§22. In-situ Observation of the Formation Behavior of the Fuzz Structure on Tungsten

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Tungsten (W) nano-structures, so called fuzz, induced by He plasma exposure, have been observed in linear plasma devices [1-2] and in a tokamak environment of Alcator C-Mod [3]. Recently, its formation and growth conditions have been identified, and both positive and negative aspects of fuzz as a plasma-facing surface have been revealed. To investigate the formation process, post-mortem transmission electron microscope (TEM) observations with focused ion beam milling were previously performed [4]. That study claimed that both helium bubbles and high surface temperature were necessary for fuzz to grow. In this study, in-situ TEM observations during He^+ ion irradiation and annealing are conducted to examine the formation mechanisms of fuzz in more detail.

In-situ observations were carried out with a TEM (JEOL-JEM2010) equipped with a low energy ion gun. For sample annealing in the TEM, a furnace type sample holder with a temperature control function, Gatan-model 628, was used. The microstructural evolution during the annealing and/or the irradiation was recorded continuously with a video recording system. The samples were irradiated with 3 keV He^+ ions of the flux of the order of 10^{17} He^+ $m^{-2}s^{-1}$ at a constant temperature from R.T. to 1273 K. In addition to the constant temperature irradiations, three patterns of irradiations with a temperature change from 1273K to 1473K were also carried out.

Fig. 1 shows the microstructural evolution of W under the 3 keV-He^+ irradiation at constant temperature from R.T. to 1273 K. With increasing the helium fluence, more helium bubbles tends to form at all the irradiation temperatures. The bubbles begin to be observed at lower fluence with increasing the irradiation temperature. This seems to be due to the easier nucleation by a higher mobility of vacancies and/or helium-vacancy complexes at higher temperatures. Despite the rapid growth of helium bubbles for the irradiation at 1273 K, a remarkable change in the surface structure on the sample edge was not observed (see figure 2 (a)). It is, therefore, concluded that fuzzy structures are not formed below 1273 K within the fluence range up to $1x10^{21}$ m^{-2}. For the samples irradiated at higher temperature above 1273K, which corresponds approximately to the re-crystallization temperature of pure-W, surface morphology changes were clearly observed with the in-situ TEM. Fig. 2 displays the microstructural evolution of the edge parts of W samples under the three different irradiation conditions above 1273 K. As shown in fig. 2 (a), fuzzy structures appeared at 1473 K under the continuous irradiation. At this temperature, even relatively large bubbles have a sufficiently high mobility and reach the sample surface, leaving a number of fissures and holes as traces. These holes grow and eventually form the fuzzy structures. It should be noted that, in addition to the coalescence of adjacent holes, the expansion of individual holes was observed. Interestingly, the similar fuzzy structures were also formed during the post-annealing (ion beam off) at 1473 K after the pre-irradiation at 1273 K, and even during a simple annealing at 1473 K with no irradiation, as shown in figure 2 (b) and (c).

These findings demonstrate that fuzzy structures can be formed at a very thin part even without helium bubbles, if the sample temperature is high enough. This structural change is probably caused by surface diffusion of W atoms driven by surface tension. Helium irradiation seems to enhance this change by activating surface diffusion and by forming a very thin area with helium bubbles. Since there is no thin part in bulk W unlike the samples used in this study, helium bubbles, which can make very thin parts, are thought to be necessary for the initiation of fuzz formation in bulk W.

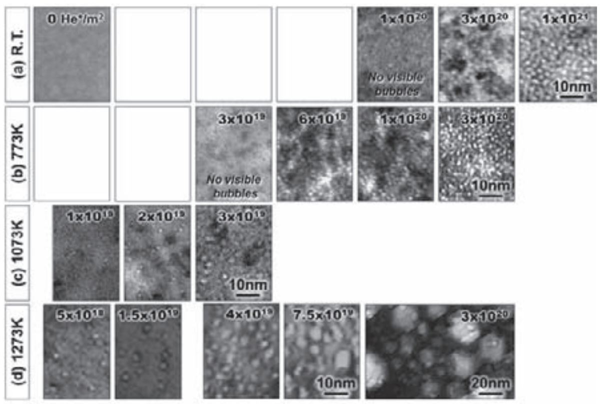

Fig. 1. The microstructural evolution of W under the 3 keV-He^+ irradiation at constant temperatures

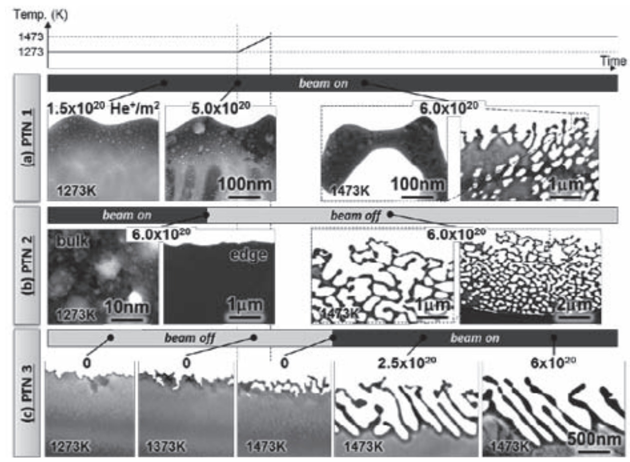

Fig. 2. The microstructural evolution of the edge parts of W under the three different irradiation conditions

1) Takamura, S. et al., Plasma Fusion Res. **1** (2006) 051.
2) Baldwin, M.J. et al., Nucl. Fusion **48** (2008) 035001.
3) Wright, G.M. et al., Nucl. Fusion **52** (2012) 042003.
4) Kajita, S. et al., J. Nucl. Mater. **418** (2011) 152.