Microstructure of Aluminum/Copper Lap Joint by Friction Stir Welding and Its Performance

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An investigation has been made of the feasibility of friction stir welding of dissimilar lap joint of an aluminum plate to a copper plate, which is difficult to weld by fusion welding methods because of the formation of brittle intermetallic compounds (IMC). The joint strength depended strongly on the depth of the pin tip relative to the copper surface; when the pin did not penetrate to the copper surface the joints showed very weak fracture loads, whereas slight penetration of the pin tip to the copper surface increased the joint strength significantly. Although the level of bond strength was quite low, it exhibited a general tendency to increase with a rise in the rotation speed. Various microstructures with different morphologies and properties were observed in the stirred zone of aluminum and Al/Cu interfacial region. Comparison of the fracture location with the microstructure suggests that IMC formed in the interfacial region was responsible for the low strength of the joints. X-ray diffraction from the fracture surfaces indicated that Al_4Cu_9 , $AlCu$, and Al_2Cu were main intermetallic compounds formed in the interfacial region.

Key Words: Friction Stir Welding, Lap Joint, Aluminum, Copper, Intermetallic Compound

1. Introduction

A suitable process is required for the welding of copper to aluminum in the electric industry, and so these two materials have been joined using many methods such as ultrasonic welding¹⁾, friction welding²⁾, and laser welding³⁾. The difficulty with fusion welding of aluminum to copper is the fact that brittle intermetallic compounds develop in the joint zone.

Over the last decade, friction stir welding (FSW) has offered a great welding quality to the joining of Al, Mg⁴⁾, Ti⁵⁾, Cu⁶⁾, and Fe alloys⁷⁻⁹⁾. Recently, some trials have been made to join the dissimilar materials, for examples dissimilar Al alloys¹⁰⁾, and aluminum to steel¹¹⁻¹³⁾.

A few preliminary studies have been reported for the FSW of aluminum-to-copper (Al/Cu) butt joint¹⁴⁻¹⁶⁾ but as far as we know, Al/Cu lap joints have not been yet investigated. This research has been aimed at investigating the performance of friction-stir welds of Al/Cu lap joint and phenomena occurring at the interface during the FSW process from the metallurgical point of view.

2. Experimental Details

A plate of commercially pure aluminum A1100H24 2.0

Fig. 1 Schematic illustration of FSW of aluminum plate to copper plate.

Table 1 Chemical composition of aluminum base metal 1100H24 (mass %).

Si	Fe	Cu	Mn	Mg	Ti	Al
0.12	0.54	0.12	0.01	0.03	0.03	Bal.

mm thick was friction-stir-welded to a plate of tough pitch copper of 99.96 %, and 1.0 mm thickness as schematically illustrated in **Fig. 1**. The chemical composition of the aluminum is listed in Table 1. Rotation and travel speeds of tool employed were listed in **Table 2**. The depth of the pin tip from the upper surface of the aluminum plate was fixed at 2.0 or 2.1 mm (0.0 and 0.1mm from the surface of the copper plate).

The tool of steel SKD61 was comprised of a shank,

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Table 2 Welding parameters and results from peel tests.

Rotation Speed s^{-1}	Travel Speed mm/s	Pin Depth mm	Fracture Load N			Weld Number
16.7	3.3	2.1	63.8	61.8	0	1
	4.2		57.9	74.6	62.8	2
	5.0		0	0	0	3
25.0	3.3		96.1	113.8	254.1	4
	4.2		56.9	65.7	83.4	5
	5.0		89.3	97.1	43.2	6
33.3	3.3		156	154	186.4	7
	4.2		137.3	176.6	232.5	8
	5.0		79.5	116.7	134.4	9
41.7	3.3		133.4	240.3	126.5	10
	4.2		170.7	155	238.4	11
	5.0		94.2	277.6	161.9	12

Fig. 2 Schematic illustration of tool used for FSW.

Fig. 3 Schematic view of specimen used for peel test.

shoulder and pin as shown in **Fig. 2**. The tool axis was tilted by 3° with respect to the vertical axis of the plate surface.

The FSW tool, fixed in the holder, was slowly pushed into the aluminum plate to the specified pin depth and then forcibly traversed along the joint line until the end of the weld was reached. The welding tool was then retracted while the tool continued to turn.

Surfaces for the observations of microstructure were etched by 1%HF aqueous solution for revealing the aluminum microstructure and subsequently by a solution composed of NH_4OH , water, and H_2O_2 for the Cu microstructure. The microstructure was observed with an optical microscope and scanning electron microscope (SEM) for close observations.

A peel test was employed to estimate the fracture load of the obtained joint. The schematic view of the specimen used for the peel test is shown in **Fig. 3**. The displacement speed was 0.3 mm/s. X-ray diffraction analyses were carried out to identify the phases formed on the fracture surfaces of joint after the peel test.

3. Experimental Results and Discussion

3.1 Microstructure of Joint

The microstructures of the base metals are shown in **Fig. 4**. The aluminum base metal showed elongated grains in the rolling direction as shown in **Fig. 4(a)**. The copper base metal presented recrystallized grains as indicated in **Fig. 4(b)**.

