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Journal of Nuclear Materials 258–263 (1998) 281–288

journal of nuclear materials

Influence of brazing conditions on the strength of brazed joints of alumina dispersion-strengthened copper to 316 stainless steel

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Abstract

Brazing of alumina dispersion-strengthened copper (DS Cu) to 316 stainless steel were conducted in order to investigate the influence of filler metals and brazing conditions on the joint strength. The brazing were performed with a silver-base (BAg-8) and three kinds of gold-base (BAu-2,4,11) filler metals with varying brazing joint clearance and brazing time. The filler metal had a greater effect on the joint strength than the brazing joint clearance and brazing time. The joint with BAu-2 was superior to the joint with other filler metals. The tensile strength of the joint with BAu-2 was as large as that of DS Cu, however, the Charpy and low cycle fatigue strength were lower than those of DS Cu. The DS Cu melted near the brazed zone, consequently recrystallization and agglomeration of alumina occurred in the diffusion layer for all filler metals. The grain size after the recrystallization was small in order of BAu-2, BAu-4 and BAu-11, that was in accordance with the order of the brazing temperature. The excellent fracture strength for the joint with BAu-2 was attributed to the smallest grain size.

1. Introduction

The first wall and divertor components of the ITER are proposed to be made of alumina dispersion-strengthened copper (DS Cu) bonded to austenitic stainless steel, since the DS Cu has excellent thermal conductivity, strength retention and microstructural stability at elevated temperatures. Hence the development of a bonding technology for the DS Cu has been investigated by brazing [1–5], friction welding [6,7] and diffusion bonding [8–11]. As for cooling pipes of the divertor, which are made of the DS Cu and joined to the stainless steel pipes and heat sink materials, the joining technique should not employ high pressure such as used in HIP, because the pipes have poor endurance against compression at elevated temperatures. Therefore, brazing will be required in the divertor component.

Brazing of the DS Cu to itself has been carried out using mainly silver-base filler metal [1–5]. However, all joints were embrittled and exhibited little ductility and low strength compared with the DS Cu base metal. Samal has suggested that gold-base filler metals (Au50–Cu50, Au35–Cu65) in the brazing improved the strength and properties of the joint [2]. Only limited data, however, were available on the strength of the brazed joint between the DS Cu and stainless steel using the gold-base filler metals.

In this work, the brazing of the DS Cu to the 316 stainless steel was conducted in order to investigate the influence of filler metals and brazing conditions on the joint strength. The brazing was performed with the silver-base (BAg-8) and the gold-base (BAu-2, BAu-4, BAu-11) filler metals varying brazing time and brazing joint clearance, by which tolerance between brazing surfaces of the actual components is affected. According to the results of FEM analyses on the tensile test, the maximum stress and strain were generated apart from the interface in large deformation [12]. The fracture strength on the tensile test does not always correspond to the bonding strength near the interface. Therefore, joint strength was characterized by tensile, Charpy impact and low cycle fatigue tests on the joints and base metals in this investigation. Moreover microstructural observations, elements analysis and a hardness of the brazed zone were examined with an optical microscope, SEM, EPMA and a Vickers hardness tester respectively.

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0022-3115/98/$19.00
PII: S0022-3115(98)00230-X

Table 1
Chemical compositions (wt.%) and melting temperatures of used filler metals

Alloys	Au	Ag	Cu	Ni	Liquid temp. (K)
BAg-8	–	72.0	Bal	–	1053
BAu-2	80.0	–	Bal	–	1163
BAu-4	82.5	–	–	Bal	1223
BAu-11	50.0	–	Bal	–	1243

2. Experimental procedure

The 316 stainless steel and DS Cu (GlidCop Al-15) were the similar to those used in the previous study [11]. A silver-base filler metal and three kinds of gold-base filler metals were employed in this investigation. Their chemical compositions and liquid temperatures were listed in Table 1. These filler metals were selected to avoid intermetallic compounds forming with the DS Cu and the stainless steel. The silver-base filler metal BAg-8 is the Ag–Cu eutectic alloy. As for gold-base filler metal, Au–Cu and Au–Ni alloys are a continuous solid solution, and the compositions of the BAu-2 and the BAu-4 show the minimum melting temperatures. As for the BAu-11, Cu content is greater than the BAu-2. The liquid temperatures are high in the order of BAg-8, BAu-2, BAu-4 and BAu-11.

