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Manufacturing study of Be, W and CFC bonded structures for plasma-facing components

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Abstract

A manufacturing study has been conducted for Be, W, and CFC bonded structures employed in plasma-facing components for the ITER. For Be tiles bonded to the Cu–Cr–Zr alloy heat sink with stainless-steel cooling pipes, a one-axis hot press with two heating processes has been used to bond the three materials. An Al–Si base interlayer has been used to bond Be to the Cu-alloy. The heating processes have been selected to match the required heat treatment conditions for the Cu-alloy. Because of the limited heat processes using a conventional hot press, the manufacturing cost can be minimized. For both the W and CFC tiles, the materials have been brazed at the same time to the Cu-alloy. Ni–Cu–Mn and Cu–Ti brazing materials have been used for the W and CFC tiles, respectively. Using the above bonding techniques, partial mockups of a blanket first-wall panel and divertor target have been successfully manufactured.

1. Introduction

Because of the required material characteristics for plasma-facing components in the International Thermonuclear Experimental Reactor (ITER), several materials, such as beryllium (Be), tungsten (W), and carbon fiber-reinforced composite (CFC), have been selected [1]. These materials are structurally bonded to the heat sinks or actively cooled components to provide high-heat removal capability. Various bonding techniques have been considered, including hot isostatic pressing (HIP), diffusion bonding, and brazing. One of the key issues regarding bonding is to ensure the reliable performance of the plasma-facing components within a reasonable manufacturing cost.

Most previous efforts have been focused on primarily joining the plasma-facing materials to dispersion-strengthened copper (DSCu) materials [2]. However, Cu–Cr–Zr alloy is preferred in the ITER design because of its lower cost, higher fracture toughness, and better irradiation resistance.

This study has been conducted to determine the optimal manufacturing processes for joining the plasma-facing materials – Be, W, and CFC – to the heat sinks or actively cooled components, which are made of Cu–Cr–Zr alloy (Cu: remaining, Cr: 0.6–0.8%, Zr: 0.07–0.15%, others: <0.05%) (hereafter, referred to as Cu-alloy). Special attention has been paid to minimize fabrication costs. Some results of this study are presented.

2. Required heat treatment for Cu–Cr–Zr alloy

To maintain its mechanical properties, the Cu-alloy requires adequate heat treatment, i.e. solution annealing and aging. Based on the material survey of the Cu-alloy, it was found that the optimal temperatures of solution annealing and aging are 980 and 475 °C, respectively. The effect of the aging temperature increase has been

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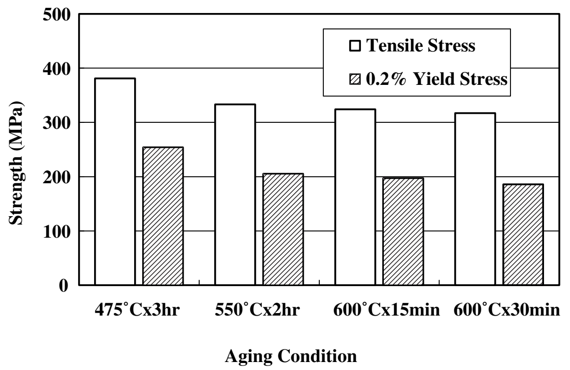


Fig. 1. Effect of aging conditions on the mechanical properties for Cu-alloy.

examined. Fig. 1 shows the results. Both the tensile strength and 0.2% yield strength are presented. The annealing temperature was kept at 980 °C. As shown in the figure, the aging temperature can be increased up to 600 °C with a modest reduction of 15% in the mechanical strength. These heating conditions will be used for the bonding processes. It is noted that the tensile strength and the 0.2% yield strength obtained in this study are slightly lower than those presented in the ITER material assessment report [3]. The difference is to be further examined, and the optimal condition, including the quenching conditions, is to be established in the future.

