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Optimization of HIP bonding conditions for ITER shielding blanket/first wall made from austenitic stainless steel and dispersion strengthened copper alloy

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Abstract

Optimum bonding conditions were studied on the Hot Isostatic Pressing (HIP) bonded joints of type 316L austenitic stainless steel and Dispersion Strengthened Copper alloy (DSCu) for application to the ITER shielding blanket / first wall. HIP bonded joints were fabricated at temperatures in a 980–1050°C range, and a series of mechanical tests and metallurgical observations were conducted on the joints. Also, bondability of two grades of DSCu (Glidcop Al-25® and Al-15®) with SS316L was examined in terms of mechanical properties of the HIP bonded joints. From those studies it was concluded that the HIP temperature of 1050°C was an optimal condition for obtaining higher ductility, impact values and fatigue strength. Also, SS316L/Al-15 joints showed better results in terms of ductility and impact values compared with SS316L/Al-25 joints.

1. Introduction

Hot Isostatic Pressing (HIP), being a promising technology to fabricate blanket structure integrated with first wall whose cooling channels are embedded within the wall so as to keep both mechanical stiffness and cooling capability, [1–7] has been selected as a reference fabrication method for the ITER shielding blanket / first wall [8]. The first wall of the ITER shielding blanket is composed of austenitic stainless steel (SS316L) circular tubes, an aluminium Dispersion Strengthened Copper alloy (DSCu) heat sink layer surrounding the circular tubes, and a SS316L backing plate as a structural layer [8]. For fabrication of these multi-layered structures, HIP bonding is utilized for the joining of three combinations of SS316L/SS316L, DSCu/DSCu and SS316L/DSCu. Simultaneous HIP bonding of these three joints in a single HIP process has been pursued in this study in order to minimize thermal effects on the material properties and to reduce the number of fabrication steps.

Optimal conditions for the simultaneous HIP bonding of SS316L/SS316L, DSCu/DSCu and SS316L/DSCu have been examined using Glidcop Al-15®, containing 0.15 wt% aluminum in the form of aluminum-oxide, or Glidcop Al-25®, containing 0.3 wt% aluminum, as DSCu and SS316L as SS316. Taking the optimal HIP temperatures for SS316L/SS316L as about 1050–1100°C [6] and DSCu melting temperature of 1083°C, test specimens were fabricated at bonding temperatures of 980°C, 1030°C and 1050°C for SS316L/Al-25, and at 1000°C, 1030°C and 1050°C for SS316L/Al-15. A series of mechanical tests and metallurgical observations was performed on these joints. The pressure and the holding time for the HIP process were fixed at 150 MPa and 2 h [6]. In addition, bondability of two grades of DSCu, Al-25 and Al-15, with SS316L was examined.

2. Experimental procedure

Two test blocks of the SS316L/Al-25 and SS316L/Al-15 HIP joints were fabricated by bonding flat plates of Al-25, Al-15 and SS316L. Test specimens were machined from these blocks by keeping the joint interface

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at the centre of each test specimen. The rolling direction of both of the SS316L and DSCu plates was parallel to the joint interface to be consistent with the fabrication process of the first wall. The following mechanical tests were conducted in air.

Tensile tests at temperatures from room temperature (R.T.) to 400°C.
Vickers hardness tests.
Charpy impact tests at R.T.
Strain controlled fatigue tests with total strain ranges of 0.5–1.2% under a triangular wave form at a strain rate of 0.1%/s and at R.T.

All tests were conducted based on the Japanese Industry Standard. For the SS316L/Al-25 joints all of the tests listed above were conducted, while for the SS316L/Al-15 joints the tests were conducted only for the 1050°C joints, except for Charpy impact tests. The results of Charpy impact tests of the SS316L/SS316L HIP joints are also reported for comparison.

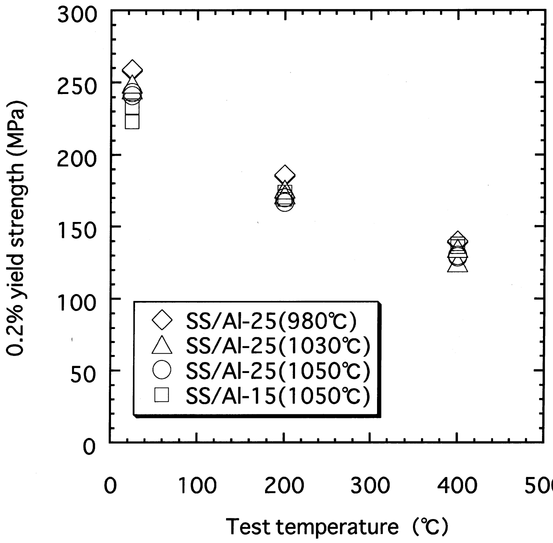

Fig. 2. 0.2% yield strength of SS316L/A1-25 and SS316L/A1-15 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

3. Mechanical test results

3.1. Tensile tests

Results of ultimate tensile strength, yield strength, total elongation and reduction of area measured in the present tests are shown in Figs. 1–4, respectively, all at R.T., 200°C and 400°C.

