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Low cycle fatigue strength of diffusion bonded joints of alumina dispersion-strengthened copper to stainless steel

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Abstract

It is proposed that the first wall and divertor components of ITER employ alumina dispersion-strengthened copper (DS Cu) joined to austenitic stainless steel. In this work, low cycle fatigue tests were performed on a direct diffusion bonded joint, a diffusion bonded joint with a Au interlayer, stainless steel and DS Cu in order to investigate their fatigue strength and fracture behavior. For the direct diffusion bonded joint, the fatigue strength in the small strain range was considerably lower than that of the DS Cu, while in the large strain range the fatigue strength was similar to that of the DS Cu. The low cycle fatigue strength of the Au interlayer joint increased compared with the direct diffusion bonded joint, and was the same as that of the DS Cu. The strain distribution in joint specimens was not uniform, because the deformation stress was different between the 316 stainless steel and the DS Cu. The fracture locations for the joint specimens varied depending on their strain distribution. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

It is proposed that the first wall and divertor components of ITER are made of alumina dispersion-strengthened copper (DS Cu) bonded to austenitic stainless steel, since the DS Cu has excellent thermal conductivity and strength at elevated temperatures. Therefore, a bonding technology for DS Cu to stainless steel has been investigated and improved [1–4]. The authors have studied the strength of the joint using direct diffusion bonding [1] and diffusion bonding with an interlayer [4]. For direct diffusion bonded joints, recrystallization and intermetallic compounds consisting of B, Fe and Cr developed in the DS Cu near the bonding interface. Its Charpy impact strength was 20% of that of DS Cu, though the tensile specimen fractured at the DS Cu and the joint had strength similar to DS Cu. Diffusion bonding with interlayer foils, such as Au, Cu and Ni, was subsequently carried out to avoid recrystallization and the formation of intermetallic compounds near the interface. The tensile strength of the joint with a Au interlayer was superior to those with Cu and Ni interlayers and similar to that of DS Cu. The Charpy impact strength of the Au interlayer joint was 50% of that of DS Cu.

It is also important to evaluate the fatigue strength of the joints, because the first wall and the divertor components are subjected to severe stress caused by thermal expansion and electromagnetic forces [5,6]. However, only a few data are available on the fatigue strength of these joint [7,8]. In this work, low cycle fatigue tests were performed on the direct diffusion bonded joint, the Au interlayer joint, stainless steel and DS Cu in order to investigate their fatigue strength and fracture behavior. Moreover, the fracture surfaces of low cycle fatigue specimens were examined by scanning electron microscopy.

2. Experimental procedures

The 316 stainless steel and DS Cu (GlidCop Al-15) were 20 mm thick plates and similar to those used in the previous study [1,4]. The direct diffusion bonded joint

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and the diffusion bonded joint with a Au interlayer were butt joints, and bonding was performed under the optimized conditions, which were obtained through research on the tensile and impact strengths for both joints [1,4]. The bonding conditions of the direct bonded joint were 1273 K for 1 h. For the Au interlayer joint, the thickness of Au interlayer was 20 μm and the bonding was done at 1123 K for 2 h. A uniaxial hot press was employed for diffusion bonding with the faying surface perpendicular to the rolling direction of the DS Cu as shown in Fig. 1. Fig. 2 shows optical micrographs taken near the interface for both joints. In the case of the direct diffusion bonded joint, recrystallization and intermetallic compounds consisting of B, Fe and Cr developed in the DS Cu near the interface. For the Au interlayer joint, however, the Au diffused into the DS Cu to a depth of approximately 100 μm, and recrystallization and intermetallic compounds were not observed near the interface.

