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Heat load test of Be/Cu joint for ITER first wall mock-ups

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Abstract

Bonding by hot isostatic pressing with an interlayer has been developed as a joining technology of beryllium (Be)/alumina dispersion strengthened copper, a candidate for the ITER first wall. Heat removal and thermal cycle tests with a heat flux of 5 MW/m^2 for 1000 cycles were carried out to evaluate the heat removal performance and the durability of these joints for two types of mock-up that were fabricated with an interlayer of either Al/Ti/Cu or pure Cu. These tests were carried out at OHBIS (Oarai Hot-cell electron Beam Irradiation System) in JAERI. Both mock-ups showed good heat removal performance at conditions simulating the ITER-FEAT operation. It became clear that the interlayer of Al/Ti/Cu excelled pure Cu from the point of cracking at the interface

1. Introduction

The first wall in the ITER blanket will be exposed to a heat flux of 0.2–0.5 MW/m^2. Beryllium and copper alloys (dispersion strengthened copper, DSCu etc.) had been selected as an armor and heat sink in the ITER design, respectively, and the joining technology by HIP has been developed [1–7]. Since the difference of thermal expansion between beryllium and DSCu is small, HIP had been considered for this joining. However, direct Be/DSCu bonding had not been successful due to the residual stresses that cause cracking at the bonded interface because beryllium is brittle. To avoid the cracking, the application of interlayer materials had been proposed and several HIP conditions were investigated by the preliminary tests [1]. From these results, two types of mock-up with an interlayer were fabricated, and high heat load tests were carried out to evaluate the heat removal performance and the durability of these joints.

2. Experimental

A photograph and conceptual figure of the first wall mock-up are shown in Figs. 1 and 2. The mock-up consists of the beryllium armor (S65C) and the DSCu (Al-25, Al_2O_3: 0.5 wt%) heat sink. The dimension of armor and heat sink is 20 mm long, 15 mm wide, 7 mm high and 40 mm long, 15 mm wide, 19 mm high with ∅ 8 mm cooling water channel, respectively. Two types of mock-up were fabricated, one with the interlayer of Al/Ti/Cu (Type 1) and the second with pure Cu (Type 2), and tested by the OHBIS (Oarai Hot-cell electron Beam Irradiation System) [8]. The HIP conditions are shown in Table 1, and vacuum plasma spraying (VPS) and physical vapor deposition (PVD) were used as coating as a pre-HIP process. The structure of Type 1 is, the beryllium armor + Al (VPS, 0.7 mm) + Al foil (JIS 4004-H16, Si: 10.3%, Mg: 1.6%, 0.12 mm) + Al (PVD, 10 μm)/Ti (PVD, 10 μm)/Cu (PVD, 10 mm) + DSCu heat sink [1]. The structure of Type 2, is the beryllium armor + Cu (PVD, 10 mm) + DSCu heat sink. The pressure and hold time of HIP were 150 MPa and 2 h, respectively. HIP temperature was selected to avoid the sensitization of stainless steel as a blanket structure material.

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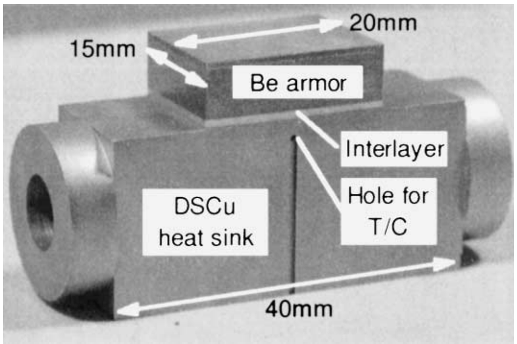

Fig. 1. Photograph of the first wall mock-up.

