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Development of Be/DSCu HIP bonding and thermo-mechanical evaluation

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Abstract

The hot isostatic pressing (HIP) joining condition and interlayer materials for Be and DSCu joining have been examined. Based on the screening test results, two HIP conditions and interlayer materials were selected for mock-up fabrication. The first technology uses an Al–Si–Mg foil inserted between the beryllium tile coated by an Al layer and the DSCu heat sink coated by an Al/Ti/Cu layer at the HIP temperature of 555 °C. Another technology uses a DSCu heat sink coated by a pure Cu layer at the HIP temperature of 620 °C. The latter technology provided the highest strength of the Be/DSCu joints. Heating tests at heat flux of 5 MW/m^2 up to 1000 were performed to compare with thermo-mechanical performance. Though the HIP technology with the Al–Si–Mg foil had lower strength, the thermo-mechanical performance of the mock-up was better, than the performance of the mock-up with the pure Cu interlayer. The presence of the Al and Al–Si–Mg interlayers act as effective compliant layers between beryllium and DSCu.

1. Introduction

In a DT fusion reactor such as the International Thermo-nuclear Experimental Reactor (ITER), the first wall will operate under severe conditions. As its location in the front wall of blanket and nearest to the plasma, the first wall receives a maximal surface heat flux of 0.5 MW/m^2 and an averaged maximal neutron wall load of 0.78 MW/m^2 [1]. The first wall is made of Be armor tiles and a Cu alloy heat sink with enclosed stainless steel (SS) cooling pipes. These materials must be metallurgically bonded to provide adequate heat removal. Hot isostatic pressing (HIP) technology has been pursued to obtain the high joining quality over large joining area. The joining between Cu alloy and SS has been successfully demonstrated by fabrication of several mock-ups and by high heat flux tests [2–6]. However, some development still is needed to demonstrate the reliable joining technology between Be armor and Cu alloy heat sink.

Alumina dispersion strengthened copper (DSCu) is proposed as heat sink material. Though the difference in thermal expansion of Be and DSCu is small, the residual and operational stresses could likely cause a damage at the bonded interface. Therefore, the interlayer materials between Be and DSCu need to be applied to avoid cracking. HIP conditions and interlayer materials were investigated via screening tests of the different joints. Thermo-mechanical performance of the HIP bonded Be/DSCu joints were evaluated via heat flux tests of the mock-ups and by finite element analysis.

2. Screening tests

2.1. HIP conditions

In the fabrication process of the first wall, the bonding of Be armor onto the DSCu heat sink is considered as the final step, after the joining of DSCu and SS. Therefore, the SS would be subjected to the same

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heat treatment as the Be/DSCu HIP process. To prevent the sensitization of the SS during this HIP process, temperatures less than 650 °C have been selected. The HIP pressure and holding time were 140 MPa and 2 h, respectively.

2.2. Materials

The materials used were GlidCop® AL-25 as DSCu and Be S-65C vacuum hot pressed (VHP). Al and Cu were selected as the materials for compliant layers. These Al and Cu layers were combined with Ti, Cr, Mo and Nb coatings. These interlayer materials were coated onto the surface of the Be tiles and the DSCu heat sink by means of physical vapor deposition (PVD) or vacuum plasma spray (VPS). Al does not form intermetallic compounds with Be and Cu is expected to provide better joining by PVD-coating than by the foil insertion. The Al–Si–Mg foils with different thicknesses were also used as interlayer in some trials. The interlayer materials and HIP conditions examined in this study are summarized in Table 1.

2.3. Mechanical tests and observations

To evaluate the strength of the HIP bonded Be/DSCu joints four-point-bending tests were performed in accordance with Japanese Industrial Standards (JIS) R1624. Test temperatures were room temperature (RT), 200 and 400 °C. The latter two temperatures were applied only to those joints that showed high strength in RT test. The test temperature of 200 °C corresponds to the temperature of Be/DSCu interface under ITER normal operation. The results of the tests are summarized in Table 2.