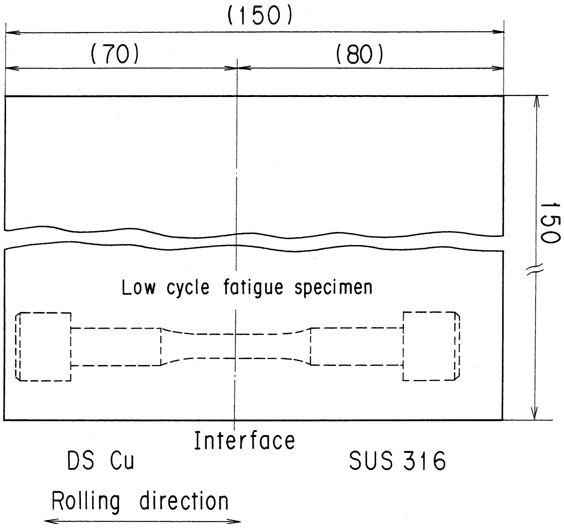

Fig. 1. Configuration of butt joint assembly (mm).

Low cycle fatigue tests were conducted on the direct diffusion bonded joint, the Au interlayer joint, the 316 stainless steel and two kinds of DS Cu. The DS Cu plate received 60% reduction by cold rolling. Since the cold-worked DS Cu was subjected to recovery during the bonding process [1], the influence of recovery on the low cycle fatigue strength was also investigated using the DS Cu annealed at 1273 K for 1 h and 1123 K for 2 h, which were the same as the bonding conditions. Fatigue specimens for the joints were machined with the bonding interface located at its center, as shown in Fig. 1. For the DS Cu specimens, the rolling direction was aligned the load direction of the fatigue test. The specimen had a diameter of 8 mm and parallel portion of 20 mm. The low cycle fatigue tests were conducted by a hydraulic fatigue machine using an axial extensometer with a gauge length of 15 mm, which was fastened to the specimen with the interface located the center of gauge length. The tests were conducted in a vacuum at room temperature using a fully reversed triangular strain wave 1×10^{-3}/s.

3. Results

3.1. Low cycle fatigue strength

Low cycle fatigue strengths are summarized in Fig. 3. In this figure, the number of cycles to failure was defined by the number of cycles at which the tensile stress decreased to 25% of the maximum tensile stress. The low cycle fatigue life of 316 stainless steel was large enough compared with the DS Cu and the joints. For the direct bonded joint, the fatigue life in the small strain range was considerably lower than that of the DS Cu annealed at 1273 K, while the fatigue life in the large strain range ($\Delta\varepsilon_t = 1.5\%$) was almost the same as that of the DS Cu. In the Au interlayer joint, however, low cycle fatigue strength was larger than that at 1273 K. This is

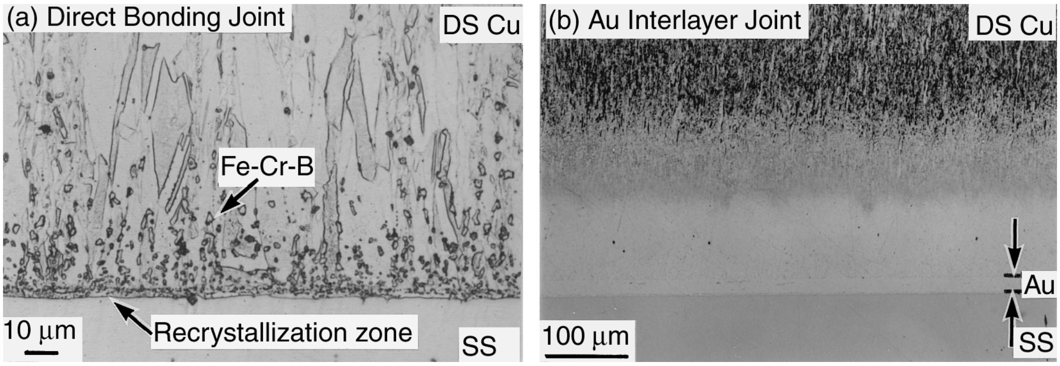

Fig. 2. Optical micrographs near the bonding interface: (a) direct bonded joint; (b) Au interlayer joint.