At pin depth of 2.0 mm, joints obtained showed very low strength; most of them were fractured during the preparation of the specimens for the peel test.

At pin depth of 2.1mm, the transverse sections of the

Fig. 4 Microstructures of base metals of aluminum (a) and copper (b).

welded joints observed at a low magnification are shown in Fig. 5. More welding flash was released in the retreating side, where the direction of the tool rotation is opposite to the travel direction of the tool. It is noted from Fig. 5 that a black microstructure was observed near the Al/Cu interface in the aluminum side when the rotation speed was higher than 16.7 s^{-1} . This black structure extended toward the advancing side of the joints with increasing the travel speed to reach the surface of aluminum at the highest travel speed. One of the main features of the aluminum macrostructure of the weld is that no clear onion ring structure or thermo-mechanically affected zone appeared in contrast to the general ones reported in many previous papers about FSW of Al alloys¹⁷⁻¹⁹.

The characteristic microstructures of an Al/Cu joint bonded at a high rotation speed are shown in Fig. 6. The microstructure of the aluminum stir zone was characterized by equiaxed fine grains (area (I)) as shown in Fig. 6 (b). Several authors suggested that the equiaxed fine grain in the stirred zone was formed through the dynamic recrystallization followed by the static recrystallization for a short period during the cooling process²⁰⁻²².

Fig. 5 Macrostructures of transverse sections of welds: (a) Weld No.1, (b) Weld No.10, (c) Weld No.6, and (d) Weld No.12 (see Table 2).

Fig. 6 Characteristic microstructures of different areas in Al/Cu FSW (Weld No. 10): (a) macrostructure of joint, (b) fine equiaxed grains zone (in stir zone) of aluminum (area I), (c) aluminum HAZ on advancing side (area III), and (d) Al/Cu interface zone (area II).

Between area (I) and the base metal of aluminum, narrow heat-affected-zones (areas IV and III) were observed which were characterized by slightly coarser grains than those of the stir zone. The HAZ at the advancing side is shown in Fig. 6 (c). In area (II), black

Fig. 7 Different microstructures formed in area close to Al/Cu interface (Weld No.4): (a) layer and grey structures, (b) copper-rich fragment with fine grains, (c) copper-rich fragment with normal grains, and (d) copper-rich fragment with layer structure.

structures were formed mainly in the aluminum close to the Al/Cu interface as shown in **Fig. 6(d)**. The copper side was characterized by thin layers of dark structure very near to Al/Cu interface as shown in **Fig. 6(d)**. This layer is different from the black structure mentioned above and can be considered to be similar to the layer structure (see **Fig. 7(a)**) from chemical composition and microstructural characterization. It is also recognized that grains in the copper close to Al/Cu interface was finer than those of the copper base metal though not obviously observed in **Fig. 6(d)**. This difference in the grain size can be attributed to the effect of rotating pin which deformed the grains close to Al/Cu interface.

The structure close to Al/Cu interface was complicated. Different kinds of structures were formed as shown in **Fig. 7**. A layer structure which consisted of mechanically mixed Cu and Al rich layers was formed in the area close to the interface as shown in **Fig. 7(a)**. Fragments of copper distributed randomly in the aluminum substrate near the interface with various size and structures. Some of the fragments contained the layer structure (see **Fig. 7(d)**) and the others contained fine grains of copper rich structure as shown in **Fig. 7(b)**. The copper rich fine grain structure not only formed in the form of fragment but also at the interfacial area as shown in **Fig. 12**. There was another form of copper fragments which had normal grain size as shown in **Fig. 7(c)**. It is noted that grey structure were accompanied by the layer structure and formed at surrounding of the copper rich fragments as indicated in **Fig. 7(a)** and **Fig. 7(c)**.

The characteristic microstructures of the Al/Cu joints at

Fig. 8 Enlarged micrographs of black structures showing different color depth: (a) light black structure, and (b) deep black structure (Weld No. 10).

Table 3 EDX analyses at points 1 to 5 indicated in **Fig. 8**(at %).

Elements	Points				
	1	2	3	4	5
Al	95	94	93	75	70
Cu	5	6	7	25	30

low rotation speed (16.7 s^{-1}) were similar to those observed at high rotation speeds (25.0 s^{-1} to 41.7 s^{-1}) in regard to the microstructures in aluminum stirred zone, but the structure near the Al/Cu interface showed none of the layer, black and grey structures which were the main characteristics structures of joints at high rotation speeds.

3.2 Chemical Analyses of Characteristic Microstructures

One of the main characteristic structures in aluminum side was the black structure (see **Fig. 6(a)**). The black structure was inhomogeneous in the depth of color as shown in **Fig. 8(a)** and **Fig. 8(b)**. The results from EDX analyses of areas shown in these figures are compared in **Table 3**. It shows that the areas showing deeper black had higher copper contents.