All of the SS316L/Al-25 joints fabricated at 980°C and 1030°C fractured at the HIP interfaces, while one of the two pieces bonded at 1050°C fractured in the Al-25 base metal at R.T. All of the test pieces fractured at the HIP interfaces in the case of higher test temperatures. All of the SS316L/Al-15 joints bonded at the temperature of 1050°C fractured in the Al-15 base metal at R.T. and 200°C, though all of the test pieces fractured at the HIP interfaces at 400°C.

As for the ultimate tensile and yield strengths, no significant differences were observed among the SS316L/Al-25 joints bonded at 980°C, 1030°C and 1050°C. As for the total elongation and reduction of area, shown in

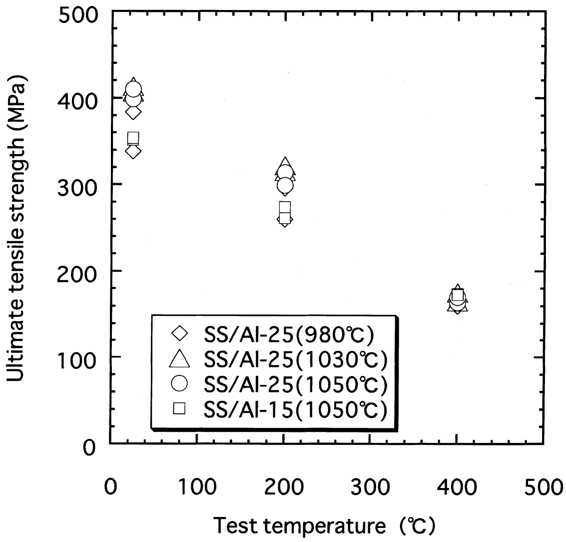

Fig. 1. Ultimate tensile strength of SS316L/A1-25 and SS316L/A1-15 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

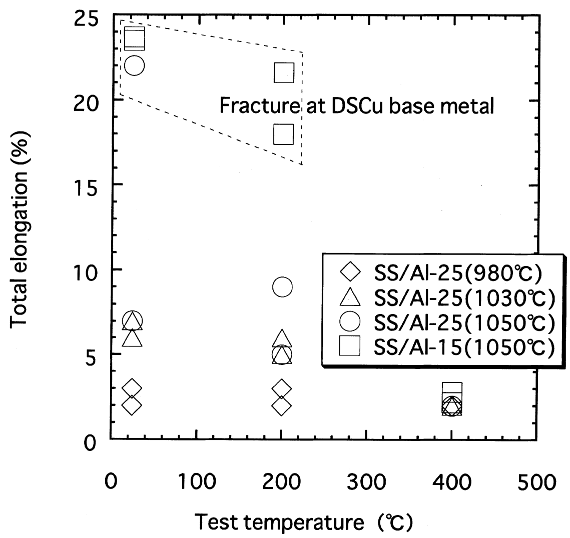

Fig. 3. Total elongation of SS316L/A1-25 and SS316L/A1-15 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

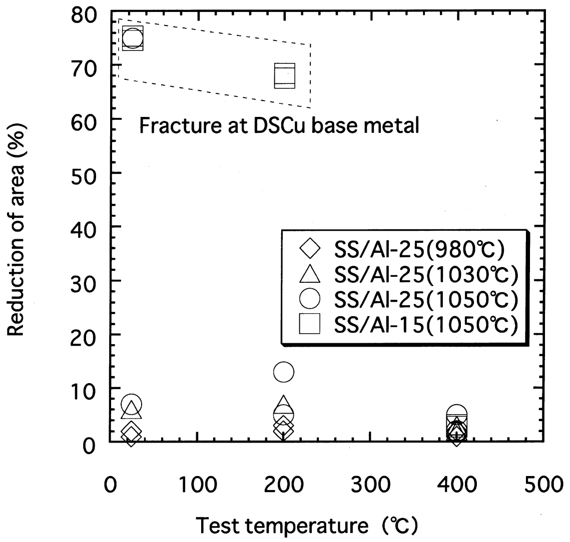

Fig. 4. Reduction of area of SS316L/A1-25 and SS316L/A1-15 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

Figs. 3 and 4, the SS316L/Al-25 joints bonded at 1050°C showed slightly higher ductility compared with those bonded at 980°C and 1030°C, though there were no differences in bonds tested at 400°C.

