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Development of divertor plate with CFCs bonded onto DSCu cooling tube for fusion reactor application

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Abstract

This paper presents the high heat flux experiment of divertor mock-ups with CFC–Cu duplex structure. A plasma-facing component (PFC), which is served as a protection wall against heat and particle loads from fusion plasma, is one of the critical components of next fusion devices such as ITER. A divertor plate which is one of the PFCs must be capable of withstanding cyclic heat load of 5–20 MW/m^2 in ITER. To investigate the thermal fatigue behavior, a thermal cycling experiment was conducted in Particle Beam Engineering Facility. As a result, the divertor mock-up with a dispersion strengthened copper cooling tube could withstand a heat flux of 20 MW/m^2 for 1000 cycles. On the other hand, the mock-up with an oxygen-free-high conductivity copper cooling tube showed a water leakage at about 400 cycles due to thermal fatigue cracking.

1. Introduction

In the ITER-EDA, the development of divertor plates has been energetically carried out in JAERI. The divertor plates are subjected to the most severe heat loads from the plasma among the PFCs, such as first walls and divertor plates. For instance, a vertical target, which is one of the divertor high heat flux components, is required to withstand the heat fluxes of 5–20 MW/m^2 during the operation [1]. JAERI has been developing CFC/Cu duplex structures for the divertor plate. An oxygen-free-high-conductivity copper (OFHC-Cu) has been utilized as a structural material of the divertor plate from the high thermal conductivity and the good braze performance points of view [2–5]. However, it was pointed out from the previous experiments that the OFHC-Cu cooling tube of the divertor plates had a serious problem on the thermal fatigue resistivity [6]. Hence, an alumina-oxide dispersion strengthened copper (DSCu) was proposed for the structural material of the divertor plate from the fatigue lifetime and mechanical strength points of view. To investigate the thermal fatigue resistivity of the DSCu, thermal cycling experiment of divertor mock-ups with the DSCu cooling tube was conducted in the Particle Beam Engineering Facility (PBEF) [7] in JAERI.

2. Divertor mock-ups and experimental setup

Fig. 1 shows schematic drawing of the divertor mock-ups. The mock-ups have a real-scale length of the ITER vertical target. The type-1 mock-up has a DSCu (Al_2O_3: 0.3 wt%) cooling tube with a duplex structure. The outer skin (thickness: 1.0 mm) of the tube was made of OFHC-Cu to improve the braze performance. The outer skin and the inner core (DSCu) were cladded together in the hot extrusion process. On the contrary, the type-2 mock-up has a cooling tube made of OFHC-Cu. The cooling tubes of both mock-ups have a twisted tape inside to improve its heat transfer. Both mock-ups have "saddle-shaped" armor tiles made of a unidirectional CFC material. These armor tiles were brazed onto the cooling tubes and the heatsink with a Ti–Cu–Ag braze material at a braze temperature of 850°C. These mock-ups have a backplate made of stainless steel (304SS) as a support structure. The backplate and the

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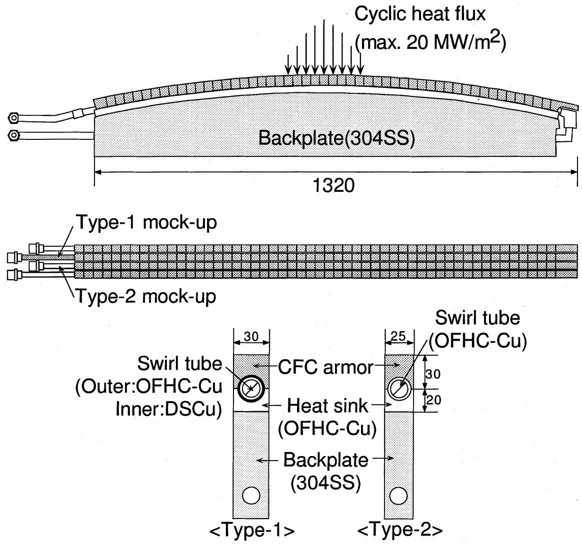


Fig. 1. Schematic drawing of divertor mock-ups.

heatsink were also brazed together with the Ti–Cu–Ag braze material.

