Effects of Alloying Copper and Silicon on the Bondability of Dissimilar Metal Joints of Aluminum Alloys to Steel*

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The effects of Cu and Si in aluminum alloys on the joint properties of Aluminum alloys/steels were evaluated by correlating the interfacial microstructures with the joint strength using diffusion bonding. It was found that joint strength was improved by adding Cu to aluminum alloys, because Cu suppressed formation and growth of a reaction layer. Moreover, the effect was much larger by Cu and Si combined addition. The fracture for the joints with higher strength occurred within the base aluminum alloys. As a reaction layer is thicker, the fracture mode was changed from an interfacial fracture to an aluminum alloy matrix and a reaction layer fracture, regardless of containing copper. For all investigated alloys, the highest joint strength was obtained in a certain value of reaction layer thickness, in particular, the optimum thickness value with the highest joint strength for Cu and Si combined alloy was smallest. By Cu and Si combined addition, our proposed guideline of the interfacial structure to obtain the joints strength more than 70 MPa was satisfied more easily. It was concluded that alloying of both Cu and Si to aluminum alloys improves the bondability of the joints.

Key Words: Dissimilar metal joints of aluminum alloys to steels, Solid-state diffusion bonding, Alloying elements, Interfacial fracture, Reaction layer

1. Introduction

Since Kyoto Protocol which regulates the emission of greenhouse gas was adopted, the reduction of gas consumption of cars has been emphasized around the world. One of the useful processes to improve gas consumption is reducing car weight. To reduce car weight, materials lighter than steels have been used in car bodies like aluminum alloys or magnesium alloys¹⁾. Industrially, dissimilar metal joints of aluminum alloys and steels have been applied partially to automobile bodies using rivets. To accomplish lighter weight of cars and lower cost of their joints, many studies on the metallurgical bonding of aluminum alloys and steels have been reported, however, the study for evaluating the effects of alloying elements on bondability of their joints has not been sufficiently conducted. In particular, although the effect of Cu on improving joint strength had been partly confirmed²⁾, the mechanism of the joint strength with Cu had not been clarified.

In this study, we investigated the effect of Cu addition in aluminum alloy on bondability of the dissimilar metal joints using diffusion bonding.

2. Experimental procedures

Table 1 shows the chemical compositions of materials used in this study. A cold rolled steel (SPCE) containing few alloying elements and four types of aluminum alloys, A2 (Si: 0.6, Cu: 0 (in wt. %)), AC (Si: 0.6, Cu: 1.0), C2 (Si: 1.5, Cu: 0), CC (Si: 1.5, Cu: 1.0) were used.

Table 1 Chemical composition of specimens.

(a) Aluminum alloys									
material	Chemical composition (mass%)								
	Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
A2	0.6	0.6	0.18	-	-	0.07	-	0.02	Bal.
C2	0.6	1.5	0.18	-	-	0.07	-	0.02	Bal.
AC	0.6	0.6	-	1.0	-	-	-	-	Bal.
CC	0.6	1.5	-	1.0	-	-	-	-	Bal.

(b) Steel						
material	Chemical composition (mass%)					
	C	Mn	Si	P	S	Fe
SPCE	0.01	0.15	0.01	0.012	0.005	Bal.

Joints of this bonding experiment consisted of a plate steel sandwiched between two cylindrical aluminum alloys. The original oxide films on the surface of specimens were eliminated by a series of treatments including grinding with emery papers, acetone cleaning, and drying during 1 hour. After these treatments, diffusion bonding was immediately carried out in a vacuum of 1.0×10^{-2} Pa at heating temperatures ranging from 773 to 823 K for a holding time from 300 to 1800 s with a pressure of 2.5 MPa. The heating rate was 3 K/s.

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The interface of joints was analyzed by using scanning electron microscope (SEM), electron probe microanalysis (EPMA), and transmission electron microscope (TEM). The thickness of the reaction layer at the bonded interface was measured using SEM image. The three images for each sample were randomly taken in the center of a bonded interface and twenty measurement of the reaction layer thickness for each picture were made at even intervals with image processing software. Then, the average value of thickness of the reaction layer was calculated from sixty measurements for each sample.

