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Effects of Silicon Alloying on Mechanical Properties of RSW Joints between Al-Mg-Si Alloys and High Tensile Strength Steels

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Effects of silicon alloying on joint properties of Al-Mg-Si alloy sheets with cold rolled high tensile strength steel sheets by the resistance spot welding process were investigated, focusing on the existing state of silicon in each material. The joint strength was improved by control of silicon contents in both materials as well as process conditions. Microstructural analysis revealed that the joint strength was dominantly influenced by the thickness distribution of the intermetallic compound layer at steel/aluminum alloy joint interface. Silicon played an important role on the formation behavior of intermetallic compound layer, where silicon was enriched in solid solution or distributed as submicron oxides.

Keywords: *Dissimilar metal joints of aluminum alloys and steels, Resistance spot welding, Joint strength, Intermetallic compound layer*

1. Introduction

The application of aluminum alloys to automotive parts has been recently making progress for vehicle weight reduction to minimize carbon dioxide emissions. However, to respond to demand for further lightening of car bodies, development of dissimilar joints of aluminum alloys and steels is needed as a new key technology. The technical subject is improvement of poor joint strength due to formation of the brittle intermetallic compounds (IMC) layer (Al_3Fe, Al_5Fe_2 phase, and so on) at joint interfaces during welding process. To develop the joint strength, it is important to control the thickness of the IMC layer [1,2]. The formation behavior of the IMC layer is influenced by several factors such as process parameters, material combinations, and joint geometry [3,4]. Especially, it is crucial to clarify the effects of additional elements in order to design aluminum alloys and steels which are suitable for dissimilar joints [5-9]. As for silicon, which is one of the primary alloying elements for both aluminum alloys and steels, there are few studies by practical processes such as resistant spot welding (RSW) except for roll bonding or diffusion bonding process [2,6-8].

In this paper, the effects of silicon alloying on joint properties and interfacial microstructure of Al-Mg-Si alloy sheets with cold rolled high tensile strength steel sheets by RSW process was studied focusing on the existing state of silicon in each material.

2. Experimental Procedure

Al-Mg-Si alloy and cold rolled high tensile strength steel sheets with various levels of silicon content in several thicknesses were used, as shown in Table 1 and 2. Before the welding operations, all these specimens were degreased with acetone, followed by polishing the faying surfaces of some of aluminum alloy specimens with emery paper (number 2000), to investigate the effects of oxides originally formed in the aluminum alloy surfaces. The welding operation was performed by a single phase rectifier type resistance spot welding machine of DENGENSHA NRDAIS-90-601G with 90kVA rated capacity. The welding conditions were as shown in Table 3, which was referred to in a previous work [4]. The tensile strength of these joints was measured by a cross tension test in accordance with JIS Z 3137. The interfacial microstructure of spot welds was investigated using an optical microscope, a scanning electron microscope (SEM), a transmission electron microscope (TEM), and a secondary ion mass spectrometer (SIMS). The specimens for TEM were cut out from the joint interface regions and prepared using the focused ion beam (FIB) system of a HITACHI FB-2000A with micro sampling attachment. The characterization of the IMC layer at joint interface was performed from high angle annular dark field-scanning transmission electron microscope (HAADF-STEM) images, diffraction patterns, and energy dispersive X-ray spectrometer (EDX) images, using the TEM of a JEOL JEM-2010F at 200keV accelerating voltage.

Table 1 Chemical composition and thickness of Al-Mg-Si alloy sheets used in this investigation.

Specimen designation	Chemical Composition (mass%)					Thickness (mm)
	Mg	Si	Fe	Mn	Ti	
A1	0.64	0.57	0.19	0.07	0.02	1.0
A2	0.64	0.94	0.19	0.07	0.02	
A3	0.69	1.46	0.19	0.07	0.02	

Table 2 Tensile strength, chemical composition and thickness of cold rolled high tensile strength steel sheets used in this investigation.

Specimen designation	TS (MPa)	Chemical Composition (mass%)			Thickness (mm)
		C	Si	Mn	
S1	638	0.067	0.01	2.14	1.2
S2	631	0.057	0.48	1.20	
S3	797	0.077	0.69	1.58	
S4	987	0.175	1.38	1.98	

Table 3 Welding conditions for cold rolled high tensile strength steel/aluminum joints.