Among the joints examined, the HIP bonded at 620 °C with PVD-Cu interlayer, No. 8 in Table 1, showed the highest bending strength at RT. The Be_2Cu and BeCu intermetallic phases were formed in the joints. For this joint, the bending strength at elevated test temperatures of 200 and 400 °C was reduced down to 140 and 130 MPa with the fracture at Be_2Cu/BeCu and Be/Be_2Cu interfaces, respectively.

Table 2
Four-point-bending test results of HIP bonded Be/DSCu joints

No.[a]	Temperature (°C)	Strength (MPa)		Fracture location
1	RT	111.5	107.6	Ti/DSCu
2	RT	118.2	131.2	Ti/DSCu
3	–	–	–	Nb/DSCu (not bonded)
4	RT	191.9	187.3	Ti
	200	228.5	197.5	Ti
	400	82.1	90.5	Be/Al
5	–	–	–	Be/Al (not bonded)
6	RT	151.1	164.8	Al/Mo
7	RT	116.7	155.8	Be/Al
8	RT	231.2	258.1	Be_2Cu/BeCu
	200	141.1	145.3	Be_2Cu/BeCu
	400	131.3	135.3	Be/Be_2Cu

[a] Al (VPS, 0.7 mm)/Ti (PVD, 5 μm)/Cu (PVD, 10 μm).

Table 1
Interlayer materials and HIP conditions for Be/DSCu joints

No.	Pre-HIP coating				HIP conditions			
	On Be	On DSCu			Interlayer	Temperature (°C)	Holding (h)	Pressure (MPa)
1	Al (PVD, 10 μm)	Al (PVD, 10 μm)	Ti (PVD, 10 μm)		Al–Si–Mg (foil, 0.74 mm)	555	2	150
2	Al (VPS, 0.7 mm)	Al (PVD, 10 μm)	Ti (PVD, 10 μm)		Al–Si–Mg (foil, 0.12 mm)	555	2	150
3	Al (PVD, 10 μm)	Al (PVD, 10 μm)	Nb (PVD, 10 μm)		Al–Si–Mg (foil, 0.74 mm)	555	2	150
4	Al (VPS, 0.7 mm)	Al (PVD, 10 μm)	Ti (PVD, 10 μm)	Cu (PVD, 10 μm)	Al–Si–Mg (foil, 0.12 mm)	555	2	150
5	Al (VPS, 0.7 mm)	Al (PVD, 10 μm)	Cr (PVD, 2 μm)	Cu (PVD, 10 μm)	Al–Si–Mg (foil, 0.12 mm)	555	2	150
6	Al (VPS, 0.7 mm)	Al (PVD, 10 μm)	Mo (PVD, 5 μm)	Cu (PVD, 10 μm)	Al–Si–Mg (foil, 0.12 mm)	555	2	150
7	[a]	Cu (PVD, 10 μm)			–	555	2	150
8	–	Cu (PVD, 10 μm)			–	620	2	150

[a] Al (VPS, 0.7 mm)/Ti (PVD, 5 μm)/Cu (PVD, 10 μm).

The joint with complex interlayer of Al (VPS) + Al–10Si–2Mg foil + Al (PVD)/Ti (PVD)/Cu (PVD) HIP bonded at 555 °C, No. 4 in Table 1, showed also relatively high strength. Moreover the joint characterized the properties of toughness and ductile in the base material in the fracture side. In this HIP joint, the interlayer materials diffused excellently, because the position of the fractures was different from the HIP original interfaces. Microscopic photographs of the joints with a complex interlayer and with a pure Cu interlayer are shown in Figs. 1 and 2. Line analysis by electron probe microanalyzers (EPMA) across the HIP bonded interfaces are also presented in Figs. 1 and 2. Magnesium in the Al–Si–Mg foil well diffused into the VPS Al layer on the Be side removing oxides from the Al surface. Mg might remove oxides from the Al surface because of higher oxide action.