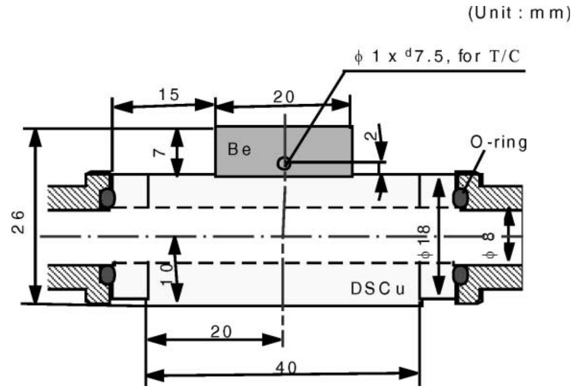

Fig. 2. Conceptual figure of the first wall mock-up.

The surface temperature was measured by the IR camera. Internal temperature in beryllium and copper (see Fig. 2, distance of 2 mm from interface) were measured by thermocouples. The mock-up was bolted up by the mechanical jack, and was sealed by the fluorine rubber O-ring and the edge of connecting pipe [9]. As for the cooling condition of the mock-up, the flow rate of cooling water was 11 m/s, the inlet pressure was 1.5 MPa, and the inlet temperature was 35 °C. Heat flux distribution on the surface of mock-up at 5 MW/m^2 is shown in Fig. 3. All experiments were carried out with the residual pressure of $\sim 3 \times 10^{-3}$ Pa.

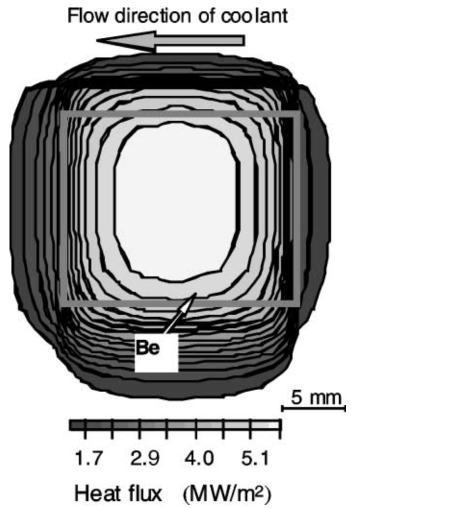

Fig. 3. Heat flux distribution in the surface of mock-up at the 5 MW/m^2.

3. Results and discussion

3.1. Heat removal tests

Heat removal tests for the two types of mock-up were carried out. An electron beam pulse length of 15 s was selected since it was sufficient to achieve saturation. The result of the heat removal test is shown in Fig. 4. The two type of mock-up showed good heat removal properties because the temperature of beryllium measured by the thermocouple showed approximately linearly increasing for a function of heat flux. The calculated temperature of beryllium by ABAQUS version 5.8 code [10] that assumed no thermal resistance at the interface also agreed with the experimental data [1]. This calculated data is shown in the same figure. This agreement showed that both joints were sound without thermal resistance at the interface.

3.2. Thermal cycle test

Prior to the thermal cycle test, the heat flux was decided. Temperature and thermal stress of the Be/DSCu interface will be important to evaluate the durability of these joints. For the ITER-FEAT normal operation, the

Table 1
HIP bonding condition for mock-ups

No.	Pre-HIP coating on Be	Interlayer	Pre-HIP coating on DSCu	Temperature (°C)
Type 1	Al[a] (0.7 mm)	Al foil JIS 4004-H16 (0.12 mm)	Al[b]/Ti[b]/Cu[b] (each coating is 10 μm)	555
Type 2	–	–	Cu[b] (10 μm)	620

[a] Coated by VPS.
[b] Coated by PVD.

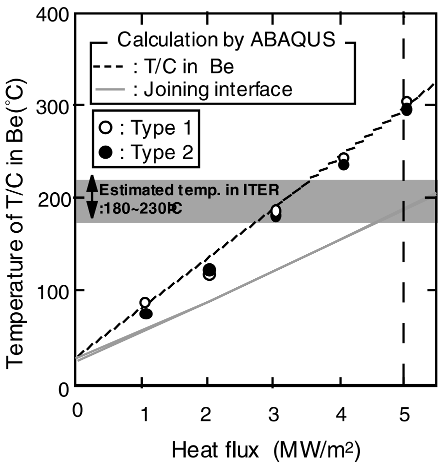

Fig. 4. Result of heat removal test.

temperature of the Be/DSCu interface is 180–230 °C with a surface heat flux of 0.5 MW/m^2 and coolant temperature of 100–150 °C. However, to simulate the thermal stress by the OHBIS, the interface temperature will be lower value because the coolant temperature is lower than ITER condition. Therefore, the interface temperature was simulated in this test, and heat flux was selected as 5 MW/m^2 (see Fig. 4). Though this condition is severe as a thermal stress, it is appropriate as a method for confirming the soundness of these joints.