There were no significant differences observed in the ultimate tensile and yield strengths between the SS316L/Al-25 and SS316L/Al-15 joints. On the other hand, the SS316L/Al-15 joints showed higher ductility than the SS316L/Al-25 joints at lower test temperatures (R.T. and 200°C) owing to their fracture at the base metal. Hence Al-15 shows better bondability with SS316L in terms of ductility.

3.2. Hardness measurements

The results of Vickers hardness measured across the HIP interfaces are shown in Fig. 5 for the SS316L/Al-25 joints bonded at 980°C, 1030°C and 1050°C. No significant differences were observed among the three joints.

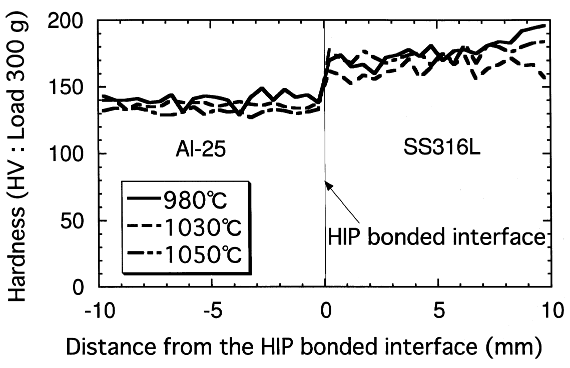

Fig. 5. Vickers hardness of SS316L/A1-25 bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

3.3. Impact tests

The results of Charpy impact tests are shown in Fig. 6 for the SS316L/Al-25 (980°C, 1030°C, 1050°C), SS316L/Al-15 (1000°C, 1030°C, 1050°C) and SS316L/SS316L (1000°C × 4 h, 1050°C × 2 h, 1100°C × 2 h) joints. The SS316L/Al-15 joints bonded at 1050°C fractured at the Al-15 base metal, while all of the SS316L/Al-25 joints fractured at the HIP bonded interface. Both SS316L/Al-25 and SS316L/Al-15 joints bonded at 1050°C showed the highest impact energy value. It was also observed that all of the SS316L/Al-15 joints gave the higher impact values compared with those of the SS316L/Al-25 joints. All of the SS316L/SS316L joints fractured at the base metal, and their impact values slightly increased as the HIP temperature increased. It was found that HIP bonding even at temperature as low as 1050°C gave bonding comparable to that at 1100°C in terms of impact properties.

3.4. Fatigue tests

The results of the fatigue tests at room temperature are shown in Fig. 7, where the data are plotted in the

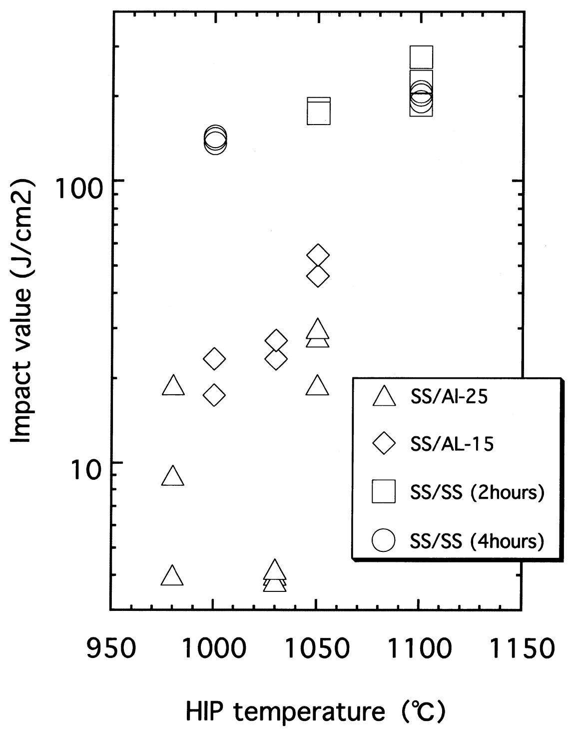

Fig. 6. Impact value of SS316L/A1-25, SS316L/A1-15 and SS316L/SS316L HIP bonded joints.