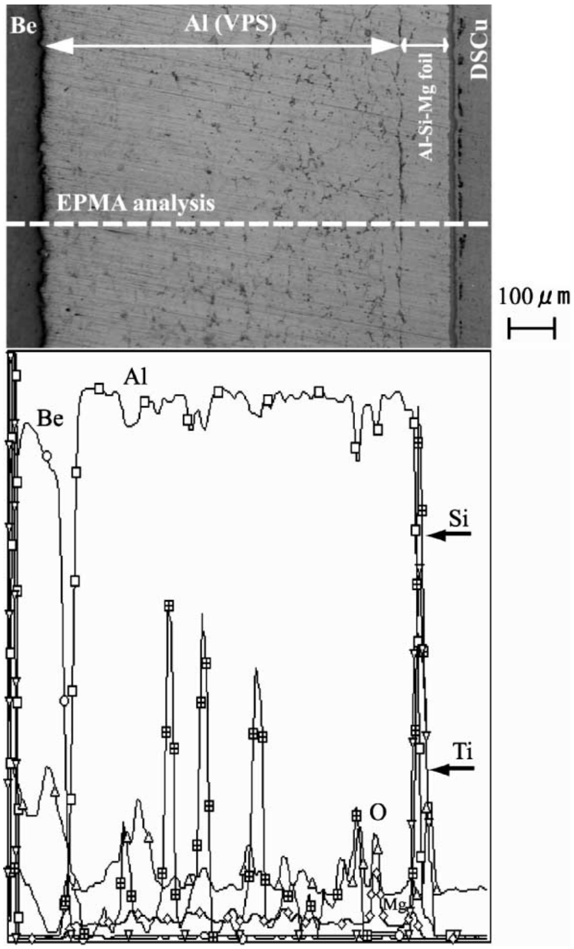

Fig. 1. SEM image and line analysis by EPMA on HIP bonded Be/DSCu joints with Al–Si–Mg and Al/Ti/Cu interlayers.

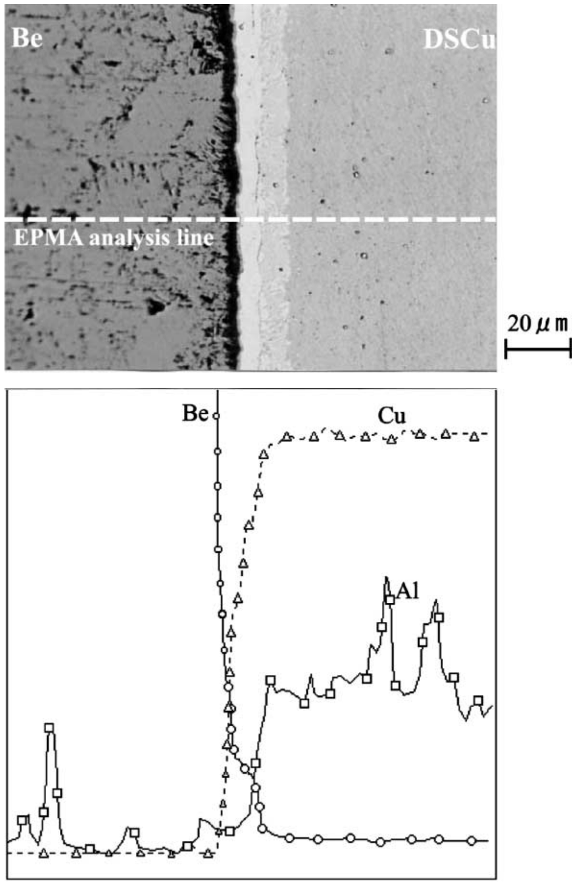

Fig. 2. SEM image and line analysis by EPMA on HIP bonded Be/DSCu joints with PVD-Cu interlayer.