3. Experiment

The thermal cycling experiment was performed by means of the cyclic irradiation of the hydrogen ion beam onto the CFC armor tiles. Both mock-ups were cyclically heated at the same time to directly compare the thermal fatigue behavior. The experimental conditions and the ITER divertor design requirement values are summarized in Table 1. The maximum heat flux of 20 MW/m^2, which corresponds to the nominal heat flux onto the ITER divertor plate in the transient operation phase, was loaded on the central part of the mock-ups. The heating duration was 15 s to simulate the transient operation. The coolant temperature and the pressure were 25°C and 2 MPa. To observe the change of the thermal response of the mock-ups, the temperature evolutions of the CFC armor tiles and of the heatsink were monitored by an infrared camera and thermocouples, respectively.

4. Experimental results

In the thermal cycling experiment, the maximum temperature of the armor tiles was around 2000°C at the end of the heating period. After 380 thermal cycles, one of the armor tiles of the type-1 mock-up detached. And one of the other CFC armor tiles showed a hot spot on the surface during the heating period. The hot spot was

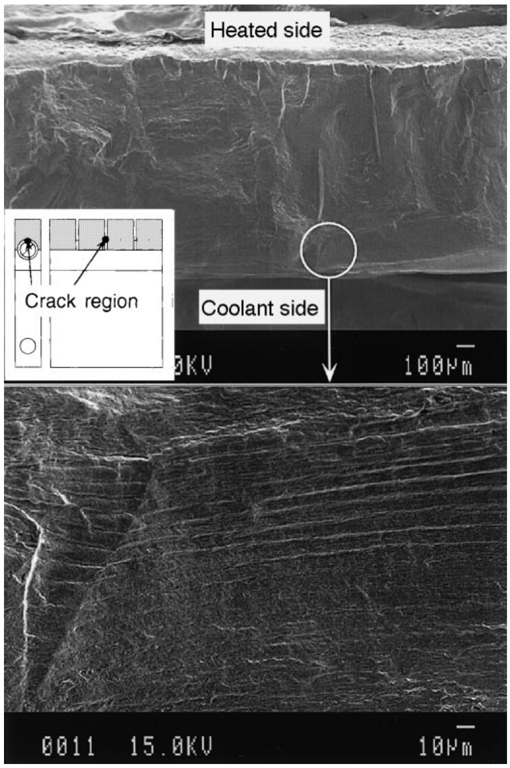


Fig. 2. Fracture surface of the OFHC-Cu cooling tube (Type-2 mock-up). Upper: Whole cross section of the fracture surface. Lower: Close-up view of the white circle in the upper picture.

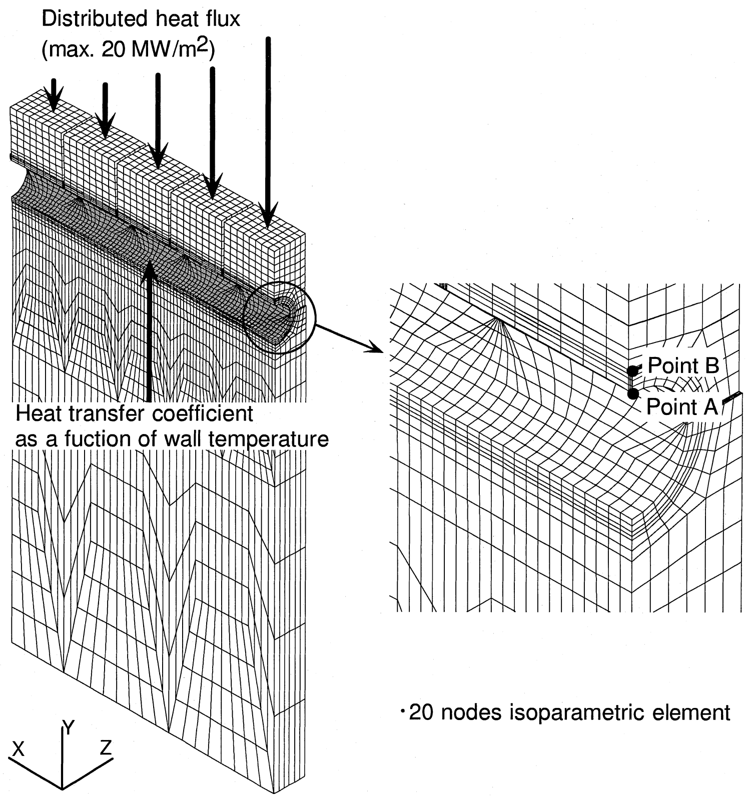
Table 1
Experimental conditions and ITER divertor requirements

