§24. Temperature Impact on W Surface Exposed to He Plasma in LHD and its Consequences for the Material Properties

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Choice of plasma-facing materials for next generation fusion machines, such as ITER and DEMO, has to take into consideration the intensive fluxes of light elements, such as He and H isotopes, which the first wall materials will be subjected to. This irradiation can let to important damages at the surface, affecting the properties and life span of the materials, hence the efficiency of the reactor. For W, one of the most promising candidates, incident He particles can drastically affect the surface: formation of dislocation loops, bubbles or W-fuzz was observed [1]. These changes at the material surface can modify the mechanical properties and increase hydrogen retention in the structure; understanding of He damages in W are thus of prime importance in a context of spreading use of this material.

One key parameter to examine is the material temperature: indeed, W operation temperature in fusion can reach up to 500 ºC, and temperature rise affects vacancy and interstitial mobility in the material, which has a strong impact on the final microstructure of the material after irradiation as preliminary studies in laboratory confirmed [2].

In order to complement existing laboratory studies with real plasma device conditions, we exposed W samples to He plasma in LHD thanks to a new temperature controlled sample-holder that we conceived and set up. The control of temperature of the samples during exposure was performed thanks to only one ceramic heater with sufficient heating capacity. Tungsten samples were set on a semi-circular stainless steel sample holder, holding the heater on one end and connected to the water-cooled probe base on the other end. The low thermal conductivity of the material allowed the formation of a range of temperature along the radius of 65ºC to 600ºC, estimated via finite element analysis in the conception phase and confirmed in situ by thermocouples and infrared camera measurements (Fig. 1). Samples were exposed to estimated fluences of ~10^{23} He/m^2 with a wide range of He enegiies thanks to Charge-exchanged simulations codes applied to LHD plasma parameters and TRIM simulations.

Structure was observed via TEM (Transmission Electron Microscopy). TDS (Thermo Desorption Spectrometry) performed in Nagoya University after H laboratory implantation in Kyushu University of samples exposed to LHD He plasma allowed to estimate the differential H trapping in the material due to the He damages.

The impact of high temperatures (and fluence) on the He irradiation damages observed was accessed for the first time in real-plasma exposure conditions. Both dislocation loops and bubbles appeared from low to medium temperatures and saw an impressive increase of size (factor 4 to 6) most probably by coalescence as the temperature reaches 600 ºC, with 500 ºC appearing as a threshold for the bubbles growth. Annealing of the samples up to 800 ºC highlighted the stability of the dislocation damages formed by He irradiation at high surface temperature, as bubbles and dislocation loops seem to conserve their characteristics.

Additional studies on cross-sections (Fig. 2) showed that bubbles were formed much deeper (70-100 nm, C and D areas) than the heavily damaged surface layer (10-25 nm depending on the incident He fluence, A area), rising concern about the impact on the material mechanical properties conservation and potential additional trapping of H isotopes.

Nano-indentation measurements confirmed that He irradiation had indeed an impact on the material properties: dislocation loops cause the hardness to increase as they form and develop, while the formation of large bubbles at high temperatures and fluences causes a decrease of the material hardness. Another major concern is potential variation in the hydrogen potential trapping and retention in tungsten due to its modified microstructure. The first results from TDS measurements showed an increase of the deuterium retention in LHD helium irradiated tungsten compared to the pristine one: more studies are needed to understand and quantify the impact on hydrogen recycling and will soon follow.

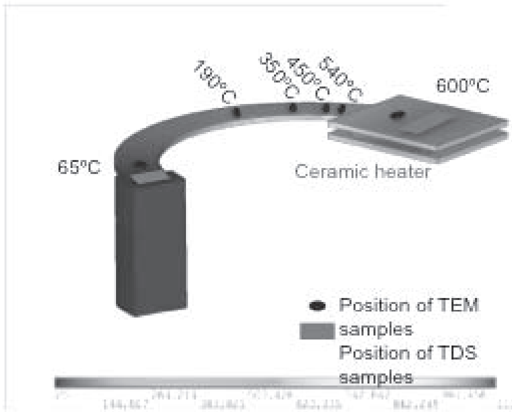

Fig. 1. 3D view of temperature-controlled sample-holder with heat transfer simulations.

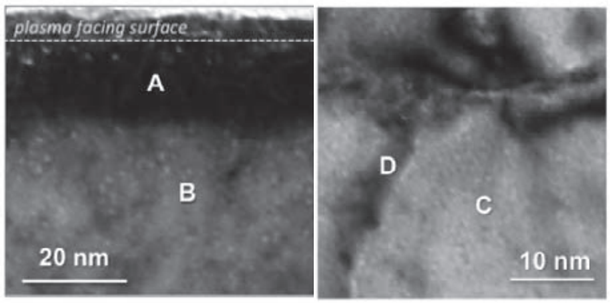

Fig. 2. TEM image of cross-sectioned samples: underneath the heavily damaged layer (A), many He bubbles are formed (B) up to 70-100 nm deep in the bulk (C & D).

1) Y. Ueda et al., J. Nucl. Mater. 386-388 (2008) 725.
2) S. Kajita et al., J. Nucl. Mater. 421 (2012) 22-27.