3. Thermo-mechanical performance

3.1. High heat flux tests

The HIP bonded Be/DSCu mock-ups were manufactured using the selected two HIP conditions (No. 4 and 8 in Table 1) to examine the thermo-mechanical performance and the quality of the Be/DSCu joints. The dimensions and appearance of the mock-ups are shown in Fig. 3.

Heat flux tests were performed at Oarai Hot-cell Beam Irradiation Stand (OHBIS) [7,8] and were carried out up to 1000 cycles at heat flux of 5 MW/m^2. A hot spot was observed on the surface of the mock-up with Cu interlayer. Clearly, higher temperatures than predicted were observed at the edge of the Be tile surface by infrared camera after 800 cycles. Initial cracking was located in the Be tile ~0.7 mm from the Be/Cu interface. The crack with a maximum depth of 2.8 mm from the Be tile edge was observed in this mock-up. On the other hand, no cracks were observed in the mock-up with Al–Si–Mg foil insertion.

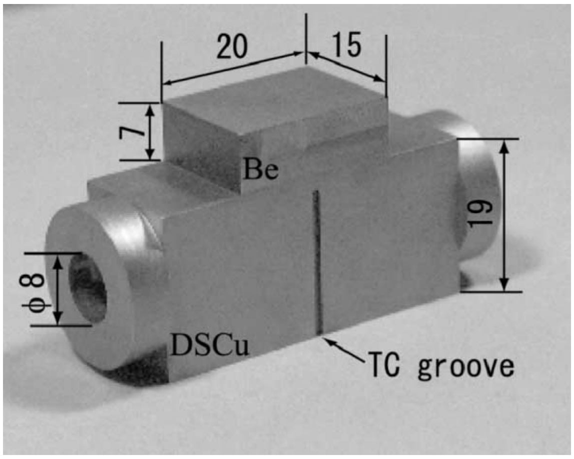

Fig. 3. HIP bonded Be/DSCu mock-up for heat flux test (values are in mm).

3.2. Finite element analysis

Thermal stress analysis was performed to evaluate thermo-mechanical performance of HIP bonded Be/DSCu joints in heat flux tests. The analysis code used was ABAQUS version 5.8 [9]. The three-dimensional finite element model is shown in Fig. 4. The material properties of Be and DSCu are taken from the ITER Material Properties Handbook [10]. The heat transfer coefficient at the cooled surface was computed as a function of wall temperature based on Araki–Ikeda's equation [11]. The heat flux was applied with the distribution corresponding to the real heat flux profile measured at OHBIS. In the analysis, Cu and Cu/Ti/Al interlayers were not included, because they were too thin to affect the thermal performance. Only plastic deformation of Be according to isotropic hardness law was analyzed. Stress free condition was assumed at each HIP temperature and the residual stresses were also analyzed.

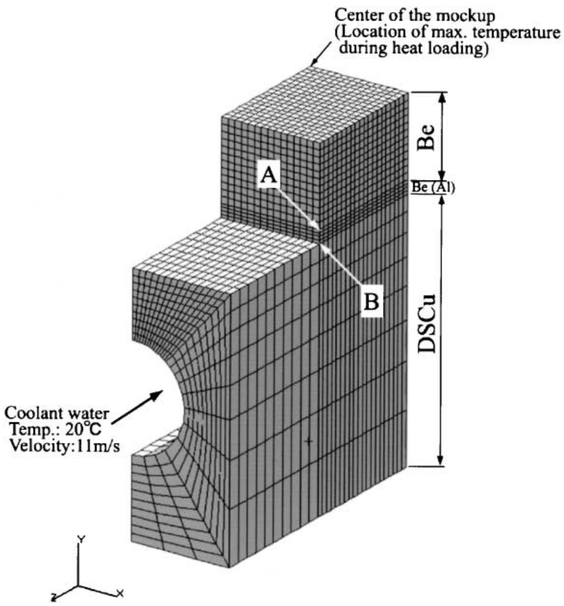

Fig. 4. Finite element model with 8 nodes isoparametric element.