The brazing conditions were investigated with varying the filler metals, brazing time and brazing joint clearance between the stainless steel and DS Cu as listed in Table 2. The brazing were conducted with higher temperature than the liquid temperature of the each filler metals only by 40 K in order to avoid a recovery and a

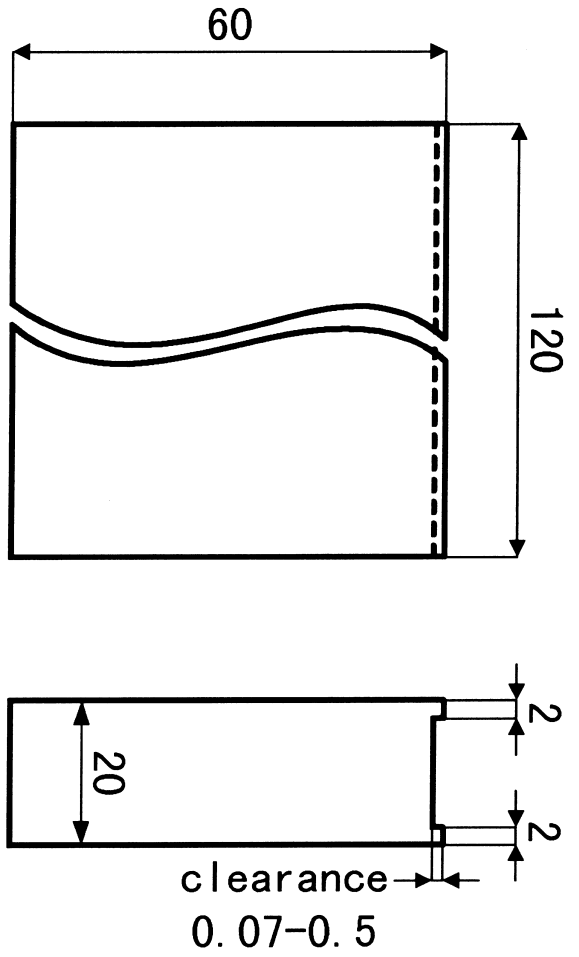

Fig. 2. Configuration of brazing surface of stainless steel to control brazing joint clearance (mm).

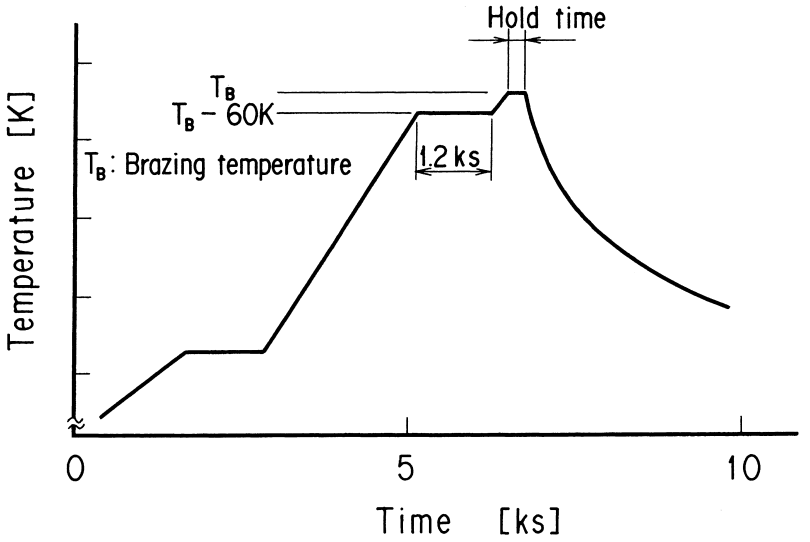

Fig. 1. Temperature curve of heating process during brazing.

