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Degradation of tungsten monoblock divertor under cyclic high heat flux loading

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HIGHLIGHTS

- Degradation of pure W monoblock divertor during high heat loading at 20 MW/m^2 was evaluated and crack formation mechanism was discussed.
- Macro-crack formation could occur due to complexed low temperature cleavage fracture accompanied by plastic deformation.

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ABSTRACT

The degradation behavior of the ITER divertor under the cyclic high heat flux loading has been varied in the previous studies, which would be induced by the intrinsic difference in the thermo-mechanical properties of each pure W material. Therefore, the experimental characterization of the thermo-mechanical properties of the W materials and the numerical structural analysis using these data are necessary to clarify the degradation mechanism and the prediction of the fracture scenario and lifetime. In this study, the degradation behavior of the pure W monoblock divertor mockup during the cyclic high heat flux loading test at 20 MW/m^2 was evaluated and the macro-crack formation mechanism was discussed based on the structural analysis. The macro-crack formation of the divertor mockup in the present study could occur due to a complexed low temperature cleavage fracture accompanied by the plastic deformation under cyclic loading. The fatigue, especially the low temperature fatigue with plastic deformation, could be a mechanism factor for the macro-crack formation. However, further study considering the thermo-mechanical fatigue and the effect of the low temperature plastic deformation is necessary to quantitatively evaluate the macro-crack formation mechanism by the fatigue.

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1. Introduction

Tungsten (W) is a primary candidate for the plasma facing material of the fusion reactor divertors because of its high melting point, thermal conductivity, sputtering resistance, and low tritium retention [1]. During the operation of the fusion reactor, the divertor will be subjected to the cyclic high heat flux loading. As a result, degradation of the thermal and mechanical properties at the surface and near-surface region of the divertor may occur due to the recrystallization, the crack formation, the deformation, and the melting of the W material [2,3].

One of the most important degradation issues of the W monoblock divertor for the ITER suffered by the cyclic high heat flux loading is a crack formation from its top surface to the cooling pipe along the heat conduction direction [2]. The thermo-mechanical fatigue and thermal shock are considered as one of the most likely mechanisms for the crack formation. However, the clarification of the mechanism based on the quantitative structural evaluation was limited [3–7]. Moreover, some cyclic high heat flux loading tests of the ITER divertor mockup showed clear crack formation [2], whereas some tests showed no crack formation and showed relatively large deformation [3]. For example, Merola et al. noted that the mock-up made out of the forged W bar tested to 5000 cycles at 10 MW/m^2 and 1000 cycles at 20 MW/m^2 showed the crack formation and that the mock-up made out of the rolled W

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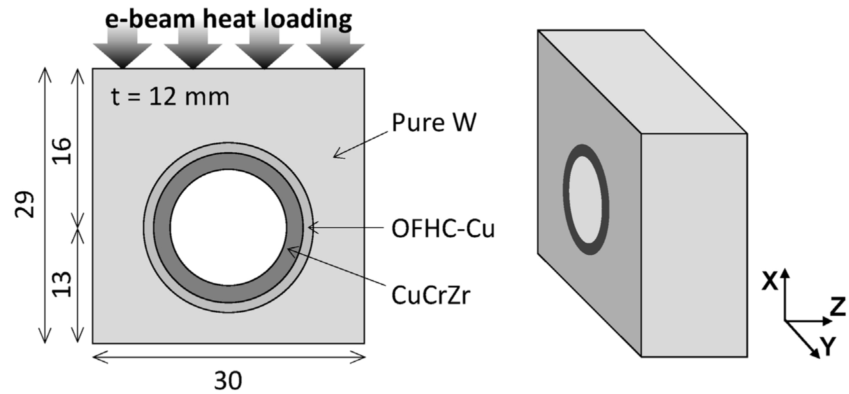

Fig. 1. Schematic illustration of divertor mockup.

plate tested to the same cycles at the same heat load conditions showed no crack formation and relatively large deformation [8]. Although crack formation tended to occur more easily in the forged W due to its microstructure in comparison with the rolled W in general, some rolled one also showed crack formation by the cyclic high heat flux loading test up to 20 MW/m^2 [2]. Because all the W materials employed for the monoblock body examined by these cyclic high heat flux loading tests were pure W, which satisfied the requirement for the ITER divertor, the intrinsic thermo-mechanical properties of each individual W material would be different, which might be affected by the fabrication processes of the materials [8]. Therefore, the experimental characterization of the thermo-mechanical properties of the W material utilized for the divertor and the numerical structural analysis using these properties data are necessary to clarify the degradation mechanism and to predict the fracture scenario and lifetime of the divertor.