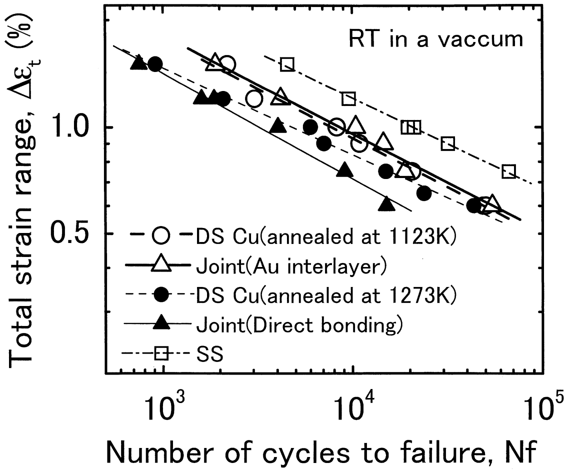

Fig. 3. Low cycle fatigue strength on direct bonded joint, Au interlayer joint, 316 stainless steel and DS Cu annealed at 1273 K for 1 h and 1123 K for 2 h.

attributed to difference in the microstructure caused by recovery.

3.2. Fracture behavior

The direct bonded joint specimen fractured at the interface in the case of small strain range, whereas fracture occurred at the DS Cu approximately 6 mm from the interface for specimens corresponding to $\Delta\varepsilon_t = 1.5, 1.2\%$. The longitudinal section view of the specimen fatigued at $\Delta\varepsilon_t = 1.0\%$ for the direct bonded joint is shown in Fig. 4. In this case, the test was stopped before complete fracture. As can be seen from this photo, the fatigue crack propagated along the recrystallized zone of the DS Cu several micrometers from the interface. The fracture specimens for the Au interlayer joint are shown in Fig. 5 for the case of $\Delta\varepsilon_t = 1.5\%$ and 0.6%. The specimen fractured in the 316 stainless steel in the case of small strain range (less than $\Delta\varepsilon_t = 1\%$) as shown in Fig. 5(b). On the other hand, as shown in Fig. 5(a), in the case of large strain range the fracture location was in the DS Cu similar to behavior for the large strain range for the direct bonded joint.

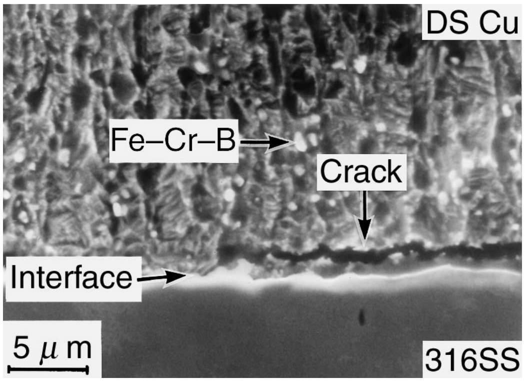

Fig. 4. Longitudinal section view of a specimen for direct bonded joint (tested at $\Delta\varepsilon_t = 1.0\%$).

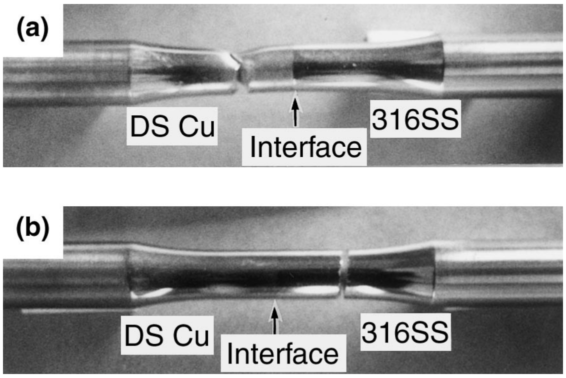

Fig. 5. Fracture specimens for the Au interlayer joint: (a) $\Delta\varepsilon_t = 1.5\%$; (b) $\Delta\varepsilon_t = 0.6\%$.