Table 2
Conditions for brazing and results of mechanical properties of all joints

Joint ID	Filler metal	Clearance (nm)	Brazing temp (K)	Brazing time (s)	Tensile tests at RT					Charpy absorbed energy at 273 K (J)
					0.2% Proof stress (MPa)	Tensile strength (MPa)	Elong. (%)	Reduc. of area (%)	Position of fracture	
BSC-1	BAg-8	0.09	1093	300	240	245	1.0	2.5	Filler metal	2
					240	245	1.7	4.2	Filler metal	2
BSC-2	BAg-8	0.21	1093	300	245	305	1.0	5.4	Filler metal	2
					–	320	1.7	5.7	Filler metal	2
BSC-3	BAu-2	0.20	1203	300	230	415	22.0	68.1	DS Cu	6
		0.19			250	415	13.3	24.0	Diffu. layer	5
					230	410	11.3	15.1	Diffu. layer	7
					230	410	21.7	66.6	DS Cu	6
BSC-4	BAu-4	0.17	1263	300	215	220	0.7	0.3	Diffu. layer	3
					–	380	5.0	5.7	Diffu. layer	3
BSC-5	BAu-11	0.21	1283	300	230	380	5.3	10.1	Diffu. layer	6
					–	365	4.7	7.6	Diffu. layer	5
BSC-6	BAu-2	0.07	1283	300	230	375	8.3	28.0	Diffu. layer	11
					230	335	6.7	26.5	Diffu. layer	12
BSC-7	BAu-2	0.30	1203	300	230	360	4.3	11.7	Diffu. layer	7
					230	335	3.3	8.6	Diffu. layer	6
BSC-8	BAu-2	0.50	1203	300	230	355	5.6	14.0	Diffu. layer	10
					230	400	21.0	67.0	Diffu. layer	5
BSC-9	BAu-2	0.10	1203	300	230	370	5.7	21.1	Diffu. layer	10
					230	405	21.0	68.3	Diffu. layer	9
BSC-10	BAu-2	0.10	1203	600	230	405	11.7	15.4	Diffu. layer	7
		0.20			235	410	22.7	67.6	Diffu. layer	7
BSC-11	BAu-2	0.20	1203	1200	204	250	2.0	8.8	Diffu. layer	10
					235	400	11.7	24.5	Diffu. layer	12