The result of thermal cycle tests up to 1000 cycles with 5 MW/m^2 and 15 s are shown in Figs. 5 and 6. The temperature saturated in 300 °C in the Type 1, however the temperature saturated in 500 °C in the Type 2. Response speed of the corner temperature for the Type 1 was rapid, and the corner temperature was stable up to 1000 cycles. However, the temperature response speed of Type 2 slowed down, and the corner temperature increased from 800 cycles. From these results, it was estimated that the interface of Type 2 had some changes that cause worse heat removal property than that of Type 1 by thermal cycles.

After the thermal cycle tests, no visible changes were observed in either mockup. Detachment of the interface for both mock-ups was measured by the laser. Change of the shape was not observed in the Type 1, and was observed in the Type 2. Photograph and measured result in the interface of Type 2 is shown in Fig. 7. A crack with maximum depth of 2.8 mm from the beryllium tile edge

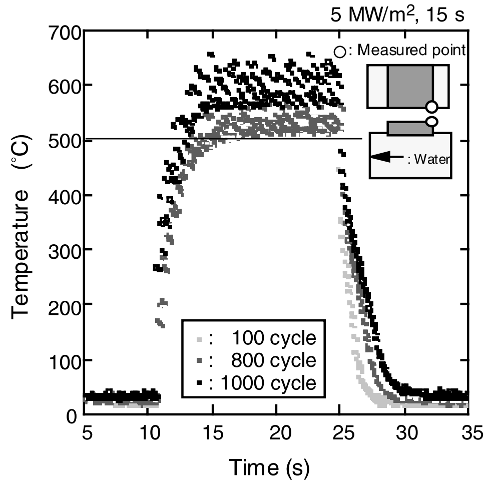

Fig. 6. Surface temperature at the corner of the beryllium (Type 2).

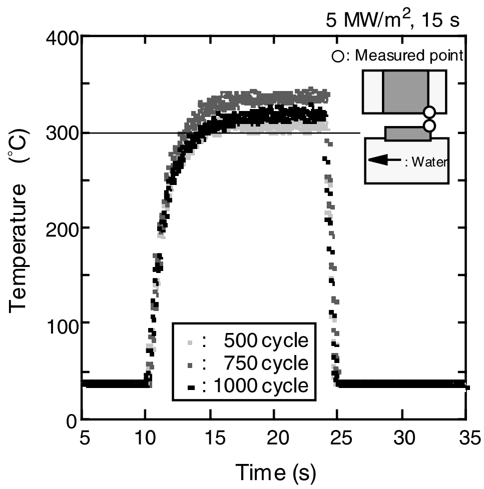

Fig. 5. Surface temperature at the corner of the beryllium (Type 1).

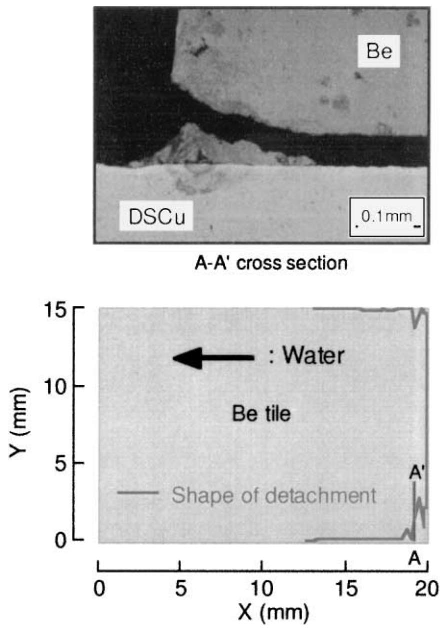

Fig. 7. Visual observations after thermal cycle test (Type 2).

was observed at Be/DSCu HIPed interface in the specimen with Cu interlayer. This appears to be the reason why this crack slowed the temperature response speed in the corner of beryllium armor. From these results, it became clear that the HIP methods of Type 1 excelled Type 2.