The equation (1) was used to evaluate the fraction of un-bonded region at the bonded interface (Fr). The region where the reaction layer formed and the region where the reaction layer was not observed were defined as bonded region (A) and un-bonded region (B), respectively.

$$Fr = \sum B / (\sum A + \sum B) \quad (1)$$

Tensile tests at room temperature were performed to measure the tensile strength of bonded joint. The test was performed using a Instron type tensile testing machine. The cross-head speed was 3.0×10^{-2} mm/s.

3. Result and discussion

3.1 Interfacial reaction layer

To investigate the effect of Cu on the interfacial reaction layer, microstructure observation and composition analysis were performed. Typical backscattering electron images (BEI) for the cross-sections of the diffusion couples with bonding temperature (T) of 785 K and bonding time (t) of 1800 s are shown in Fig. 1. A gray colored interfacial reaction layer with a thickness of several μm (3 - 5 μm) formed at the Al alloy/SPCE interface in Fig. 1. To identify chemical composition at the interfacial reaction layer, we performed point analysis at the each points of Fig. 1. The result of this point analysis is shown in Table 2. According to past investigations³⁾ and a phase diagram of the binary Fe-Al system⁴⁾, the interfacial reaction layers on the steel (SPCE) side (points of odd numbers) was estimated to be Fe_2Al_5 . The interfacial reaction layer on the A2 side was estimated to be FeAl_3 . The result of TEM analyses at the C2 side is shown at Fig. 2. From Fig. 2, the interfacial reaction layer on the C2 side was found to be $\text{Al}_{12}\text{Fe}_3\text{Si}$. Similarly, the point analysis showed that the interfacial reaction layers on the AC and CC sides were ternary Al-Fe-Si IMC containing Cu.

At the interfacial reaction layer, EPMA was performed. The result of this analysis is shown in Fig. 3. At the areas where the existence of ternary Al-Fe-Si IMC containing Cu was estimated,

the segregations of Si and Cu was confirmed.

Fig. 1 BEI of the interface in Al alloy/steel joint bonded at 785 K for 1800 s.

Table 2 EPMA quantitative analysis of each point in Fig. 1.

Sample	Point	Chemical composition (mol%)				
		Fe	Al	Si	Mg	Cu
A2-SPCE	①	23.1	74.6	2.3	0.02	—
	②	20.8	77.0	2.0	0.12	—
AC-SPCE	③	25.6	72.6	1.7	0.0	0.1
	④	21.7	76.2	1.5	0.4	0.3
C2-SPCE	⑤	25.3	70.7	3.9	0.03	—
	⑥	16.8	72.5	10.0	0.72	—
CC-SPCE	⑦	25.8	71.6	2.6	0.0	—
	⑧	16.4	73.8	7.6	0.1	2.1

(a) Bright-field image

Fig. 2 TEM image and corresponding diffraction pattern at the interface in C2/SPCE joint bonded at 798 K for 1800 s.

Fig. 3 EPMA mapping analysis of the interface in Al alloy/steel joint bonded at 785 K for 1800 s.

(a) Low silicon

(b) High silicon

Fig. 4 Effect of copper on tensile strength.

3.2 Joint strength and thickness of reaction layer

The relationship between tensile strength and mean thickness of reaction layer is shown in Fig. 4. The mean thickness of the reaction layer was estimated by the method described in experimental procedure. As shown in Fig. 4, high joint strength was obtained in a certain range of the reaction layer thickness. Both the much thinner reaction layer and the thicker reaction layer caused the decrease of joint strength.

The fracture surface for the joints with higher strength occurred within an aluminum alloy matrix as shown in Fig. 5 and Table 3. As a reaction layer is thicker, the fracture mode was changed from an interfacial fracture to an aluminum alloy matrix and a reaction layer fracture regardless of containing Cu. Furthermore, by combined addition Cu and Si to aluminum alloys, joint strength was improved and the optimum thickness value with the highest joint strength was thinner. On these effects of combined addition of Cu and Si, the studies have reported that a ternary Al-Fe-Si IMC contributes to firming thin and uniform reaction layer⁵⁾. In this study, Cu in aluminum alloy accelerated forming a ternary Al-Fe-Si IMC and it was estimated that this ternary IMC conducted to high joint strength.