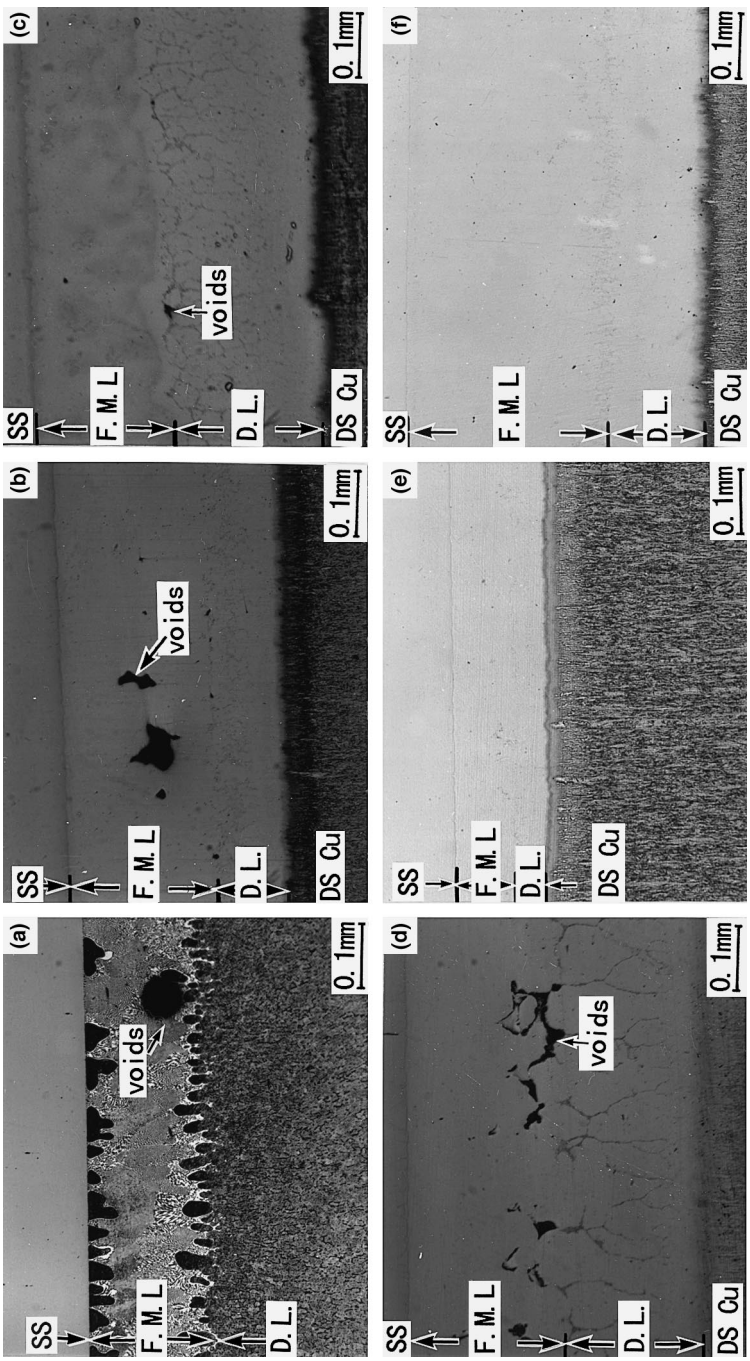

Fig. 3. Optical micrographs near brazing zone: (a) BSC-2 (BAg-8); (b) BSC-3 (BAu-2); (c) BSC-4 (BAu-4); (d) BSC-5 (BAu-11); (e) BSC-6 (BAu-2); (f) BSC-11 (BAu-2).

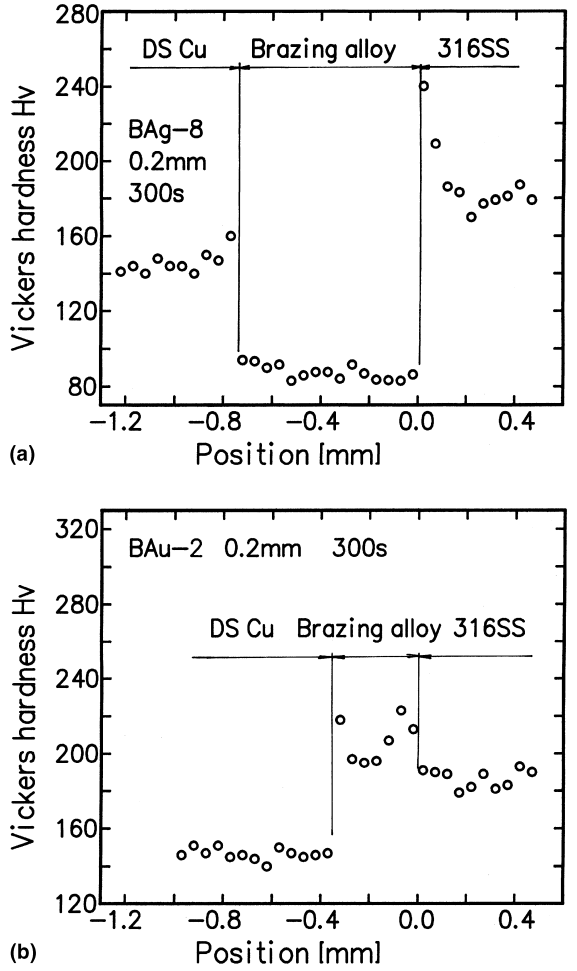

Fig. 4. Vickers hardness distributions near brazed zone for BAg-8 and BAu-2 joints with brazing joint clearance of 0.2 mm and brazing time of 300 s: (a) BSC-2 (BAg-8); (b) BSC-3 (BAu-2).

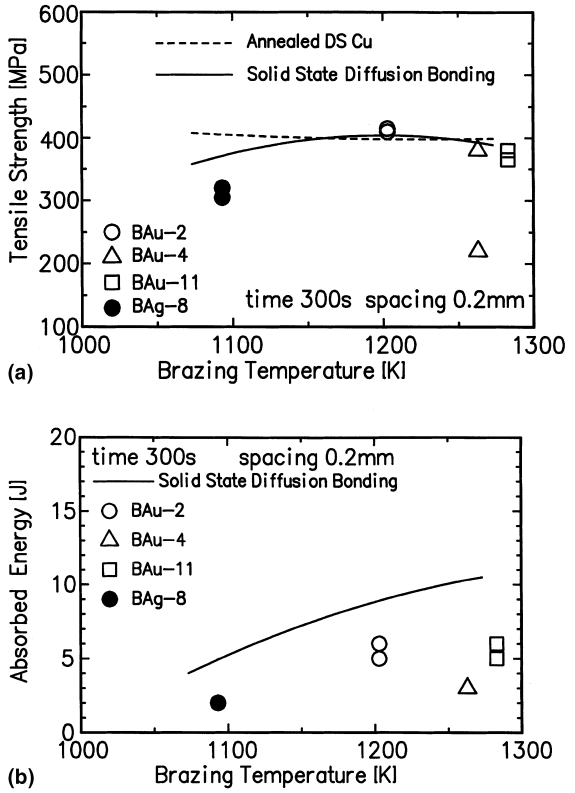

Fig. 5. Tensile strength and Charpy-absorbed energy of joints in comparison with annealed DS Cu and immediate diffusion bonding. (a) Tensile strength. (b) Charpy-absorbed energy.

