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Fracture strengths of HIPed DS-Cu/SS joints for ITER shielding blanket/first wall

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Abstract

Fracture toughness and crack propagation tests were performed to investigate the effect of HIP temperature and fracture behavior of HIPed DS-Cu/SS joints. Test specimens of DS-Cu/SS HIPed joints were manufactured by bonding flat plates of DS-Cu and SS under HIP temperatures of 980°C, 1030°C and 1050°C. J_Q of the joint at HIP temperature of 1050°C was larger than the other two joints. For the crack propagation test, two types of test specimens were prepared. One had a notch along the HIPed interface and the other in DS-Cu and normal to the interface. The crack in the former specimen propagated along the interface. On the other hand, the crack in the latter specimen propagated in the DS-Cu perpendicular to the loading direction, stopped at the interface, and then exfoliated along the HIPed interface. In the fracture tests, the crack was observed propagating in DS-Cu side at approximately 5–10 μm away from the interface.

1. Introduction

A module structure integrated with the first wall (FW) with built-in circular cooling tubes has been proposed to ITER shielding blankets. In the FW, dispersion strengthened copper (DS-Cu : GlidCop® AL-25 LOX) is used as a heat sink layer. Coolant tubes made of type 316LN-IG (SS : ITER Grade, N_2 : 0.06–0.08 wt%) stainless steel are embedded in the DS-Cu layer to remove thermal loads (surface heat flux of 0.5 MW/m^2 and volumetric heating of up to 20 MW/m^3).

For the fabrication of this FW/shielding blanket structure, simultaneous solid Hot Isostatic Pressing (HIP) bonding of all of the DS-Cu/SS,DS-Cu/DS-Cu and SS/SS combinations in a single HIP step has been proposed by JAERI to minimize thermal effects on the material properties and also to minimize the number of fabrication steps. Mechanical properties including tensile strength, impact value and fatigue strength of HIPed joints had been extensively investigated [1–4]. In these mechanical tests, it was observed that fracture of most of the HIPed joints occurred near the HIPed interface of DS-Cu/SS. Here, fracture toughness measurement, crack propagation test and fracture test were performed to examine fracture behavior of the HIPed DS-Cu/SS joints, to characterize the DS-Cu/SS HIPed joints and to examine crack propagation behavior at the HIPed interface. In this paper, results of these tests were reported and discussed.

2. Test specimen preparation

GlidCop® AL-25 and rolled plate of type 316L stainless steel were used as DS-Cu and SS in this study, respectively. Mechanical properties of DS-Cu and SS are shown in Table 1. Taking into account the optimal HIP temperature for SS/SS bonding known as 1050–1100°C [5–8] and DS-Cu melting temperature of 1083°C, HIP conditions to be investigated for the DS-Cu/SS joints were selected as 980°C, 1030°C and 1050°C. The pressure and holding time during HIP process were kept to

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Table 1
Mechanical properties of GlidCop Al-25 and 316L stainless steel at room temperature

	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness test
DS-Cu	356	441	30	75 (RB)
SS [a]	255	567	61	138 (HB)
SS [b]	263	544	59	149 (HB)

[a] Used for fracture toughness tests.
[b] Used for crack propagation and fracture behavior tests.

be the same for the three cases, 150 MPa and 2h, respectively.

3. Fracture toughness test

3.1. Test procedure

Fracture toughness tests were carried out using compact (CT) specimens shown. Each specimen had a knife edge to attach a clip gage and no side grooves. Fracture toughness values were evaluated by the J–R curve method (power law curve fitting procedure) defined in ASTM-E813 and using Young's modulus and Poisson's ratio of the heat treated DS-Cu base metal under the same temperature as HIP joining, i.e. 117.6 GPa, obtained by tensile tests using round bar specimens of DS-Cu base metal, and 0.3, respectively. Tests were performed under air atmosphere and at room temperature. For comparison, similar tests were also carried out for the DS-Cu base metal.

3.2. Results

For all of the specimens, fracture was observed in the DS-Cu side along the HIP interface, very close to the HIP interface. Typical fractured surfaces of the CT specimens are shown in Fig. 1 for 980°C and 1050°C joints. As is revealed in Fig. 1 (a), a crack propagated nonuniformly across the width of the CT specimen, showing rather unbalanced propagation features, for the 980°C and 1030°C joints, while fairly uniform crack propagation features can be observed for the 1050°C joints. At the same time, clear difference was observed at the fracture surface between 980°C and 1030°C joints and 1050°C one, rather brittle features for the former joints and fairly ductile one for the latter joint. Though the present fracture toughness tests did not satisfy all of the recommendations of the ASTM, J_Q was evaluated from the valid data. J-integral was calculated from load-displacement curves and crack extension was measured on partial cracks. The J–R curves obtained from the present test results are shown in Fig. 2 together with that of the DS-Cu base metal. J_Q of the HIP joints bonded at temperature of 980°C, 1030°C and 1050°C were 21.2, 0.31 and 3.22 kJ/m^2, respectively, and the base metal was 38.31 kJ/m^2.

