§17. Microstructural Characterization for the Exfoliation Mechanism of the Mixed-material Deposition Layer during Long Pulse Discharges in LHD

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Controls of particle balance and impurity generation from the wall are the key issues for establishment of a fusion reactor. The Large helical device (LHD) has an important advantage for steady state operation (SSO). First wall panels and divertor plates of LHD are stainless steel (SUS316L) and graphite, respectively. The former is the major material in LHD, and the graphite area is only about 5% of the total plasma facing area. The temperature of the first wall is almost kept at room temperature (R.T.) during plasma discharges. In the recent SSO experiment, a high-performance ultra-long pulse helium discharge of 48 min with n_e ~1.2×10^{19} m^{-3}, $T_{i,e}$ ~2 keV was successfully achieved by the higher heating power of 1.2 MW. However, such ultra-long pulse helium discharges had been disturbed by two major issues that are closely related with plasma wall interactions (PWI). The first issue is the dynamic change of the wall pumping rate during discharges. The second issue is the termination of the discharge by sudden mixing of C and Fe impurities with intensive sparks. This report was focused on the second issue.

Large amounts of deposition layers are formed due to the sputtering erosion and deposition of the plasma facing materials (PFMs) during the long pulse discharge. The first-wall and divertor tiles of the LHD are made of stainless steel (SUS316L) and isotropic graphite, respectively. Thus, a special feature of the deposition layers formed in the LHD is that it has a mixed-material structure of metal (mainly Fe) and carbon [1-2]. The accumulated mixed-material deposition layer could have been exfoliated as small dust, and then mixed into the plasma. The behavior of impurities such as small dust has been gradually understood by using a CCD camera and spectroscopy analysis. Actually, strong light emission from the deposition dominant area was observed just at the moment of the termination of the 48 min discharge. This issue is caused by the microscopic modifications of the wall surface. In this study, in order to achieve the steady-state ultra-long pulse discharge, physical characteristics of the mixed-material deposition layers formed on the LHD PFMs were analyzed by using nano-geological diagnosis [2] and nano-mechanical property testing, and then, were discussed with regard to an exfoliation mechanism of the mixed-material deposition layer.

The mixed-material deposition layers for nano-material testing were collected from two remarkable thick deposition areas among the PFMs. The first area is from the surface of the carbon dome tile of the closed divertor. The second area is from a stainless steel faraday shield of the ICH antenna. After collection of the mixed-material deposition layer, a nano-geological diagnosis was performed by using focused ion beam fabrication (FIB), transmission electron microscope (TEM) observation, and Energy dispersive X-ray spectroscopy (EDS) mapping for understanding the microstructure and chemical composition of the deposition layer. A compression fracture test and hardness test in nano-scale were also performed for evaluating the mechanical strength of the mixed-material deposition layer in nano-scale. A dynamic ultra-micro hardness tester of DUH-211 was used for measuring the mechanical strength of a fracture toughness (MPa) and conversion Vickers hardness (HV*).

Fig. 1-(a) and -(b) shows cross-sectional bright field TEM images (BF-TEM) and corresponding EDS mapping of C and Fe. In the case of (a), since the deposited position had been surrounded with the carbon divertor and the dome tiles, the main component of the deposition layer was C. On the other hand, in the case of (b), since the deposited position had been surrounded with the stainless steel faraday shield, the main component of the deposition layer was Fe. This result indicates that a short range transport and deposition of the sputtered materials acts as a main role for the formation of the mixed-material deposition layer. The maximum fracture strength (σ_f) and conversion Vickers hardness (HV*) of the mixed-material deposition layer (a) and (b) were ~0.9 GPa and »4 GPa, and were ~165 HV* and ~21 HV*, respectively. These results indicate that the C-rich mixed-material deposition layer is harder and more brittle than the Fe-rich mixed-material deposition layer.

The physical and mechanical characteristics mentioned above are very helpful for discussing about the exfoliation mechanism of the mixed-material deposition layer. For reducing the exfoliation, suppression of creating the brittle deposition layer is important. Therefore, we can consider that the carbon materials should be eliminated as much as possible.

1) M. Tokitani et al., J. Nucl. Mater. 417 (2011) 668–672
2) M. Tokitani et al., J. Nucl. Mater. 438 (2013) S818–S821

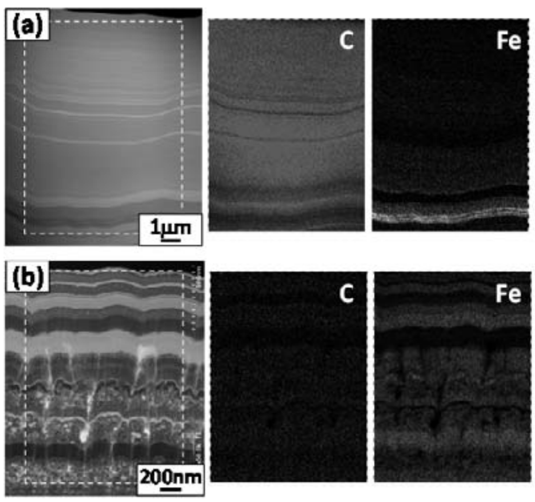

Fig. 1. Cross-sectional BF-TEM images and corresponding EDS mapping images of C and Fe inside the dashed square lines in BF-TEM images. (a): from divertor tile, (b) from first-wall