Development of a Large-scale Monoblock Divertor Mock-up for Fusion Experimental Reactors in JAERI

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Abstract. In a design of fusion experimental reactors, the divertor is required to withstand a steady-state heat load range of 5-10MW/m^2, and a transient heat load of up to 20MW/m^2. JAERI has developed a high thermal conductivity carbon fiber composites (CFCs), reduced activation brazing techniques, and three layer high strength copper tubes. Based on these technologies, a 1 m long divertor mock-up, which is relevant to a reactor-scale divertor plate, has been fabricated. The mock-up has 30 CFC armors, whose dimension is 30 mm long, 30 mm wide, and 60 mm high. The center of the armor is drilled and directly brazed to the cooling tube, so-called the monoblock type. After heating tests with an intense ion beam, it has been successfully demonstrated that the mock-up withstands a heat load of 5 MW/m^2, 30s for 3000 cycles, and a heat load of 20 MW/m^2, 10s for 1000 cycles without failure.

1. Introduction

It is one of the key issues for fusion experimental reactors to develop the divertor plate which can endure high heat flux and high particle flux from plasma. In the design of next fusion devices such as the International Thermonuclear Experimental Reactor [1], a heat load to the divertor plate is estimated to be 5-10 MW/m^2 in steady-state operation for several hundreds seconds, and up to 20 MW/m^2 in a transient mode for several seconds. To endure these thermal loads, the divertor plate should be actively cooled. Further the divertor should have the sufficient lifetime for the steady-state operation, which is estimated to be several thousands cycles. To satisfy this condition, the lifetime of the divertor, in particular, the lifetime of coolant tubes becomes critical, and it is necessary to develop a high performance cooling tube, which has high strength and high heat removal capability. A monoblock divertor design is one of the candidate designs of the divertor plate [2]. Advantage of the monoblock design is that thermal stress of the cooling tube can be reduced to 50 % of a nominal flat tile design. This means that it can be expected to realize longer lifetime of cooling tubes. Another advantage is that fallen-off of armor tiles could be avoidable. In this paper heating test results of the monoblock divertor mock-ups are presented.

2. Development of High Performance Cooling tube

Heat loads onto the divertor plate causes high thermal stresses and strain within a cooling tube. The cooling tube should withstand these thermal stresses and remove heat loads of 5 - 20 MW/m^2 efficiently. From view point of strength, dispersion strengthened copper or precipitation hardened copper is attractive because of its high tensile strength, which is almost the same as that of stainless steel. As these cooling tube should be bonded with armor tiles, it is preferable that the cooling tube does not loose its strength after bonding process such as brazing. Considering brazing process, dispersion strengthened copper is more attractive than precipitation hardened copper, because it can retain its strength up to 900 ¡C, while the precipitation hardened copper such as CuCrZr looses its strength at temperature of over 600 ¡C. Therefore dispersion strengthened copper, in particular, Aluminum Oxide dispersion strengthened copper (DSCu) is selected as the cooling tube material.

For brazing CFC armor tiles onto a DSCu cooling tube, however, it has turned out that DSCu is too strong, and the tiles are detached because of large difference of thermal expansion rate between the armor and the cooling tube. Based on previous results[3], a soft copper layer of oxygen free copper (OFCu) is introduced as an interlayer to overcome this problem, which can reduce residual stresses caused by brazing process. To optimize the OFCu thickness, numerical analyses and experimental studies have been carried out. Figure 1 shows the estimated residual stresses as a function of OFCu thickness, which is calculated with a finite element code, ABAQUS. From this figure it can be seen that the residual stress drastically dropped at the 1 mm thick OFCu, and the residual stress at 2 mm thick is lower than that of 1 mm thick, but the change becomes small. These numerical results imply that the interlayer thickness of more than 1 mm would be effective to reduce the residual stresses. To demonstrate these results, small duplex specimens were fabricated and tested. The test specimen has 2D CFC tiles of 25 mm^L x 25 mm^W x 10 mm^t, that is brazed onto a DSCu block of the same dimensions with the OFCu interlayer. Three different thickness of the interlayer are tested; 0.5 mm, 1 mm, and 2 mm thick. The test procedure is as follows; first the test specimen is heated up to 500 ¡C in Ar gas, then fallen into water of 25 ¡C. The test results are briefly summarized in TAB. I. It can be seen that the test results show good agreement with the calculation. Though the CFC tile is detached in case of the test specimen with 0.5 mm thick interlayer, no failure have been occurred in case of the 1 mm and 2 mm thick interlayer. Based on these results, the interlayer thickness of 1 mm has been selected.