The objective of this study is to experimentally evaluate the degradation behavior of the W monoblock divertor during the cyclic high heat flux loading and to predict the degradation mechanism, especially the crack formation mechanism, based on the experimental results and the numerical structural analysis.

2. Electron beam irradiation by JEBIS

Fig. 1 shows the schematic illustration of the divertor mockup evaluated in the present study. The pure W monoblock divertor mockup with an oxygen-free high-conductivity copper (OFHC-Cu) interlayer and a copper chromium zirconium (CuCrZr) cooling pipe was utilized for the experiments. The pure W of this mockup was fabricated by the cross roll forging by Plansee AG. The OFHC-Cu interlayer and the CuCrZr cooling pipe were joined to the pure W monoblock body by the brazing by Kawasaki Heavy Industries.

The cyclic high heat flux loading test was conducted using an electron beam irradiation facility of Japan Atomic Energy Agency (JAEA) in Japan, which was called JAEA Electron Beam Irradiation Stand (JEBIS) [9]. The heat loading condition was 10 MW/m^2 up to 75 cycles and 20 MW/m^2 up to 300 cycles, which referred to technical requirements of the ITER full-W divertor qualification program (10 MW/m^2 up to 5000 cycles and 20 MW/m^2 up to 300 cycles) [10]. Because electron beam diameter of JEBIS (a few millimeters) was smaller than the heat-loaded surface area of a monoblock, scanned beam was utilized for the irradiation test. Acceleration voltage, beam current, and scanning frequency of the electron beam were 70 kV, 3 A, and 1 kHz, respectively. The heat-loaded area by the scanned beam was 30 mm × 150 mm to irradiate several monoblocks at the same time. The heating and cooling time in one cycle were 10 s and 20 s, respectively, which also referred to technical requirements of the ITER full-W divertor qualification program (typically 10 s heating and 10 s cooling) [10]. The flow rate, pressure, and temperature of the coolant water were 1 kg/s, 2 MPa, and 25 °C, respectively. The details of the heat loading test are described in the open literature [3].

3. Degradation behavior

To investigate the degradation due to the JEBIS irradiation, the metallographic structure of the outer surface and the cross-section of the divertor mockup were observed using an optical microscope and a scanning electron microscope. The outer surface observation results using a scanning electron microscope are shown in Fig. 2. A macro-crack and high density of micro-cracks were observed at the heat-loaded surface as shown in Fig. 2(a)–(d). A macro-crack was formed only at the center of the heat-loaded surface, whereas the micro-cracks were formed at whole region of that. As shown in Fig. 2(f), a few micro-cracks were also observed at the side surface of the divertor mockup. Roughening of the heat-loaded surface was observed especially around the macro-crack. The roughened surface consisted of the thermal etching of the grain boundaries (groove formation at grain boundary by diffusion and vaporization of atoms at high temperature [11]), the micro-crack formation, and the grain ejection as shown in Fig. 2(c) and (d). No melting of the mockup occurred in this experiment as reported in some previous cyclic high heat flux loading tests of the W divertor mockup [2].

Fig. 3 shows the cross-sectional metallographic structure of divertor mockup after the JEBIS irradiation observed by an optical microscope, whose position was 1 mm far from the side surface of the mockup. Regions with different contrast (region I and II) were observed as shown in Fig. 3(a). As shown in Fig. 3(b) and (c), the elongated grains and the homogenous-shaped grains were observed in the region II and region I, respectively. Fig. 4 shows the cross-sectional distribution of the grain size aspect ratio (a/b) of the divertor mockup after the JEBIS irradiation, where the values a and b are corresponding to the grain size parallel and perpendicular to the heat-loaded surface, respectively. The aspect ratio was ranged from 0.2 to 0.5 in the region II, while that was ranged from 0.5 to 1 in the region I. The homogeneous-shaped grains in the region I might indicate the recrystallization of W due to the heat loading. The facts that the recrystallization temperature of the pure W might be around 1300 °C [12] and that the temperature of the region I achieved above 1400 °C based on the finite element analysis (FEA) described in the chapter 4.3 could support this prediction.

Fig. 5 shows the cross-sectional distribution of the Vickers hardness of the divertor mockup after the JEBIS irradiation. The measurement of the hardness was performed in the same cross-section of the grain size measurement. Load and dwell time of the hardness measurement were 0.98 N and 15 s, respectively. The reduction of the hardness from approximately 9 mm from the heat-loaded surface was observed in the distribution from the point E

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