	Thermal cycling experiment	ITER divertor [1]
Surface heat flux(MW/m^2)	Max. 20	5.0 (normal operation)15–20 (transient)
Thermal cycle (cycle)	1000	1000 (design lifetime)
Coolant	Water	Water
Coolant pressure (MPa)	2	$\geqslant$ 4.0
Coolant temperature(°C)	25	150

attributable to the initial braze flaw since the hot spot appeared from the early period of the experiment. The type-2 mock-up showed a good thermal performance at the same thermal cycle. However, a water leakage of the type-2 mock-up was observed at about 400 thermal cycles. The crack initiated from the cooling tube located between the adjacent armor tiles. Fig. 2 shows the SEM images of the fracture surface. A clear evidence of the fatigue damage was found. As a result of the microscopic observation, several traces of a large strain concentration were found not only at the crack region but at the other part of the inner wall of the cooling tube located at the gap region between the adjacent armor tiles. On the contrary, the type-1 mock-up could successfully survive from the thermal loading up to 1000 cycles with no evidence of the fatigue damage while two armor tiles debonded from the cooling tube and the heatsink due to the braze flaw.

5. Discussion

Since it was difficult to directly obtain the strain evolution of the cooling tubes in the experiment, 3-dimensional finite element analyses were conducted using ABAQUS code to clarify the stress–strain behavior of both mock-ups. Fig. 3 shows the finite element model and the boundary conditions. To simulate the stress–strain behavior under the cyclic loading, elastoplastic stress analyses using kinematic hardening law were



	Armor (Unidirectional CFC)	Cooling tube (OFHC-Cu)	Cooling tube (DSCu)	Backplate
Density (kg/m^3)	1960	8920	8920	8000
Thermal Conductivity (W/m/K)	700 (parallel to CF) 26 (perpendicular to CF)	400	400	14.5
Specific heat (J/kg/K)	693	380	380	480
Elastic modulus (GPa)	100 (parallel to CF) 0.8 (perpendicular to CF)	82.3	82.4	195
CTE (x 10^{-6}/K)	−0.9 (parallel to CF) 12 (perpendicular to CF)	15.4	16.9	16

(at room temperature.)

Fig. 3. Finite element model and typical material properties.

performed. The anisotropic physical properties of the CFC armor tiles were also taken into account [8]. Three thermal cycles were simulated to get the stable stress–strain behavior of the model. The assumed heat flux was based on the Gaussian profile of the ion beam in the experiment. From the thermal-hydraulical point of view, the subcool boiling effect was also taken into account in the analysis [9–11]. The maximum surface temperature of the armor tiles was calculated to be over 2000°C, which is in good agreement with the experimental result. Based on this, the subsequent elastoplastic stress analysis was conducted. Fig. 4 shows the evolution of the strain components of the point A (see Fig. 3) of both models. The maximum mechanical strain amplitude along X-direction ($\varepsilon_{xx\mathrm{mech}}$) which has the most severe influence of the fracture of the cooling tube appeared at the outer surface of the tube (Point B) for both cases. However, the strain component at the Point B ($\varepsilon_{xx\mathrm{mech.,PointB}}$) always showed negative values at the third thermal cycle. In addition, the trace of the fatigue crack implies that the fatigue crack initiated from the inner wall of the cooling tube. Therefore, the lifetime of these models was evaluated using the strain components at the point A. The calculated equivalent mechanical strain amplitudes at the point A were 0.25% for the type-1 and 1.7% for the type-2 model, respectively. In the type-2 mock-up, the large strain amplitude was caused not only by the lower stiffness of OFHC-Cu but by the rigid constraint from the heatsink and the backplate. As a result, it was proved that the large strain amplitude initiated in the OFHC-Cu cooling tube of the type-2 mock-up caused the thermal fatigue cracking. Kojima et al. [12] and Ishiyama et al. [13] reported the fatigue behavior of OFHC-Cu and DSCu, respectively. In particular, Kojima correlated the fatigue lifetime of annealed OFHC-Cu in the Manson–Coffin-styled [14] equation as follows:

