24}/m^2$ s) of particle bombardments by low-energy (tens of eV to hundreds of eV) helium (He) and hydrogen ions [1,2]. However, the bombardments of W by the high-flux and low-energy He ions lead to the serious irradiation damages, such as the formation of voids, wave-like nanostructures, or nano-fuzzes on the surface [3–6]. The enhanced erosion and dust formation of W nano-fuzzes can have fatal influence on the stability of fusion plasmas in the fusion reactor [7].

The structural changes of W surfaces are obviously dependent on the incident He^{+} energy, W surface temperature and He^{+} fluence [3–6]. Nanostructured surfaces are often formed when W materials are irradiated at the surface temperature (T) of >1000 K and the incident He^{+} energy of >20 eV [8]. Nanometer-sized defects, including vacancies, interstitials, and dislocation loops can be formed at this early stage during He^{+} irradiation of W materials [9–11]. Radiation induced defects in W materials are of great interest since they can act as the nucleus for He bubble formation, and finally develop into nano-fuzzes in the implanted layers of W materials. Although the surface change of W materials exposed to the low-energy He ions has been widely studied, the influence of He^{+} flux and energy on the micro-structural evolution of W materials still needs to be studied. Up to now, there have been few reports about the low-energy He^{+} irradiation of W materials performed at various He^{+} fluxes and energies [8]. It is relatively difficult to control the He^{+} flux and energy among the previous irradiation techniques. A change in the He^{+} flux and energy is of great interest since they play a crucial role in controlling the W surface microstructure during He^{+} irradiation.

In this study, a high-density ($\sim 10^{18}/m^3$) plasma irradiation system has been used to efficiently control He^{+} flux and energy, and perform He^{+} irradiation of polycrystalline W materials under ITER relevant conditions. The surface damages of irradiated W materials have been observed by scanning electron microscopy, and the influences of He^{+} flux and energy on the surface damages of W materials have been reported.

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2. Experimental procedure

Polycrystalline W specimens (purity: 99.99%, Honglu Corporation, China) with a dimension of 10 × 10 × 2 mm were used for large-flux He^+ irradiations. W surfaces were mechanically mirror-polished to a surface roughness of <0.1 μm. After polishing, W specimens were annealed at 1373 K for 2 h in vacuum with a background pressure of 10^{-5} Pa to relieve internal stress and reduce the large concentration of nanometer-sized defects.

The large-power inductively coupled plasma (ICP) irradiation system built in our lab has been used to irradiate W specimens [12], as schematically illustrated in Fig. 1. In this system, the stable and large-power (P_{max} = 10 kW) ICP plasmas were generated inside the quartz tube (10 cm in diameter, 18 cm in length) by inductively coupling of 2 MHz (MHz) radio frequency (RF) to the water-cooled RF coil. The quartz tube was subject to very high thermal loads during the operation of large-power RF plasmas. A water-cooled stainless-steel Faraday shield was utilized to protect the quartz tube from the heat load of the plasma. The permanent magnets were installed on the bottom of the quartz tube to create a magnetic field for the enhancement of the plasma confinement. The molecular pump was utilized to pump the main vacuum chamber, and the base pressure was 1.0 × 10^{-4} Pa. The W specimen was placed on a specially designed holder into the high-density RF plasma. Specimen temperature was measured with an infrared STL200-A620 pyrometer. The infrared pyrometer was fixed outside of the plasma source in the ambient air. The infrared pyrometer collected a portion of the thermal radiation emitted by the W sample.

During He^+ irradiation, He pressure in the plasma source remained constant at 30 Pa. The detailed irradiation conditions were listed in Table 1. Increasing RF power from 1.5 to 8.5 kW led to an increase in the electron density from 3.0 × 10^{17} to 2.8 × 10^{18}/m^3 (Table 1). The plasma potential did not show the dependence on the RF power ranging from 1.5 to 8.5 kW. The negative bias voltage ranging from −10 to −200 V was applied to the W specimen. This results in an incident He^+ energy of 30–220 eV when taking account the plasma potential of 20 V measured by a Langmuir probe in this lab. When W specimen was floating, the energy of He^+ ions may be expressed as [13].