3. Study of beryllium-bonded structure

The first-wall panels of the ITER blanket module employ Be tiles attached to the Cu-alloy heat sink with stainless-steel (SS316L) cooling pipes, which are also joined to the SS316L structural block [1]. The three materials must be structurally bonded to handle a peak heat flux of 0.5 MW/m^2. For ITER, the HIP technique has been primarily considered as the bonding method [2]. This method generally provides reliable structural integrity, i.e. a reliable joining property. However, because of the complexity involved in the preparation prior to the HIP process and machining after the HIP, as well as the limited number of available HIP facilities, the manufacturing cost is an issue.

In this study, a one-axis hot pressing with a limited number of heating processes has been chosen to bond the three materials. The heating conditions have been selected to match the heating treatment conditions required for the Cu-alloy, as obtained in the above. Unlike HIP, hot pressing is a conventional method and has been widely used for industrial applications.

Bonding conditions between Be and Cu-alloy, with consideration given to the aging process of Cu-alloy, has been studied to achieve a joint strength that compares well to that obtained using HIP. To avoid direct interaction between Be and Cu, an interlayer has been used between the two elements [2]. Several types of interlayer were examined and the results are summarized in Fig. 2. In this figure, the bonding strength relative to that for HIP is shown. While further optimization is required, it was found that by using an Al–Si base interlayer (50 μm thick) and preconditioning of the Cu-alloy surface by Ni-plating (up to 20 μm thick), a joint strength of more than 80% that for HIP could be achieved at a bonding temperature of 560 °C, which is around the optimal aging temperature of Cu-alloy. The microstructure of the Be and Cu-alloy bonded region is shown in Fig. 3. It is noted that because the test specimen fabricated by HIP was fractured in the Be part in the joint strength testing, the strength of the HIP joint was evaluated to be close to that of Be. Needless to say, further qualitative examination of the joint strength is required for the final assessment.

In addition, one-axis hot pressing has been applied to the complex structure of the heat sink, which consists of a Cu-alloy heat sink, SS bent pipe, and SS structural block. A pipe expansion technique has also been applied to provide for good joining properties between the pipe and the heat sink. Hot pressing was conducted at 980 °C, which is the solution annealing temperature of the Cu-alloy. Fig. 4 shows the microstructure of the bonded regions in the tested sample. The bonded structures appear to be sound.

Using the above bonding techniques, a partial mockup of a blanket first-wall panel has been success-

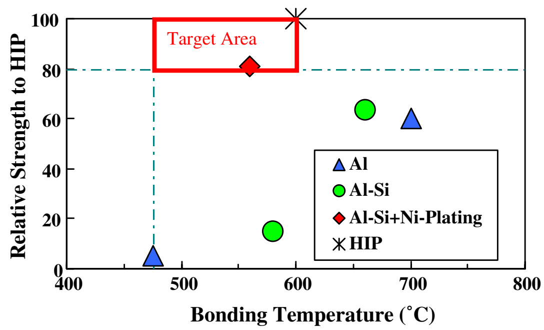


Fig. 2. Bonding strength between the Be and Cu-alloy (relative strength for the case of HIP).

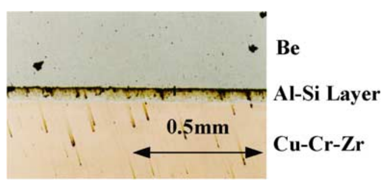


Fig. 3. Microstructure of Be and Cu-alloy bonded region.

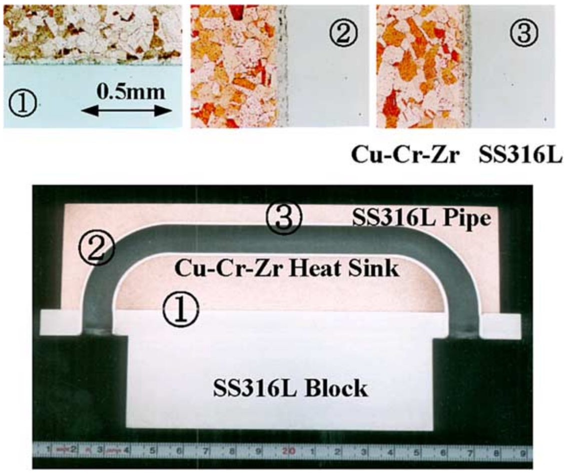


Fig. 4. Microstructures of Cu–Cr–Zr and SS316L bonded region.