$$\Delta\varepsilon_{\mathrm{t}} = 175.8N_{\mathrm{f}}^{-0.7} + 0.75N_{\mathrm{f}}^{-0.1}, \tag{1}$$

where $\Delta\varepsilon_{\mathrm{t}}$ is the total strain range (%) and N_{f} the number of cycles to failure. Based on this equation, the fatigue lifetime of the type-2 mock-up was estimated to be 10^3 cycles. On the other hand, no correlation of the fatigue lifetime of DSCu is presently available. Therefore, the strain amplitude of the type-1 mock-up was directly compared with the Ishiyama's experimental data to obtain the fatigue lifetime. As a result, the fatigue lifetime of the type-1 mock-up was estimated to be over 10^4 cycles. In these analyses, the coolant temperature was assumed room temperature to simulate the experiment. The fatigue lifetime of the ITER divertor plate is slightly less than this prediction since the coolant temperature of the ITER is designed to be 140°C.

6. Conclusions

Thermal cycling experiment of the type-1 and the type-2 mock-ups was performed in PBEF. The type-1 mock-up with the DSCu cooling tube could successfully withstand the cyclic heat flux of 20 MW/m^2 for 1000 cycles while some CFC armor tiles were debonded due to the braze flaw. The braze process should be modified and optimized for this geometry. From the thermal fatigue point of view, the CFC-DSCu duplex structure is one of the most promising solution for the ITER di-

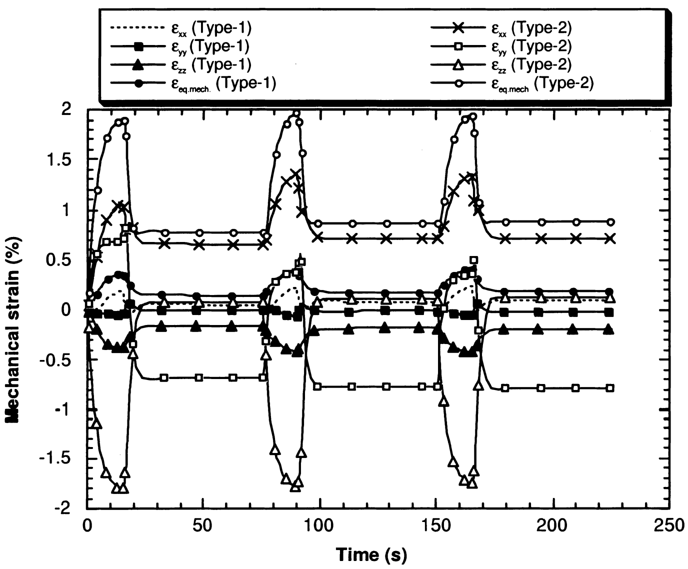


Fig. 4. Mechanical strain evolution of the Type-1 and the Type-2 model at the point A.

vertor application. On the contrary, the type-2 mock-up with OFHC-Cu cooling tube was found to have a serious problem on the thermal fatigue resistivity. For the ITER divertor application, the support structure, which consists of the heatsink and the backplate, should be modified for the OFHC-Cu. For instance, the support structure which is capable of sliding between the heatsink and the backplate is a possible solution for the OFHC-Cu cooling tube.

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