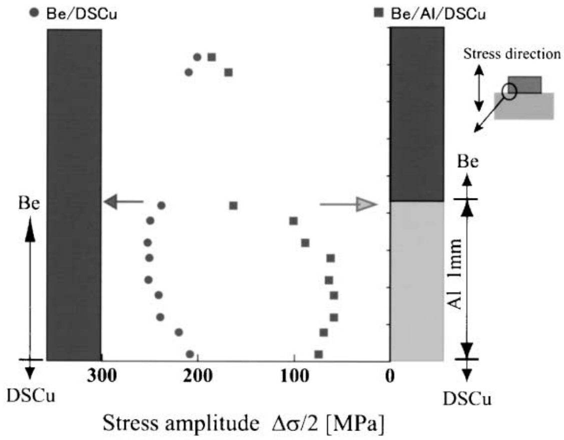

Fig. 5. Calculated stress amplitude across the joint interface.

Stress amplitudes in the Y direction near the Be/DSCu interface with and without Al layer are plotted in Fig. 5. Based on the analysis the insertion of Al layer decreased half stress amplitude of 84 MPa at the DSCu/Al interface. The thermal stresses between Be and DSCu in the mock-up with Al interlayer have been relaxed due to the function of the Al as a compliant layer. In the mock-up with the pure Cu interlayer, the maximum stress amplitude was not observed at the Be/DSCu interface, but at a distance of 0.7 mm from the Be/DSCu interface in Be which is in good accordance with the observed cracking. The HIP technology with Al/Ti/Cu interlayer is obviously more effective, due to the formation of the lower stresses at the joint interface.

4. Discussion

In HIP bonded specimens with Al, Al/Ti/Cu and Al–Si–Mg interlayers, the quality of the joint was good, because the fracture location was different from the HIP interfaces. The fracture locations in four-point-bending tests were at the Ti interlayer. Silicon in the Al–10Si–2Mg foil diffused through Al far toward the Ti layer during the HIP holding time of 2 h (Fig. 1). Silicon also appeared near the Ti layer working as a barrier for diffusion of Si into DSCu. If chemical composition of the Al–10Si–2Mg foil could be optimized and Si as the dispersion strengthened element and in Al after HIPing could be appeared, a HIP bonded Be/DSCu joint with higher thermo-mechanical performance would be obtained. In a previous study, the Be/DSCu HIP bonded joints in which Al/Ti/Cu on Be was coated by PVD without the Al–Si–Mg foil did not show any damage under heat flux of 3 MW/m^2 [12]. The presence of Mg helps to remove oxides from the Al surface during the HIP process.

For direct Be/DSCu joints it has been reported that the thickness of the diffusion layer is linear to a square root of bonding time and the shear strength is not sensitive to the thickness of the diffusion layer [13]. The Cu coating on DSCu by PVD provided higher bonding strength, in comparison with the direct Be/DSCu bonding. Though Be_xCu intermetallics were formed and it is known that they are brittle and could effect the strength of the joint, further heat flux tests need to be performed to clarify the performance limits of this joint. This type of joint seems much cheaper for manufacturing of first wall component and the maximum allowable temperature with use of the Cu interlayer is higher in comparison with the Al based interlayers.

5. Conclusion

Be/DSCu HIP bonding technologies have been developed for the first wall application. Several HIP conditions and interlayer materials were investigated. Interlayer materials between Be and DSCu have been applied to provide the reliable joining and avoid the crack formation. Based on the results of this study two HIP conditions were selected. Consequently, Al and Cu were selected as the compliant layers. With Cu interlayers, a careful control of the formation of brittle intermetallics is required. The use of the Al–Si–Mg foil in combination with VPS Al interlayer provides good bonding and an excellent thermo-mechanical performance.

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