$$E = KT_e \ln\left(\frac{m_i}{2\pi m_e}\right)^{1/2}$$

where E was He^+ energy, k Boltzmann constant, and T_e electron temperature. m_i and m_e were the mass of ions and electrons, respectively. This calculation led to E = 12 eV. Table 1 shows that W surface temperature is significantly affected by the RF power and the negative bias. When RF power varied from 1.5 to 8.5 kW, He^+ flux increased from 2.3 × 10^{21} to 1.6 × 10^{22}/m^2 s, leading to an obvious increase in W surface temperature from 960 to 1560 K. When the bias varied from −10 to −200 V, W surface temperature significantly increased from 1350 to 1560 K. In this study, all He^+ irradiations of polycrystalline W were performed at the He^+ fluence of 1.0 × 10^{26}/m^2.

After He^+ irradiation, scanning electron microscopy (SEM) (Hitachi S-4800) was utilized to observe the surface microstructures of W specimens. The SEM measurements were also carried out on specimen fracture sections that were produced by flexing to facture specimens. The resolution limit of SEM is about 10 nm.

3. Results

3.1. Effect of He^+ flux on microstructures

Fig. 2 shows the SEM images of W specimens irradiated at He^+ fluxes of (a) 2.3 × 10^{21}/m^2 s, (b) 5.4 × 10^{21}/m^2 s, (c) 7.7 × 10^{21}/m^2 s, (d) 1.0 × 10^{22}/m^2 s, (e) 1.3 × 10^{22}/m^2 s and (f) 1.6 × 10^{22}/m^2 s. Their surface temperatures are (a) 960 K, (b) 1130 K, (c) 1210 K, (d) 1350 K, (e) 1480 K and (f) 1560 K, respectively. The surface microstructures are strongly dependent on the He^+ flux ranging from 2.3 × 10^{21} to 1.6 × 10^{22}/m^2 s. After W specimens are irradiated at the fluxes of 2.3 × 10^{21} and 5.4 × 10^{21}/m^2 s, no obvious change in their surface microstructures (SEM micrographs) is formed, as

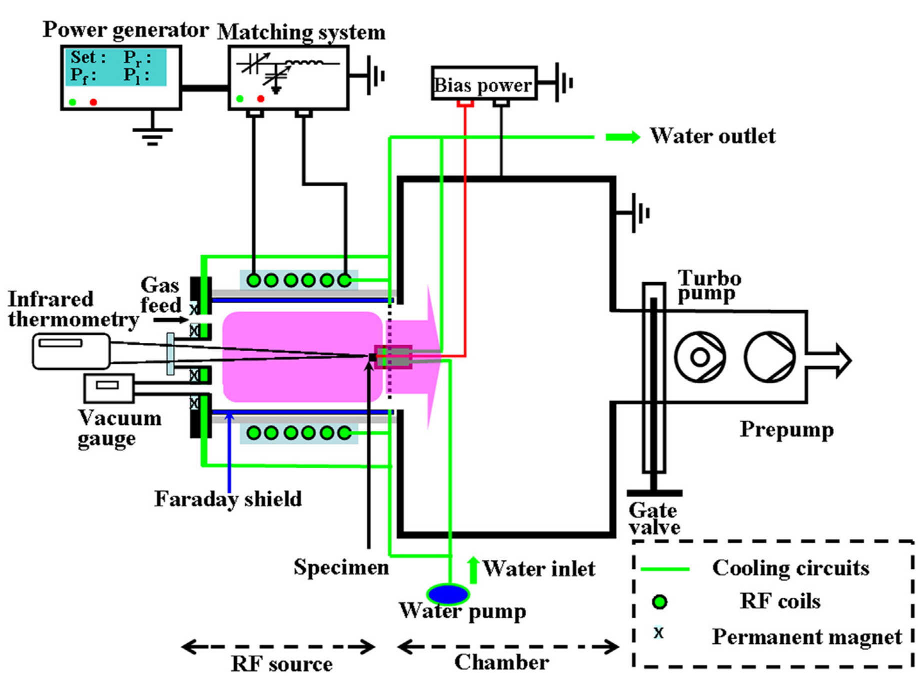

Fig. 1. The schematic of large-power RF plasma irradiation system used to irradiate W specimens.