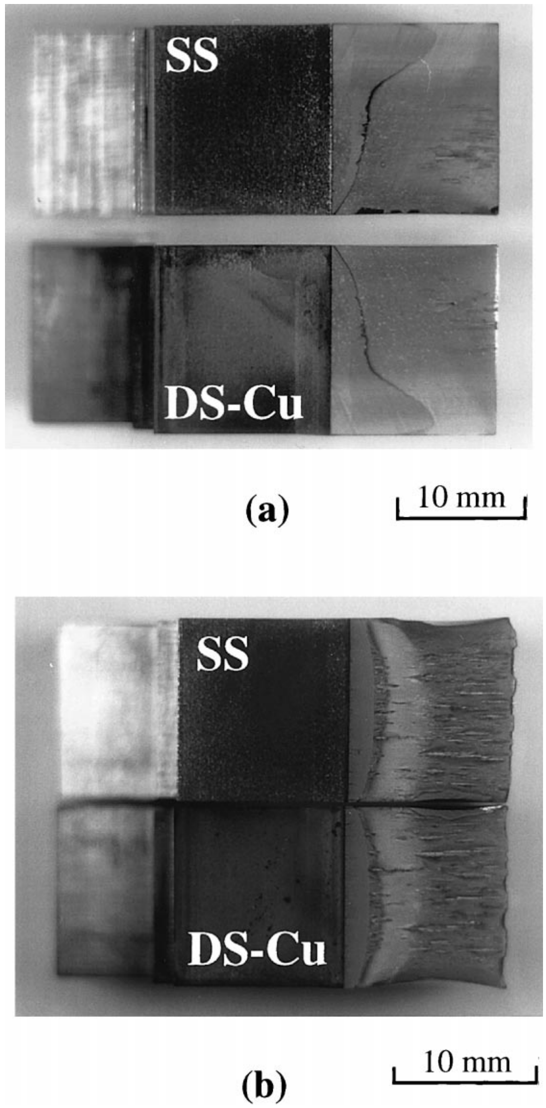

Fig. 1. Fractured surface of the compact specimen HIPed at 980°C and 1050°C.

3.3. Discussion

From the results of the present tests, J_Q of the 1050°C HIP joint specimen was larger than the other specimens. Optimum HIP conditions proposed in the previous study [2,3], i.e. temperature of 1050°C, pressure of 150 MPa and holding time of 2 h, was found to be preferable

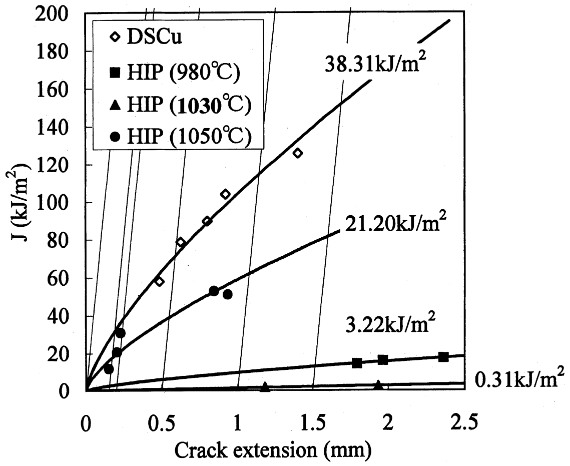

Fig. 2. Results of fracture toughness test of DS-Cu/SS joints and DS-Cu base metal.

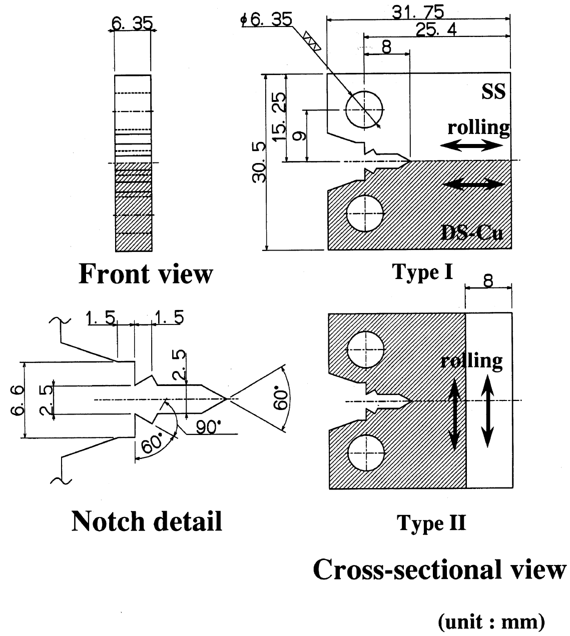

Fig. 3. Compact (CT) specimen for crack propagation tests.

to obtain higher fracture toughness of HIP bonded interface, though the number of test specimens was limited. Non-uniform crack propagation across the width of the specimen, clearly observed for the 980°C and 1030°C HIP joints, might come from the rolling characteristics of the DS-Cu base metal, and this effect needs further investigation.