softening of the DS Cu at high temperatures [11]. The heating process is shown in Fig. 1. At first in the sequence of the brazing, the filler metals were varied under the fixed brazing joint clearance of 0.2 mm and the brazing time of 300 s. Then the effect of the brazing joint clearance and the brazing time was investigated with the filler metal BAu-2, with which the strength of the joint was superior to those with other filler metals. The clearance was controlled by a groove depth of the brazing joint surface for the stainless steel as shown in Fig. 2. Butt joint was carried out with the brazing surface perpendicular to the rolling direction of DS Cu using furnace in a vacuum at 5×10^{-3} Pa or lower. The brazing surfaces were polished with a grit paper and degreased in acetone just prior to the brazing. The filler metals were twice as thick as the brazing joint clearance in the form of sheet and placed on the brazing surface. Every test specimen was machined with the bonding interface located at the center of specimen. Procedure of tensile, Charpy and low cycle fatigue tests were the same as the previous investigation [11].

3. Results and discussion

3.1. Microstructure and hardness near brazed zone

Fig. 3(a)–(d) shows optical micrographs near the brazed zone for all filler metals with the same clearance of 0.2 mm and the same brazing time of 300 s. The brazed zone was divided into the filler metal layer and the diffusion layer, in which the filler metal diffused to the DS Cu. During the brazing stage following dissolution of the filler metal, the DS Cu was melted and eroded by the liquid filler metal, since the liquid metal was supersaturated in Ag, Au or Ni. The joint with BAg-8 had thick diffusion layer and its thickness was about 0.6 mm, while this photo does not show the whole diffusion layer. For the joints with gold-base filler metals in comparison with BAg-8, however, the thickness of the diffusion layer

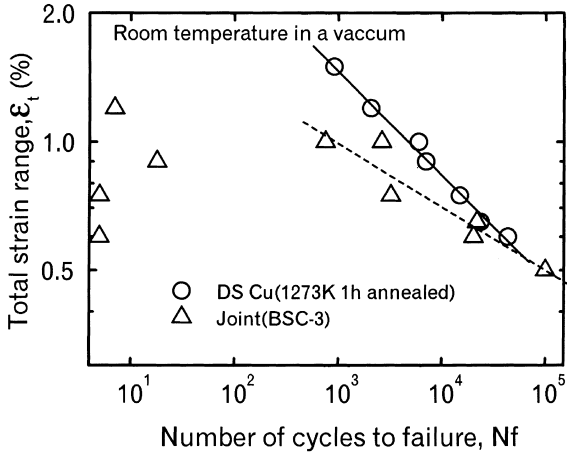

Fig. 6. Low cycle fatigue strength of joint with brazing condition BSC-3 compared with annealed DS Cu.

were below 0.3 mm and very thin, especially for BAu-2. The grain was observed in the diffusion layer, in which isothermal solidification occurred. The grain size was small in order of BAu-2, BAu-4 and BAu-11, that was in accordance with the order of the brazing temperature. It is suggested that the melting temperature of the gold-base filler metal affected the grain size in the diffusion layer after the solidification. As can be seen in this figure, there were several voids in the filler metal layer and the boundary between the diffusion layer and filler metal layer. These voids were developed by shrinkage of the liquid metal. Hence imposition of external load during the brazing process will reduce these voids.

Fig. 3(e) and (f) are the microstructure for the brazing joint clearance of 0.07 mm and brazing time 1200 s, respectively, with the BAu-2 filler metal. The thickness of diffusion layer became thin in the case of the clearance 0.07 mm owing to a small amount of the filler metal compared with the clearance 0.2 mm. As for the long brazing time, however, the thickness was almost the same as that of the brazing time 300 s, because the dissolution time was very short compared with the brazing time and the isothermal solidification occurred in the diffusion layer [1].