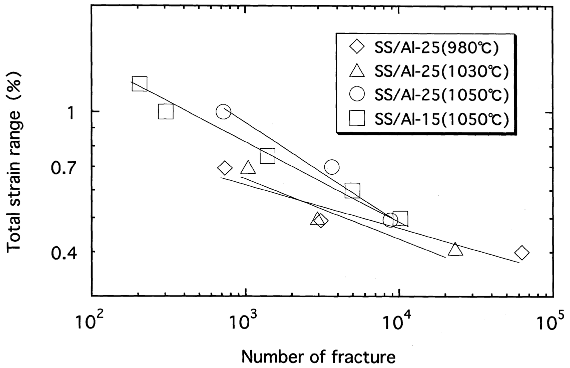

Fig. 7. Low cycle fatigue strength of SS316L/A1-25 and SS316L/A1-15 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

form of the total strain range versus the number of cycles to failure for the HIP bonded SS316L/Al-25 joints bonded at 980°C, 1030°C and 1050°C and the SS316L/Al-15 joints bonded at 1050°C.

In these tests, all of the SS316L/Al-25 joints fractured at the HIP bonded interface, but all of the SS316L/Al-15 joints fractured in the Al-15 base metal. The SS316L/Al-25 joints bonded at 1050°C showed higher fatigue strength at low cycles compared to those of 980°C and 1030°C, though the differences were negligible in the high cycle region over 10^4 cycles. There were no significant differences in the fatigue strength among the SS316L/Al-15 and SS316L/Al-25 joints.

4. Discussion

The SS316L/Al-25 joints bonded at 1050°C showed the higher ductility, impact and fatigue properties compared to those at 980°C and 1030°C, though there were no significant differences observed in the ultimate tensile strengths, yield strengths, and hardness. Also, the SS316L/Al-15 joints bonded at 1050°C showed better impact properties compared with those at 1000°C and 1030°C. It is expected that dynamic mechanical properties such as impact and fatigue properties are more important than static ones for evaluating the mechanical properties of the bonded material, and it can be concluded that the HIP temperature of 1050°C is an optimal condition. Also, the SS316L/Al-15 joints showed better ductility and impact properties than the SS316L/Al-25 joints, though there were no significant differences observed in the ultimate tensile, yield and fatigue strengths. So it is expected that the Al-15 is more suitable than the Al-25 for the material of the HIP bonded SS316L/DSCu joints.

In microscopic and SEM observation, no defects were observed at the bonded interfaces of any specimens. Also, EPMA line analyses were conducted for Fe, Ni, Cr, Mn, C, B, Cu, Al and O. Typical images obtained by line analyses (Fe and Cu) are shown in Fig. 8 for three joints. It was found that intermediate layers of up to 5 μm thickness were formed at the HIP bonded interfaces for all of the specimens. Also, diffusion of and precipitation by the SS elements in the DSCu to a depth of up to 100 μm was observed. This was clarified as Cr and Fe diffusion by EPMA line analysis. The thickness of the intermediate layer and the amount and depth of the precipitation into DSCu was slightly increased as the HIP temperature increased. All of the joints fractured at the HIP interfaces in the mechanical tests showed fracture at the interface between both DSCu and the intermediate layer. It was found through EPMA line analysis that chemical compositions in the intermediate layers were dominated by pure Cu rather than the normal DSCu chemical composition, and larger amounts of Al_2O_3 were observed at the boundaries between intermediate layers and DSCu except for the joints bonded at 1050°C. Higher dynamic mechanical properties observed for the 1050°C joints than those for the 980–1030°C joints were caused by the thickness and chemical compositions of the intermediate layer and precipitated Al_2O_3 at the boundary. The effects of the intermediate layer on the mechanical properties need further characterization. Some results on fracture characteristics of the intermediate layer formed at the HIP interface are reported in [9].

5. Conclusions

To study the optimal HIP condition for SS316L/DSCu joints, mechanical tests and metallurgical observations were conducted on the joints bonded at temperatures in a 980–1050°C range. Also, bondabilities of two grades of DSCu with SS316L were examined. The following conclusions can be made.

(1) As for the tensile strength and hardness, there were no significant differences among the HIP bonded SS316L/Al-25 joints fabricated at bonding temperatures of 980–1050°C. On the other hand, as for the ductility, impact values and fatigue strength, the joints bonded at 1050°C showed the best results among the HIP temperature ranges examined. So it was concluded that the HIP temperature of 1050°C was an optimal condition from the view point of dynamic mechanical properties, though further investigation is needed on characterization of and effects of intermediate layers formed at HIP bonded interface.