fully manufactured. First, Cu-alloy heat sink and four sets of SS316L pipes with both ends bent and a SS316L structural block are bonded diffusively by a hot press at 980 °C. Next, 16 Be tiles, measuring 50 mm in width and 10 mm in thickness, are bonded diffusively to the pre-bonded structure by a hot press under the maximum pressure of 20 MPa and at 560 °C. Fig. 5 shows a schematic view of the mockup and photos of the completed mockup and assembled component. As shown, the Be tiles in several inclined angles to the heat sink were successfully bonded using one-axis hot pressing with appropriate fixtures. Because of the limited heat processes using a conventional one-axis hot press, the manufacturing cost can be minimized.

4. Study of W and CFC bonded structures

In the ITER divertor target, W tiles are joined to the Cu-alloy heat sink to form a flat-type configuration, and CFC tiles are joined to the Cu-alloy pipes to form a mono-block type configuration, respectively. The objective of this study is to simultaneously braze both materials with different configurations in one-heat process to the Cu-alloy at the solution annealing temperature of the Cu-alloy.

Ni–Cu–Mn and Cu–Ti brazing materials, up to 100 μm in thickness, have been used for the W and CFC tiles, respectively [2,4]. Table 1 shows the bonded structures of W and CFC test samples. The bonding strength of both materials has been examined by a shear test of the bonded structures. In the test, it was found that both the bonded structures had fractures at the base materials of W and CFC, showing sufficient bonding properties.

Using the above bonding techniques, a partial mockup of a divertor target has been manufactured. Fig. 6 shows a schematic view and photos of the completed mockup. In this mockup, the interlayer of OFCu with a thickness of 1 mm has been applied to absorb thermal stresses caused by the difference in thermal expansion between the materials. The interlayer thickness was optimized for the CFC tiles by an elastic-thermal stress analysis under the assumed heat load of 5 MW/m^2 on the plasma side of the tile with a heat transfer coefficient of 1×10^5 $MW/m^2\,K$ on the cooling pipe. Though the same interlayer was used for the W tiles, the required interlayer for the W tiles has yet to be examined.

Two sets of W tiles and CFC tiles were brazed simultaneously to the Cu-alloy parts at 980 °C to form the mockup. Both the flat-type and mono-block type configurations were used for W and CFC tiles, respectively, in the mockup. Although further optimization is required, it is expected that a multiple number of tiles and the two configurations of the divertor structure can be manufactured in a one-heat process used for the Cu-alloy annealing.

5. Future work

In this study, cost-saving methods for manufacturing plasma-facing components have been investigated and

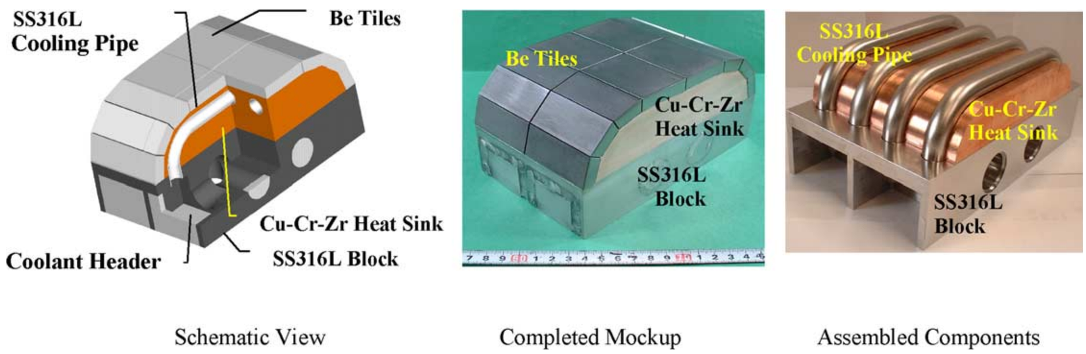
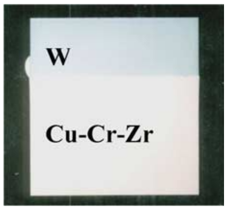
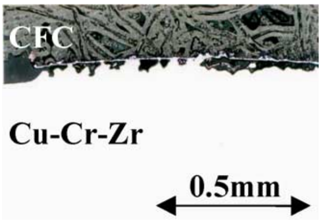
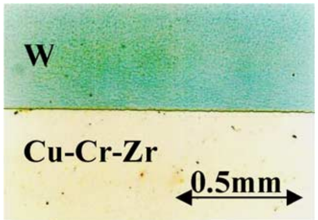