Hardness distributions near the brazed zone on the BAg-8 and BAu-2 joints are shown in Fig. 4. For the joint with BAg-8, the hardness of the filler metal layer and the diffusion layer was almost the same and lower than those of the DS Cu and the stainless steel. On the other hand, the hardness of filler metal layer for BAu-2

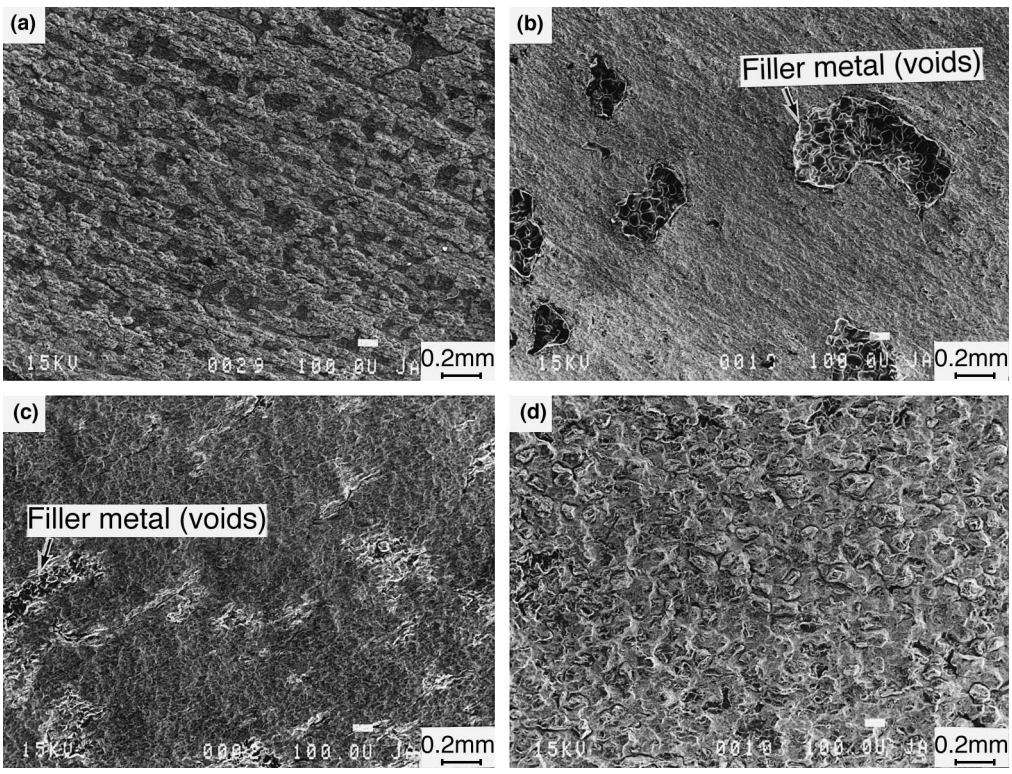

Fig. 7. SEM fractography of tensile specimens for all filler metals with brazing joint clearance of 0.2 mm and brazing time of 300 s: (a) BSC-2 (BAg-8); (b) BSC-3 (BAu-2); (c) BSC-4 (BAu-4); (d) BSC-5 (BAu-11).

was larger than those of the DS Cu and the stainless steel.

3.2. Mechanical properties of joints

Results of tensile and Charpy impact tests of all joints are summarized in Table 2. Fig. 5 shows the tensile strength and the Charpy-absorbed energy of the joints compared with those of the DS Cu and the immediate diffusion bonding [11]. The tensile specimens for BAg-8 fractured in the filler metal layer and the fracture strength was less than that of DS Cu. It is thought that the strength of the filler metal layer for BAg-8 was lower than the DS Cu from the results of the hardness. On the other hand, the joints with gold-base filler metal fractured in the diffusion layer as mentioned in the next section. The tensile strength of the joint with the BAu-2 was as large as that of the DS Cu base metal. However, Charpy impact strength of the joint was considerably lower than that of the DS Cu (52J) [11]. According to the FEM analyses on Charpy specimen of the joint [12], the Charpy strength was sensitive to the strength near the brazed zone. The degradation of Charpy strength is caused not only by the bonding strength but also by the mechanical properties of the brazed zone. The brazing joint clearance and brazing time had a little effect on the strength of the joint. Especially the joint with small clearance exhibited the superior strength on Charpy test because of the thin diffusion layer.

