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Change of surface morphology and particle retention of the plasma facing materials in the fusion devices under helium irradiation and formation of the mixed-material deposits
ヘリウムプラズマ照射とMixed-material堆積層形成による核融合装置プラズマ対向材料の表面変質と粒子捕捉特性変化

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The effects of "radiation damages by helium for metals" and "formation of the mixed-material deposition layer on the plasma facing components (PFCs)" to particle balance and dust generations in the large-sized plasma confinement devices were studied by using nanoscale material analysis. During helium discharges in Large Helical Device (LHD), heavy radiation damages such as helium bubbles and dislocation loops were densely observed on the first wall materials (SUS316L). Furthermore, mixed-material deposition layers composed by C, Fe and O have been formed on the divertor and first wall surface. Amount of hydrogen retention in such layers were 5-6 times higher than that of bulk carbon materials. These two PWI phenomena would be closely related to degradation of the materials, change of the retention property of the hydrogen isotopes and dust generation in the vacuum vessel. So we have to clearly understand them for achievement of the steady state plasma operations.

1. Introduction

Fusion engineering research has stepped into a new stage of focusing on the technical establishment of a steady state reactor system. It is one of the large phase changes for fusion researches, from the pulse operation experiment which has been performed so far.

Understanding of the particle balance, tritium inventory, degradation of the materials and impurity (dust) generation are four important issues to realize the steady state plasma operations. Then, their four issues would be basically controlled and influenced by only following two phenomena.

First one is "radiation damages by helium for metals". It is known that injected helium atoms in metals can aggregate by themselves and form He-vacancy complexes and helium bubbles even if the knock-on energy is insufficient for the displacement damage [1]. It was reported that once bubbles are formed, the material will become hard and brittle [2], and also, they could be acting as the effective trapping site for hydrogen isotopes [3].

Second one is "formation of the mixed-material deposition layer on the PFCs". During the long pulse discharges in Large Helical Device (LHD), termination of the plasma sometimes occurs with an unexpected sudden increase in impurity radiation [4], which is attributed to some kind of plasma-wall interactions (PWI). It is thought that the impurities originate from thin mixed-material deposition layer on the divertor plates. These are formed by stratified layers consisting of Fe and C elements [5].

If we can totally understand and control about helium and mixed-material effects, we would be able to approach and reach the steady state plasma operations. In this research, therefore, the effects of "radiation damages by helium for metals" and "formation of the mixed-material deposition layer on the PFCs" to particle balance and dust generations in the large-sized plasma confinement devices were studied.

2. Radiation damages by He for metals

The concentration of the helium in fusion plasma would have been expected to be about one order lower than that of hydrogen. So, the discussion about the radiation effects of helium for metals had not been made energetically until about 15 years ago. However, recent years, strong radiation effects such as formation of the dense bubbles and dislocation loops have been reported one after another in the laboratory experiments. Especially, observation results of the transmission electron microscope (TEM) have clarified the formation mechanism of the severe radiation damages in metals [1-3]. Fig. 1 shows the bright; (a) and dark; (b) field TEM images of the SUS316L exposed to helium discharges (87 s in total) in LHD. Typical core plasma parameters were as follows: T_i = 0.7–1.7 keV, n_e = 0.3–8.1×10^{19} m^{-3}. White dot contras in (a) and (b) shows helium bubbles and dislocation loops, respectively. Although total exposure time was only 87 s, very dense fine helium bubbles of about 1–2 nm in diameter and considerably large amounts of dislocation loops were formed. The damages would be caused by charge-exchanged (CX) helium atoms which are not affected by magnetic field, and their energy and flux are sufficiently higher to create these defects. As mentioned in section 1, these defects would change the physical properties of the material surface. Also, once these defects are created, they are difficult to eliminate even up to the high temperature (near the melting temperature of the materials). In the future fusion devices, sequential wall conditioning, for example, glow discharge cleaning (GDC), would not be conducted. Such types of the helium radiation damages might become a serious issue for plasma operations.