Elasto-plastic thermal stress analysis with temperature distributions under heat load of 5 MW/m^2 was performed to consider the role of the interlayer in the two mockups [1]. Stress free condition was assumed at the temperature, 600 °C, and the residual stress was calculated. Calculated Tresca stress distributions are shown in Figs. 8 and 9. The thermal stress change during one heat cycle is also shown as '$\Delta\sigma$' in the same figures. It was confirmed that the Al interlayer acts to relax the thermal stress between beryllium and DSCu in the Type 1 mock-up. Thermal stress under ITER-FEAT normal operation was estimated to be lower than that in the thermal fatigue tests. Even the mockup with pure Cu interlayer would maintain sufficient thermo-mechanical performance. However, Be/DSCu HIPing technology using Al/Ti/Cu interlayer should be selected when the heat flux becomes more severe.

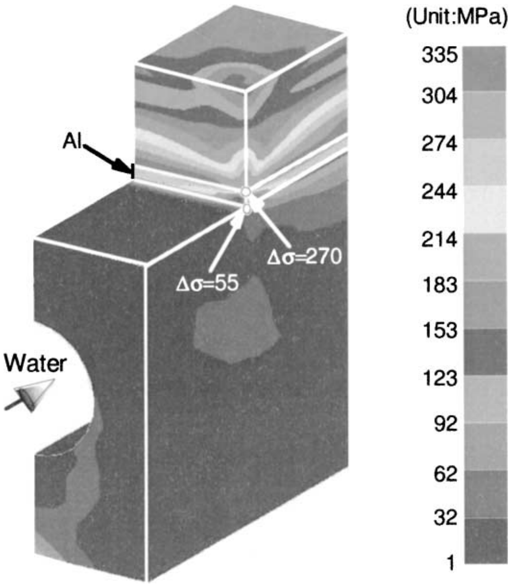

Fig. 8. Calculated tresca stress distributions (Type 1).

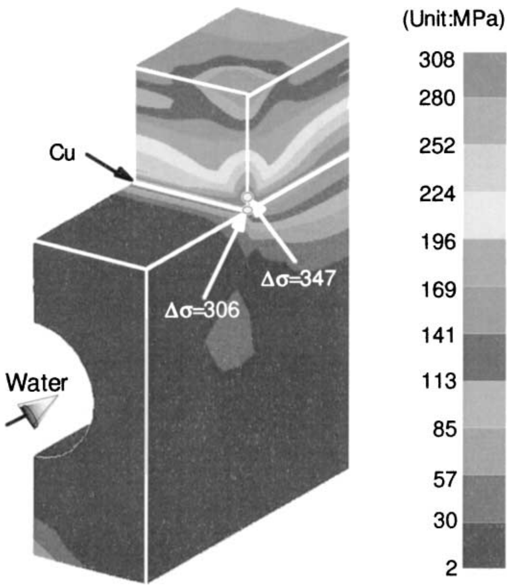

Fig. 9. Calculated tresca stress distributions (Type 2).

4. Conclusion

First wall mock-ups with the interlayer of Al/Ti/Cu (Type 1) and pure Cu (Type 2) were fabricated by HIP. Heat removal and thermal cycle tests of the two type of mock-up were carried out, and the following results were obtained:

- As for the heat removal test, the two types of mock-up showed good heat removal properties under the condition of 1–5 $MW/m^2 \times 15$ s.
- As for the thermal cycle test, obvious damage could not be observed in these mock-ups up to 1000 cycles $\times$ 15 s at 5 MW/m^2. However, the crack was observed at the corner of interface in Type 2 after the tests.

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