Electrode	Cu-Cr alloy (Dome-radius type: 150R-16ϕ)
Welding current	18-32kA
Welding time	40ms (2cycles)
Electrode force	3.0kN

3. Results and Discussion

3.1 Effects of Silicon in High Tensile Strength Steels

Fig.1 shows the variation in the cross-tensile strength and nugget size of the dissimilar joints between the specimen A2 and S1-S3 (A2/S1-A2/S3 joints) with welding conditions, in which the surface of specimen A2 was not polished before spot welding. The higher welding current increased the cross-tensile strength. Moreover, the increase in silicon content in steels developed the cross-tensile strength. In particular, the A2/S2 joint had higher cross-tensile strength than the A2/S1 joint with change of the fracture morphology from a shear type to a plug type, although these two steels of the joints showed the similar tensile strength. This means that the joint strength depended on the interfacial structures between steels and aluminum alloys. The actual nugget size increased with increase in silicon content of steels at the same welding condition, as shown in the macrostructure of cross section of spot welds (Fig.2), although the nugget size was underestimated in case of plug type fracture (Fig.1). The increase in silicon content in steels brought about the higher bulk and contact resistance by increasing the amount of silicon in solid solution and forming silicon oxides at surface regions, respectively [10]. These increases in electrical resistivity were considered to result in much higher heat generation during resistance spot welding. Thus, the joint area between steels/aluminum alloys which dominates the joint strength was enlarged by

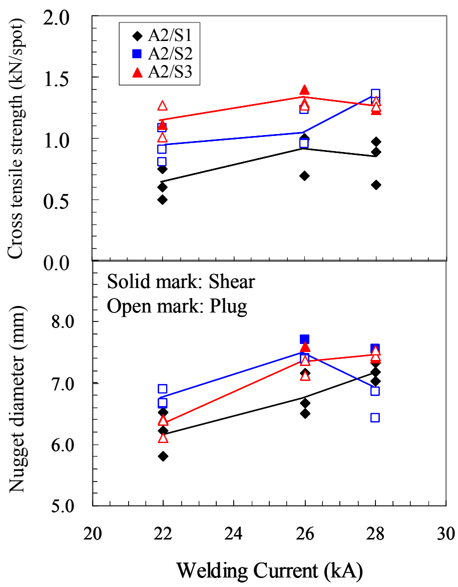

Fig. 1 Variation in the cross tensile strength and nugget diameter with the welding current.

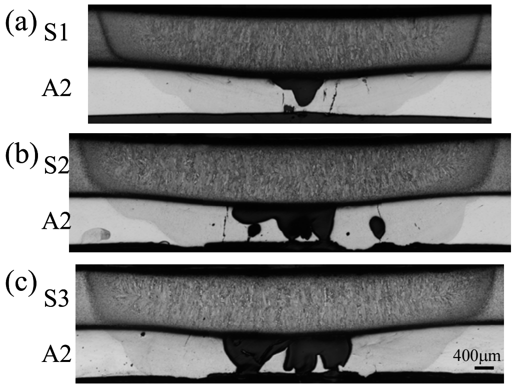

Fig. 2 Macro structures of spot welds (26kA, 40ms): (a) A2/S1, (b) A2/S2, and (c) A2/S3.

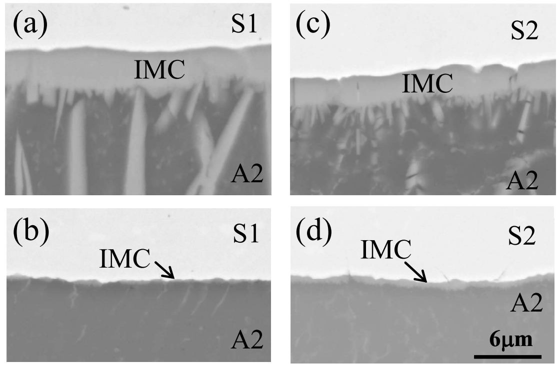

Fig. 3 SEM microstructures of IMC layer formed at the interfaces of steel/ aluminum spot welds (26kA, 40ms): (a) A2/S1, 0.7mm apart in distance from center position in a radial direction, (b) A2/S1, 3.4mm, (c) A2/S2,

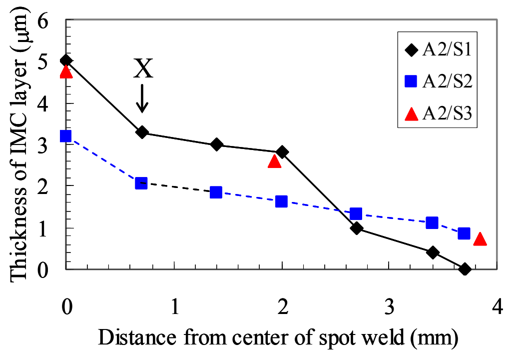

Fig. 4 Effects of Si contents in steels on the thickness distribution of IMC layer (26kA, 40ms).