(a) Macro scale

(b) Micro scale (region A)

Fig. 5 SEM image of fracture surface of CC/SPCE joint (Thickness of reaction layer: 0.44 μm, Tensile strength: 146 MPa).

Table 3 EDX quantitative analysis of point ① to ④ in Fig. 5 (b).

point	Al	Fe	Mg	Si	Cu
①	96.95	0.07	1.49	1.19	0.29
②	96.40	0.14	1.27	1.55	0.64
③	95.14	0.67	1.37	2.29	0.53
④	96.97	0.47	1.46	0.66	0.44

3.3 Fraction of un-boned region

As mentioned in section 3.2, thin and uniform reaction layer contributes high joint strength. On formation of the interfacial reaction layer, we investigated the relationship between thickness of reaction layer and fraction of un-boned region at interface about each joint. The results are shown in Fig. 6. Fraction of un-boned region decrease as a reaction layer is thicker. Moreover, adding Cu to aluminum alloys promoted decrease of this fraction. It was suggested that adding Cu to aluminum alloy accelerates the formation of a ternary Al-Fe-Si IMC, and this ternary IMC decreased fraction of un-boned region, consequently improved joint strength. This effect was remarked for the joint of aluminum alloy adding Si and Cu combined.

Fig. 6 Effect of Cu on fraction of un-boned region.

3.4 Range of IMC thickness to obtain 70 MPa in tensile strength

The value of tensile strength was superimposed on the graph of the correlation between thickness of reaction layer and fraction

of un-boned region as shown in Fig. 7. Circles in Fig. 7 shows joint strength higher than 70 MPa and are ranged as shown in Table 4. Higher tensile strength joints tended to distribute at the lower-left corner of the graph. This indicates that formation of thin and uniform reaction layer and low fraction of un-boned region led to high joint strength. Thus, we draw the guideline to obtain high strength of the joints; i.e. the thickness of the reaction layer less than 1.5 μm and fraction of un-boned region less than 30%. When this guideline of interfacial condition is satisfied, joint strength higher than 70 MPa can be obtained. Furthermore, we read off the value of reaction layer thickness at intersection of the guideline and approximate line of interfacial structure. The estimated value is listed in Table 5. Adding Cu to aluminum alloy broadened the range of reaction layer to obtain joint strength higher than 70 MPa. Moreover, for the joint of aluminum alloy of Si and Cu combined addition, the range was broadest. This broadening means that reaction layer to obtain joint strength higher than 70 MPa can be easily controlled. Consequently, these results also show that alloying of both Cu and Si to aluminum alloys improves the bondability of the joints.

Fig. 7 Guideline of reaction layer to obtain joint strength higher than 70 MPa.

Table 4 Relationship between tensile strength and mark in Fig. 7.

Tensile strength (MPa)	~70	70~80	80~90	90~100	100~
Mark	No circle	○	○	○	○

Table 5 Range of IMC thickness to obtain 70MPa in tensile strength.

	Range of IMC thickness
A2-SPCE	0.60 μm ~ 1.10 μm
AC-SPCE	0.50 μm ~ 1.20 μm
C2-SPCE	0.30 μm ~ 1.45 μm
CC-SPCE	0.20 μm ~ 1.45 μm

4. Conclusions

From the correlation of the interfacial reaction layer and tensile strength, the effect of Cu on interfacial reaction layer and joint strength of dissimilar metal joints of aluminum alloys and steels has been evaluated.

At the interface of the joint of aluminum alloy containing 1.0 wt. % Cu, formation of a ternary Al-Fe-Si IMC was confirmed. It was suggested that adding Cu to aluminum alloys accelerated the formation of a ternary IMC at interfacial reaction layer. The ternary IMC contributes the growth of thin and uniform reaction layer, and leads to the improvement of the joint strength. Furthermore, the highest joint strength was obtained for the joint of aluminum alloys adding combined Si (1.5 wt. %) and Cu.

We confirmed adding Cu broadens the range of reaction layer to obtain joint strength higher than 70 MPa. This broadening was clearly larger by Cu and Si combined contained. It can be concluded that adding Cu to aluminum alloy improves the bondability of dissimilar metal joints of aluminum alloys and steels and the best bondability was obtained for the joint of aluminum alloys containing Si (1.5 wt. %) and Cu (1.0 wt. %) in this study.

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