4. Crack propagation test

4.1. Test procedure

Crack propagation tests were carried out with CT specimens HIPed under the above mentioned conditions. Two types of test specimens were used as shown in Fig. 3; one with a notch along the HIPed interface (type I) and the other with a notch in DS-Cu, perpendicular to the interface (type II). These tests were performed following ASTM-E 647. Precracks of 1.3 mm deep from a machined slot was prepared by a pre-fatigue test. Test environments were in air and at room temperature.

4.2. Results

For the type I specimen the crack propagated along the interface perpendicular to the loading direction during the testing, while the crack in the type II specimen propagated in the DS-Cu also perpendicular to the loading direction, stopped at the interface, and then exfoliated along the interface. The crack propagated through the DS-Cu region never propagated into SS region in the type II specimen. The relationships between ΔK and da/dN are shown in Fig. 4. The crack along the interface (the type I specimen) propagated much faster than the crack in DS-Cu (the type II specimen).

4.3. Discussion

From the test results shown in Fig. 4, the crack propagation characteristics in the type II was judged to be governed by the crack propagation properties of the DS-Cu base metal itself, while the case of type I the crack was propagated much faster than the DS-Cu base metal along the HIP interface, but 5–10 μm away from

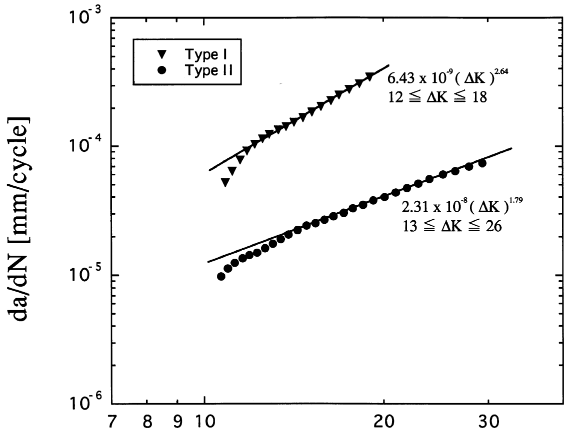

Fig. 4. da/dN versus ΔK for crack propagation tests.

the interface into DS-Cu region. Crack propagation features observed for the type II specimen is preferable from structural integrity view point, as the crack propagated through the DS-Cu heat sink layer never propagates through the SS cooling pipe, a pressure-bearing boundary.

5. Fracture behavior test

In the observation of the fractured surface of the crack propagation test specimens, the crack in type I specimen was found propagating in the DS-Cu side along the HIP interface, 5–10 μm away from the HIP interface, and the fractured surface of the SS side was also covered with a thin DS-Cu layer. A crack propagation test and a fatigue test were performed using a CT specimen and a fatigue test specimen (round bar), respectively, to investigate the crack propagation behavior at DS-Cu/SS HIPed interface in more details. In the case of a three-points bending specimen, a precrack with 1.3 mm deep was developed by a pre-fatigue test and the crack was observed by SEM (Scanning Electron Microscope) when the crack was extended by 0.5 mm deep.

SEM images of the CT and round bar specimens after the crack propagation and fatigue tests are shown in Figs. 5 and 6, respectively. The crack in the CT specimen was propagated in a zigzag manner in the DS-Cu side, approximately 5 μm away from the interface. The top of the crack on a round bar specimen was also within the intermediate layer formed between DS-Cu and SS, as show in Fig. 6.

From the above two test results, the crack was found to propagate within the intermediate layer of 5–10 μm or along the interface between the intermediate layer and DS-Cu region. It was suggested that the crack might propagate along larger grain boundaries in the intermediate layer and the mechanical strengths of the intermediate layer might be lower than that of each base metal. To characterize the interface layer in more details and to investigate its effect on mechanical strengths of the DS-Cu/SS HIP joints quantitatively, further tests are planned to measure the mechanical properties in the micro region.

6. Conclusions

Fracture toughness tests of DS-Cu/SS HIPed joints and DS-Cu base metal have been conducted to examine the optimum HIP temperatures from 980°C to 1050°C. J_{IC} of the HIP joints for three HIP temperatures were obtained. Crack propagation tests of the DS-Cu/SS HIPed joints has been performed to evaluate fracture behavior. Fracture tests of the DS-Cu/SS HIPed CT and round bar specimens have been also performed to examine the crack propagation characteristics in more details.