To remove a heat load of 20 MW/m^2, it is necessary for a cooling tube to enhance heat transfer. Based on the previous studies [4], a twisted tape insert is applied for the present cooling tube, which is called as a swirl tube. In manufacturing the swirl tube, it is essential to fix the twisted tape inside the tube rigidly. To realize this, a thin OFCu layer of 0.5 mm thick is adapted inside of the DSCu cooling tube. As the results of these R&Ds above, three layer DSCu cooling tube has newly been developed, which consists of a 1 mm OFCu outer-layer, a 1.5 mm thick DSCu core layer, and a 0.5 mm thick OFCu inner-layer. The OFCu outer layer is the interlayer for brazing CFC tiles and the DSCu tube. The OFCu inner layer is for fixing the twisted tape insert. Fabrication of the three layer DSCu swirl tube is as follows; first a copper bullet which consists of three copper layers is prepared, then a swirl tube is extruded from the bullet with a twisted tape insert at one process.

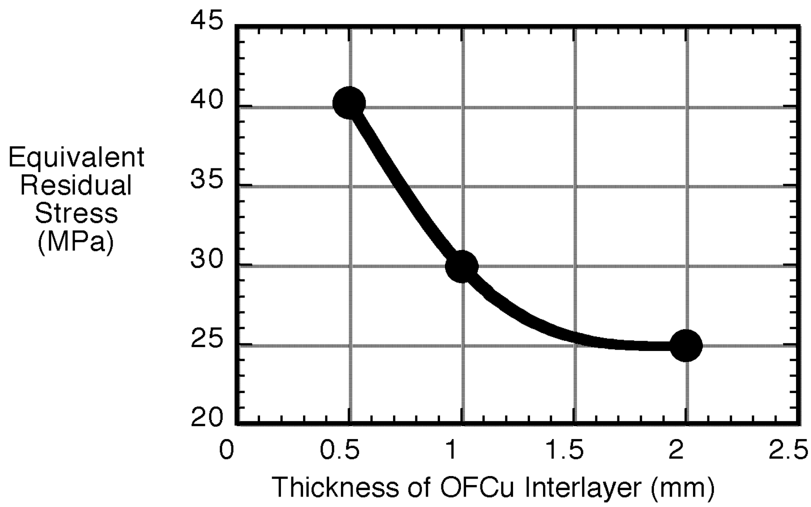
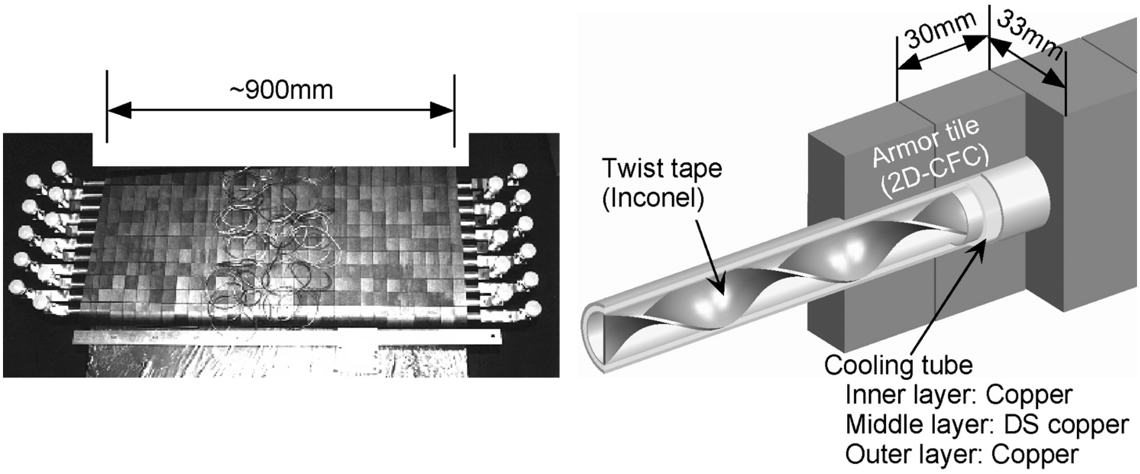


FIG. 1. Equivalent residual stress as function of OFCu interlayer thickness

TAB. I: RESULTS OF BONDING STRENGTH TEST

OFCu thickness	0.5 mm	1 mm	2 mm
Result	tile detached	no failure	no failure



(a) Overall view of the mock-ups (Eleven mock-ups are bundled together.)   *(b) Cut off view of the mock-up*

FIG. 2.   Monoblock divertor mock-ups

3. Monoblock Divertor Mock-ups

A monoblock divertor mock-up has been fabricated as shown in FIG. 2. The major dimension of the mock-up is 900mm(length) x 33mm(width) x 60mm(thickness) as shown in FIG.2 (a), whose size is relevant to a divertor for a fusion reactor such as ITER. The armor tiles are made of two-dimensional carbon-fiber-composite (2D-CFC) material which has thermal conductivity of ~400W/m/K in two direction at room temperature. The cooling tube is the three layer DSCu swirl tube described in section 2 (FIG. 2. (b)). These armor tiles and the cooling tube were brazed with Cu-Ti braze filler to achieve low induced radioactivity under neutron irradiation.