EDX analyses of the different structures revealed that

Fig. 9 Compositions of black, grey, and layer structures in comparison with Al/Cu phase diagram.

the layer structure had different compositions depending on its position. The more the layer structure close to the copper base metal, the higher was its content of copper and vice versa. Therefore, the layer structure of the copper fragments in the aluminum side had less percentages of copper than the one formed next to the copper substrate. On the other hand, the analysis of the grey structure indicates that its aluminum content was almost 50% aluminum.

The results from EDX analyses of the different structures are indicated in the Al-Cu phase diagram in **Fig. 9**. This suggests that all these microstructures consisted of or included intermetallic compounds.

3.3 Hardness of Characteristic Microstructures and Joint Strength

The distribution of hardness along the horizontal center line of aluminum plate is shown in **Fig. 10**. The hardness values were slightly lower in the HAZ than stir zone. This is attributable to the difference in grain size in both areas (see **Fig. 6**). The hardness distribution along the vertical axis to the weld is shown in **Fig. 11**. The average hardness of the aluminum stir zone was 30 Hv. The black structure showed higher hardness depending on its copper content. Meanwhile, the hardness of the layer and fine grain copper

Fig. 10 Hardness distribution along centerline of aluminum plate.

Fig. 11 Hardness distribution (Hv0.49N) perpendicular to Al/Cu joint (Weld No. 10).

Fig. 12 Hardness values of layer structure, point A, and fine grain copper structure, point B, (Weld No. 10).

Fig. 13 Cross sections of fracture surfaces after peel test (Weld No. 12): (a) microstructure of cross section, and (b) and (c) closer views of rectangular area in (a).

structures were much higher than the other areas as shown in **Fig. 12**.

The fracture load of the joints in peel test is shown in **Table 2**. Although the measured value of the fracture load was scattered quite widely, it showed a general tendency to slightly decrease by increasing the travel speed from 3.3 to 5.0 mm/s. Increasing the rotation speed from 16.7 to 41.7 s^{-1} improved the fracture load.

For joints bonded at rotation speeds of 25.0 s^{-1} to 41.7 s^{-1} , the fracture on peel test occurred along the path as shown in **Fig. 13**. Aluminum and copper fracture areas are shown in **Fig. 13(a)**. Enlargement of some areas on copper side (**Fig. 13(b)** and **Fig. 13(c)**) presented the layer structure covered with grey structure. This suggested that the fracture occurred mainly at grey structure which can be regarded as an intermetallic compound from its hardness and chemical composition. The chemical compositions of these structures shown in **Fig. 9** indicated that intermetallic compounds of Cu contents of 50% or more were formed in these structures.

Fig. 14 Fracture surfaces of joint after peel test (Weld No.11): (a) brittle morphology on aluminum side, (b) brittle morphology on copper side, (c) ductile morphology on aluminum side, and (d) ductile morphology on copper side.

Fig. 15 Fracture surfaces of aluminum side (a) and copper side (b) for joint welded at rotation speed of 16.7 s^{-1} .

SEM micrographs of the fracture surfaces corresponding to the crack path shown in **Fig. 13** are shown in **Fig. 14**. The fracture surfaces consisted mainly of two types of morphologies: ductile fracture and cleavage fracture which is more prominent.

In contrast to these joints, at a low rotation speed (16.7 s^{-1}) aluminum and copper fractured surfaces were rather flat except for tear ridges of aluminum in very narrow areas as shown in **Fig. 15**.

In order to identify the intermetallic compounds formed

Fig. 16 X-ray diffraction patterns from fracture surfaces of aluminum (a) and copper sides (b) (Weld No.10). The diffraction lines from aluminum, copper, Al_4Cu_9 , AlCu , and Al_2Cu were indicated by $\circ$, $\square$, $\bullet$, $\blacksquare$, and $\blacktriangle$, respectively.

in the joint bonded at higher rotation speeds (25.0 – 41.7 s^{-1}), X-ray diffraction patterns from fractured surfaces of the aluminum and copper sides were analyzed as shown in **Fig. 16(a)** and **Fig. 16(b)**. As can be seen from these, intermetallic compounds of Al_4Cu_9 , AlCu , and Al_2Cu were detected from both aluminum side and copper side. This suggests that intermetallic compounds of Al_4Cu_9 and AlCu were formed in the grey and layer structures where the crack on the peel test was developed preferentially.

These results suggest the possibility to achieve a good quality joints between aluminum and copper using FSW by obstruct or reduce the formation of the intermetallic compounds. It is conceivable that this can be achieved by inserting intermediate metal, carefully controlling the pin depth, and changing the pin design which will be our next trial to improve the joints performance.

4. Conclusions

1. The lap joint of a commercially pure aluminum plate to a copper plate could be obtained by FSW process.
2. A slight difference in pin depth (0.1 mm) had a great effect on the performance of the lap joints.
3. Different microstructures were formed in the joint with varieties of morphologies and properties.
4. The joint bonded at rotation speeds from 25.0 s^{-1} to 41.7

s^{-1} had higher strength than at a rotation speed of $16.7 s^{-1}$.

5. Joints bonded at higher rotation speeds were fractured mainly in brittle manner in the grey and layer structures owing to the formation of intermetallic compounds such as Al_4Cu_9 and $AlCu$.

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