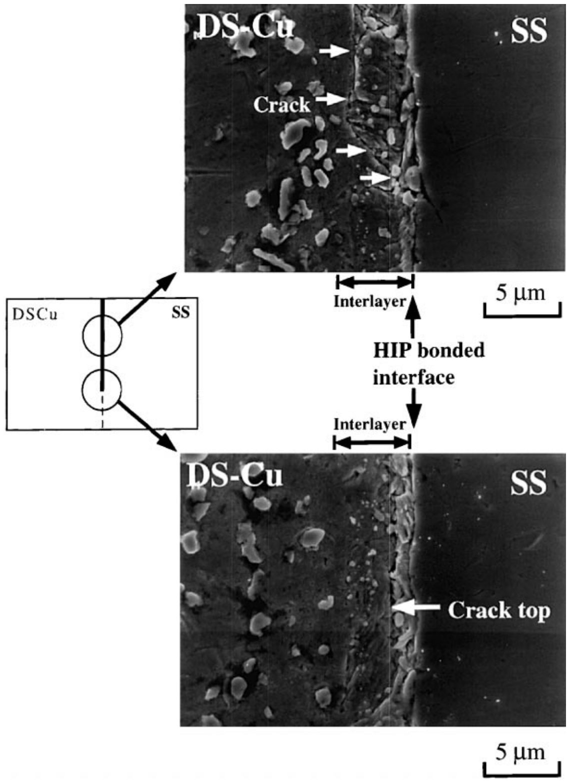

Fig. 5. SEM images of the crack (halfway and top) for a three-point bending specimen.

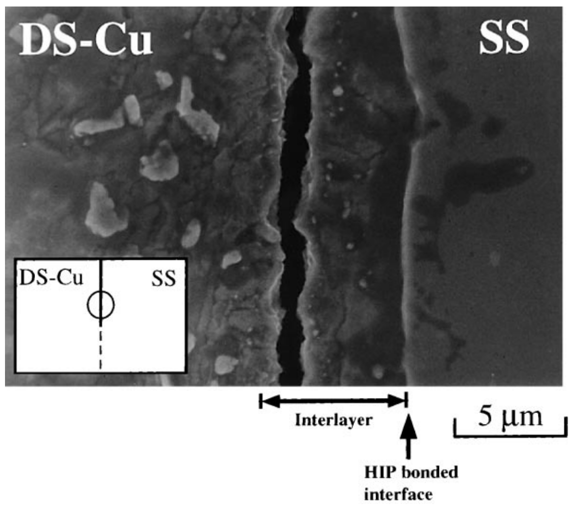

Fig. 6. SEM image of the crack (halfway) for fatigue test using a round bar specimen.

Through the present tests the following conclusions were obtained.

(1) The DS-Cu/SS HIPed joints bonded at 1050°C had the highest fracture toughness value among the three HIP temperatures, but it was lower than that of the DS-Cu base metal by a factor of 2. From the viewpoint of an optimum DS-Cu/SS HIPed condition, temperature of 1050°C, pressure of 150 MPa and holding time of 2 h was recommended among the temperature examined.

(2) Crack propagation curve were obtained for two types of specimens, with initial notches parallel to and perpendicular to the HIP interface. The specimen with an initial notch parallel to the HIP interface, which is perpendicular to the load direction, had much faster crack propagation than DS-Cu base metal. On the contrary, another specimen with an initial notch perpendicular to the HIP interface has lower crack propagation, close to the DS-Cu base metal, and the crack propagated through the DS-Cu region, stopped at the HIP interface and exfoliated along the interface, which suggests a preferable features from structural integrity viewpoint to avoid crack penetration through the pressure boundary of SS.

(3) Fracture tests have confirmed that cracks were propagated along the HIP interface either within the intermediate layer formed by HIP process between DS-Cu and SS or along the interface between the intermediate layer and the DS-Cu region, 5–10 μm away from the original HIP interface.

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References

[1] S. Sato, T. Kuroda, T. Hatano, K. Furuya et al., Proceedings of the 4th International Symposium on Fusion Nuclear Technology, Tokyo, to appear.
[2] S. Sato, T. Hatano, T. Kuroda, K. Furuya et al., these Proceedings.
[3] S. Sato, T. Kuroda, T. Kurasawa, K. Furuya et al., J. Nucl. Mater. 233–237 (1996) 940–944.
[4] H. Nishi, T. Araki, Trans. Jpn. Soc. Mech. Eng. A 61 (1995) 711 (in Japanese).
[5] S. Sato et al., Proceedings of the 15th Symposium on Fusion Engineering, Cape Cod, to appear.
[6] T. Kurasawa et al., Fusion Eng. Design 27 (1995) 449.
[7] K. Mohri et al., Fusion Eng. Design 27 (1995) 438.
[8] T. Kurasawa et al., Proceedings of the 18th Symposium on Fusion Technology, Karlrushe, to appear.