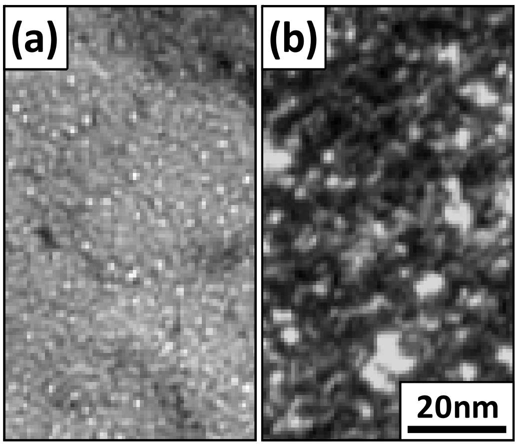

Fig. 1 (a) Bright field and (b) dark field TEM image of SUS316L after exposed to the helium plasma for 87 s at the first-wall position.

3. Formation of the mixed-material deposition layer on the PFCs

The PFCs in fusion machines would be used not only metal materials but also carbon related materials. The formed deposition layer could be the mixed-materials including both elements. Fig. 2 shows the cross-sectional TEM image of the mixed-material deposition layer formed on the graphite divertor tile used for 8 years in LHD. The deposition layer has very fine and stratified structures in the nanometer level. The bright layers were mainly composed by C, and dark layers were metals (Fe, Ni, Mo) It is considered that the deposition elements were piled up in turn, and finally reached ~8 μm thick in total. The reason why such a stratified structure is seen is attributed to the scheme of the operation sequence of LHD. In general, thick deposited layer could be unstable and possible source of impurity (dust) for plasma. Especially, metallic dominant layers including many types of the defects seem to be brittle and acting as the initiator of the exfoliation of the whole deposition layer [6]. In addition, retained hydrogen atoms in the mixed-material deposition layer were about 5 times higher than that of the bulk graphite.

These two PWI phenomena would be closely related to degradation of the materials, change of the retention property of the hydrogen isotopes and dust generation in the vacuum vessel.

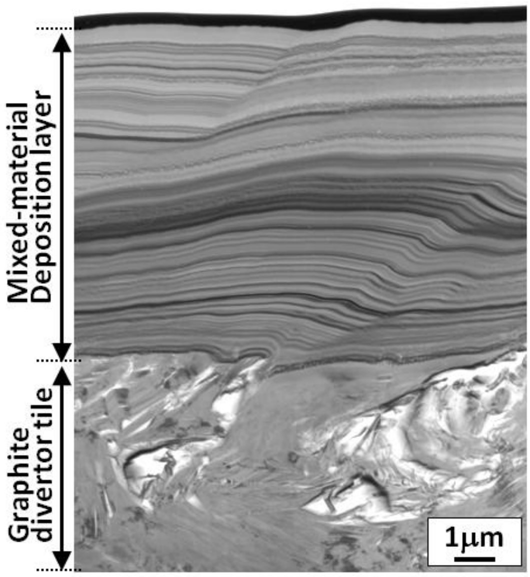

Fig. 2 Cross-sectional TEM image of the mixed-material deposition layer formed on the graphite divertor tiles in LHD.

Acknowledgments

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References

[1] H. Iwakiri et al., J. Nucl. Mater. 283–287, (2000) 1134.
[2] H. Iwakiri et al., J. Nucl. Mater. 256–253 (1998) 873.
[3] H. Iwakiri et al., J. Nucl. Mater. 307–311 (2002) 135.
[4] T. Mutoh et al., Nucl. Fusion 47 (2007) 1250.
[5] R. Kumazawa et al., Fusion Sci. Technol. 58 (2010) 524.
[6] M. Tokitani et al., J. Nucl Mater. 417 (2011) 668.