Low cycle fatigue strength of annealed DS Cu and joint with the brazing condition BSC-3 is shown in Fig. 6. The low cycle fatigue strength of the joint was lower than that of the DS Cu at large strain range, where the specimens fractured in the diffusion layer like the tensile specimens. Some specimens showed very short fatigue lives and contained the voids in the filler metal layer as a result of fractography. Imposition of external load during the brazing is desired to reduce these voids.

3.3. Fractography and EPMA analyses

Fig. 7 shows SEM micrographs of the stainless steel side fracture surface on tensile specimens for all filler metals, which were the brazing joint clearance 0.2 mm and the brazing time 300 s. The tensile specimens with BAg-8 fractured in the filler metal. For gold-base filler metals, however, the specimen fractured in the diffusion layer. As can be seen in Fig. 7(d), the surface showed intergranular fracture. Fig. 8 is EPMA photographs in the diffusion layer of the joint BSC-3 (BAu-2) as an example. The melting of DS Cu caused recrystallization and agglomeration of alumina dispersoids in the grain boundary. As the results of EPMA, the recrystallization and the agglomeration occurred in the diffusion layer for all filler metals. The grain size was small in order of BAu-2, BAu-4 and BAu-11 similar to the results of optical microscope observations. These recrystallization and agglomeration made the fracture strength lower than that of DS Cu. The excellent fracture strength for the joint with BAu-2 was attributed to the smallest grain size.

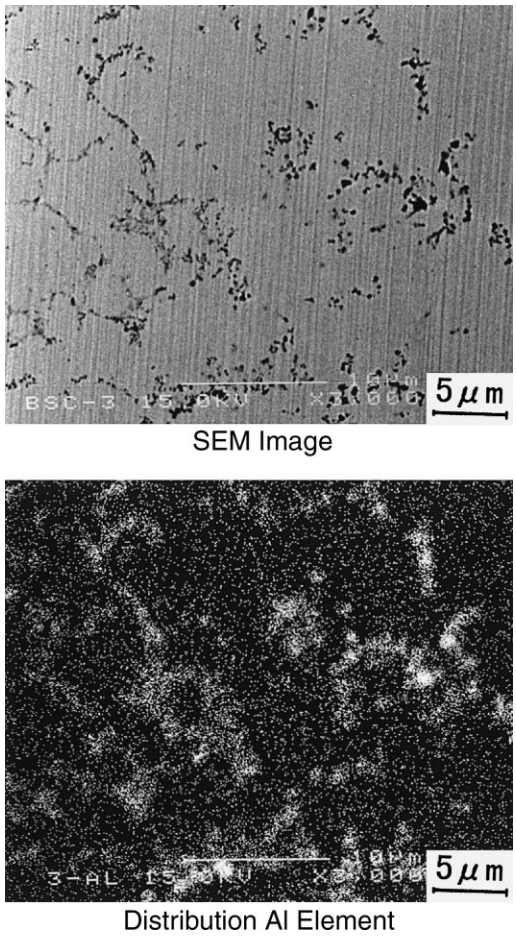

Fig. 8. EPMA analysis in diffusion layer of the joint BSC-3 (BAu-2).

4. Conclusions

Brazing of the DS Cu to the 316 stainless steel were conducted in order to investigate the influence of filler metals and brazing conditions on the joint strength. Conclusions are summarized as follows:

1. The filler metal had a greater effect on the strength of the joint than the brazing joint clearance and brazing time. The tensile strength of the joint with BAu-2 was superior to the joint with other filler metals. For the joint with BAu-2, the tensile strength was as large as that of DS Cu, however, the Charpy and low cycle fatigue strength were lower than that of DS Cu.

2. The recrystallization and the agglomeration of alumina occurred in the diffusion layer for all filler metals and the grain size was small in order of BAu-2, BAu-4 and BAu-11, that was in accordance with the order of the brazing temperature. The excellent fracture strength for the joint with BAu-2 was attributed to the smallest grain size.
3. There were several voids in the filler metal layer and the boundary between the diffusion layer and filler metal layer. Some specimens, which contained the voids, exhibited low strength. Imposition of external load during the brazing is desired to reduce these voids.

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