Fig. 5. First-wall panel mockup.

Table 1
Bonded structures between CFC/W and Cu-alloy

	CFC bonded structure (Cu–Ti brazing material)	W bonded structure (Ni–Cu–Mn brazing material)
Appearance		
Microstructure of bonded region		

revealed encouraging results. However, to ensure the applicability of the studied methods, additional high-heat-flux testing of the bonded structures is required.

6. Conclusions

A manufacturing study has been conducted to reduce the manufacturing costs of the Be, W, and CFC bonded structures used in the plasma-facing materials of ITER. In the case of Be tiles bonded to the Cu-alloy heat sink with SS cooling pipes, a one-axis hot press with two heating processes has been applied to bond the three materials. Cu-alloy and SS materials are bonded diffusively by a hot press at 980 °C, which is the solution annealing temperature of the Cu-alloy. Then, Be tiles are bonded diffusively to the pre-bonded structure by a hot press under 20 MPa and at 560 °C, which is the aging temperature of the Cu-alloy. The heating processes have been selected not to degrade the mechanical characteristics of the Cu-alloy. Because of the limited heat processes employed in using a conventional one-axis hot press, the manufacturing cost can be minimized. In the case of W and CFC tiles, both materials can be simultaneously brazed to the Cu-alloy heat sink or pipe at the solution annealing temperature of the Cu-alloy. Ni–Cu–Mn and Cu–Ti brazing materials have been used for the W and CFC tiles, res-

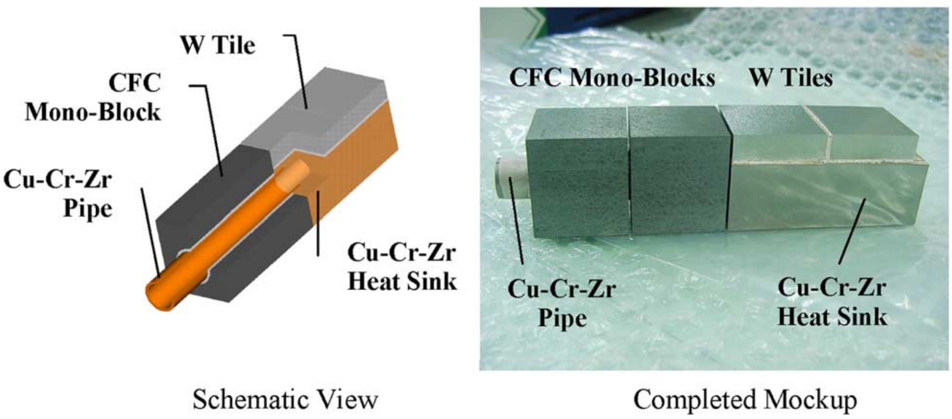


Fig. 6. Divertor target mockup.

pectively. The interlayer of OFCu, with an optimal thickness, has also been applied. Using the above bonding techniques, partial mockups of a blanket first-wall panel and divertor target have been successfully manufactured.

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