4. Experimental Results

The monoblock divertor mock-up has been tested at a hydrogen ion beam test facility in JAERI [5]. The high heat flux test was carried out to investigate the soundness of the monoblock structure against a cyclic heat loading. A high heat flux experiment was performed at a heat flux of 5MW/m^2 to simulate the steady state thermal condition and of 20MW/m^2, 10 s to simulate the transient thermal condition of the divertor plate. Figure 3 shows the maximum surface temperature evolution of the mock-up up to 3000 cycles at 5 MW/m^2. The temperature evolution indicates no degradation of thermal performance in the experiment, and also shows good agreement with the surface temperature prediction from a finite element analysis. This implies the mock-up could sustain its original thermal performance under cyclic thermal loading of 5MW/m^2. In addition, the mock-up could also withstand the cyclic thermal loading of 20MW/m^2.

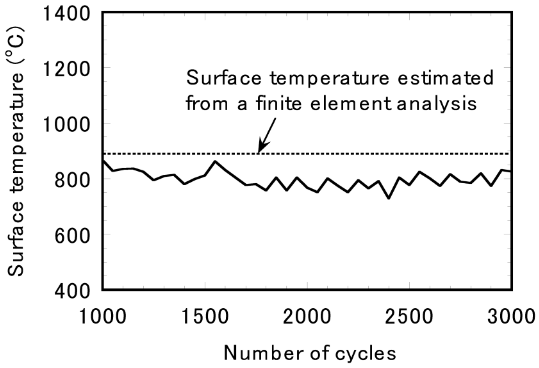


FIG. 3. Maximum surface temperature evolution for 3000 thermal cycles.

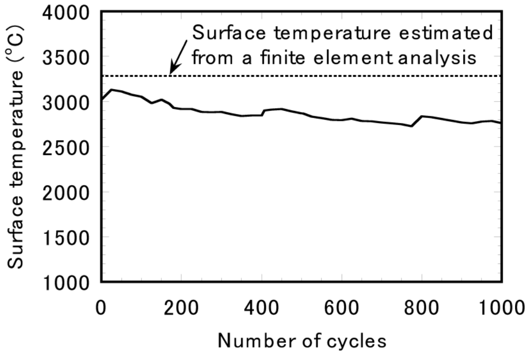


FIG. 4. Maximum surface temperature evolution for 3000 thermal cycles. (Surface temperature gradually decreased due to erosion of armor tile by sublimation.)

Figure 4 shows the maximum surface temperature evolution at $20MW/m^2$. While surface temperature gradually decreased due to erosion of the armor tile by sublimation, no temperature excursion caused by detachment of the armor tile was found through 1000 cycles.

Figure 5 shows a cross sectional view of the mock-up after the experiment simulating transient thermal condition. In spite of the severe erosion of the heated surface, no detachment of the braze interface between the armor tiles and the cooling tube was found in the microscopic observation after the experiment.

5. Conclusion

The three layer DSCu swirl tube has newly been developed for fusion application. This cooling tube realizes both high strength of as high as stainless steel, and excellent bonding performance with CFC armor tiles. This tube consists of three layers; a 1 mm thick OFCu outer later, a 1.5 mm thick DSCu core layer, and a 0.5 mm thick OFCu inner layer. The reduced activation brazing technique with Cu based braze has also been developed, which does not include silver. Based on these technologies, the large monoblock divertor mock-

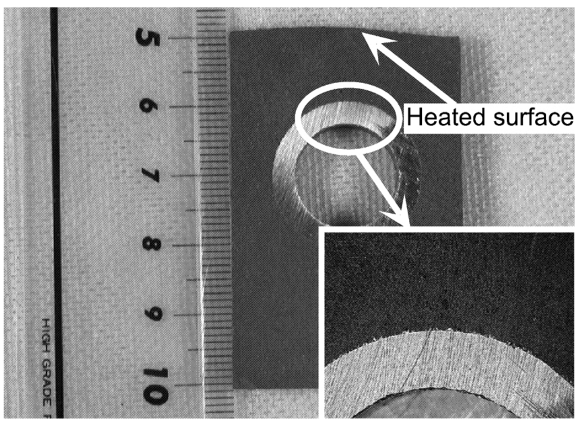


FIG. 5. Cross sectional view of the mock-up (No detachment is found at the braze interface.)

ups have been fabricated, whose dimension is relevant to a fusion reactor. As a result of high heat flux experiments, the mock-ups have successfully been proved to withstand a steady state heat load of 5 MW/m^2 for more than 3000 cycles, and a transient heat load of 20 MW/m^2, 10 s for more than 1000 cycles. No degradation of surface temperature has been observed through these experiments. After the experiments, the bonding interface is investigated, and no cracks are observed.

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