4. Discussion

As mentioned above, the fracture locations of the joint specimens varied depending on the strain range. Fig. 6 shows the cyclic stress–strain curves of both joints as well as the stainless steel and DS Cu obtained at half of the number of cycles to failure. Comparing the cyclic stress–strain curves of the stainless steel and the DS Cu, the strain hardening of the stainless steel was larger than that of DS Cu annealed at 1273 K and 1123 K. The stress–strain curve of stainless steel intersected those of DS Cu at a strain amplitude of approximately 0.55% for DS Cu annealed at 1273 K and 0.65% for 1123 K. The deformation stress of the stainless steel was smaller than DS Cu at small strain amplitudes (less than the strain at the crossover points). Hence, the strain distribution in the joint specimen was not uniform. In the case of large strain range, the strain in the DS Cu was larger than that in the stainless steel, because the deformation stress of the DS Cu was smaller than that of the stainless steel. Therefore, the specimen fractured at the DS Cu in the case of large strain range. On the contrary, for the small strain range the strain in the stainless steel was larger than that in the DS Cu. The fracture location of the joint corresponded with its strain distribution except for the small strain range of the direct diffusion bonded joint.

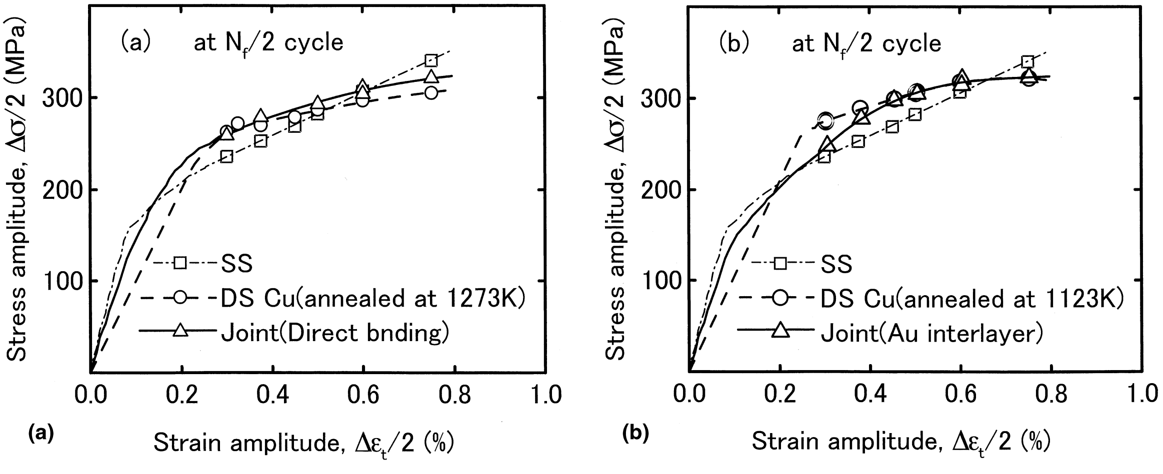

Fig. 6. Cyclic stress–strain curves: (a) direct bonded joint; (b) Au interlayer joint.

Since this had both recrystallization and intermetallic compounds near the interface, it fractured at the interface.

5. Conclusion

1. For the direct diffusion bonded joint, the specimen fractured at the interface in the case of small strain range because of defects. The fatigue strength in the small strain range was considerably lower than that of the DS Cu annealed at 1273 K. In the large strain range, however, the fatigue strength was almost similar to that of the DS Cu and the specimen fractured in the DS Cu from the interface.
2. For the Au interlayer joint, the specimen did not fracture at the interface and the low cycle fatigue strength was larger than the direct diffusion bonded joint. This joint had a low cycle fatigue strength similar to the DS Cu annealed at 1123 K.
3. The strain distribution in the joint specimen was not uniform, because the cyclic stress–strain behavior was different between the 316 stainless steel and the DS Cu. The fracture locations of joint specimens varied depending on their strain distribution.
4. The fatigue strength of the DS Cu annealed at 1123 K was larger than that at 1273 K.

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