(2) The SS316L/Al-15 joints showed better ductility and impact properties than the SS316L/Al-25 joints, so it is expected that the Al-15 is more suitable than the

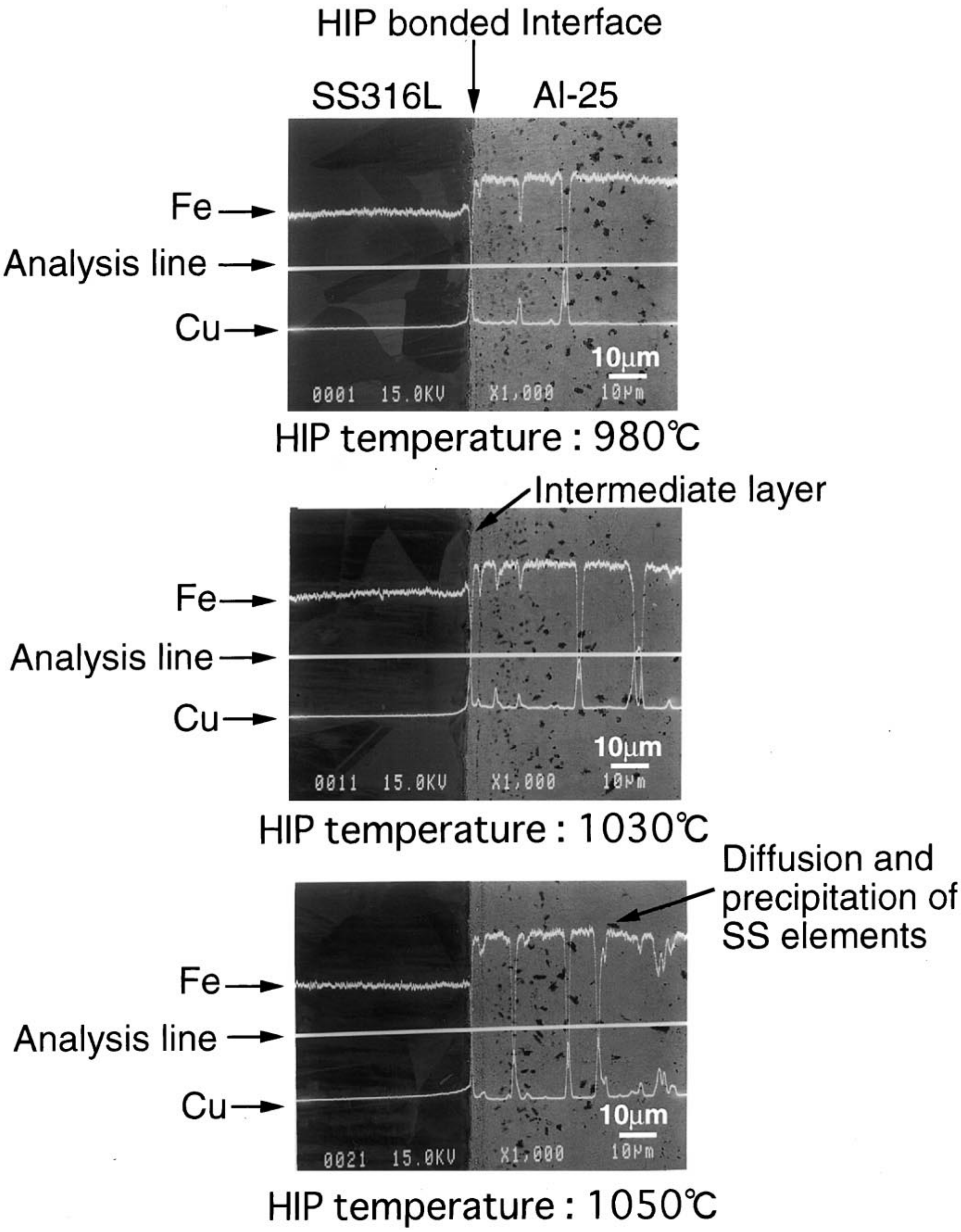

Fig. 8. EPMA line analyses of Fe and Cu observed for SS316L/A1-25 HIP bonded joints (HIP temperature: 980°C, 1030°C, 1050°C).

Al-25 for the DSCu material of the HIP bonded SS316L/DSCu joints.

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