higher silicon content in steels. Moreover, the silicon in steels also influenced the formation behavior of the IMC layer. Fig.3 shows the SEM microstructure of the IMC layer. The IMC layer had two types of morphologies; one formed planar structures along the interface, another formed plate-like structures which developed in the direction toward the aluminum matrix. As for the A2/S1 joint for the lowest content of silicon in steel, the thickness and size of these IMC phases changed markedly at the position of the spot welds. Especially, on the border of nuggets, the IMC phases of planar structure became much thinner and were aligned discontinuously along the interface (Fig.3(b)). On the other hand, the A2/S2 joint for the higher content of silicon controlled the non-uniform distribution of the thickness and size of them. Fig.4 shows the thickness distribution of the IMC layer. In this measurement, the IMC phase of only the planar structure was taken into consideration on the basis of the assumption that the IMC phases which are in contact with both steel and aluminum dominates the joint strength. It has been reported in the previous works that the most effective thickness of the IMC layer is around 1 micron [1,6]. In the case of thickness less than about 1 micron, the increase in area of un-bonded region, where no IMC layer was formed at the interface, decreased the joint strength. In contrast, the thick IMC layer of more than about 1 micron changed the fracture mode from a ductile fracture in the aluminum to a brittle fracture at the aluminum/IMC interface and/or the inside of the IMC layer, resulting in a decrease in joint strength [2]. Thus, from this viewpoint, the improvement of joint strength for the joints of much higher silicon content in steels was considered to be due to formation of the thinner IMC layer (about 1 micron) at wider area of the joint interface (especially on the border of the nugget), as shown in Fig.4.

As described above, silicon in steels influenced the thickness distribution of the IMC layer. To clarify the role of silicon in steels, the existing state of silicon at joints was investigated. Fig.5 and Table 4 show the HAADF-STEM images of the IMC layer and results of the analysis according to the diffraction patterns and EDX spectra. It was revealed that the IMC phase of planar structure was Al_5Fe_2, and that of plate-like structures Al_3Fe, respectively. Moreover, it was proved that the decrease in thickness of the IMC layer corresponded approximately to that of Al_5Fe_2, in which silicon was concentrated and sub-micron silicon oxides were distributed. These silicon oxides were originally formed at the steel surface regions during the steelmaking process [11] and remained after joining.

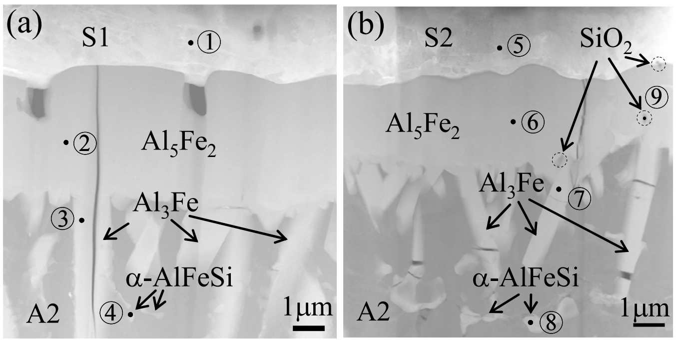

Fig. 5 HAADF-STEM images of IMC layer at the position X in Fig.4: (a) A2/S1, (b) A2/S2.

Table 4 EDX and diffraction pattern analysis of each selected point in Fig.5.

Joint designation	Point	Composition of detected element by EDX semi-quantitative analysis (at%)					Identified structure from diffraction pattern
		Al	Fe	Si	Mn	O	
A2/S1	①	0.5	96.8	0.1	2.6	-	Fe
	②	71.3	27.3	0.5	0.9	-	Al_5Fe_2
	③	76.8	22.7	0.3	0.2	-	Al_3Fe
	④	84.9	8.8	6.1	0.2	-	α-AlFeSi ($Al_{8.3}Fe_2Si$)
A2/S2	⑤	0.2	97.4	0.9	1.5	-	Fe
	⑥	71.6	27.2	0.9	0.3	-	Al_5Fe_2
	⑦	76.6	22.9	0.3	0.2	-	Al_3Fe
	⑧	76.3	16.0	7.5	0.2	-	α-AlFeSi ($Al_{8.3}Fe_2Si$)
	⑨	63.1	19.6	4.3	0.5	12.5	SiO_2

Thus, from these results, it is supposed that silicon and silicon oxides in Al_5Fe_2 caused the uniformly wider and thinner IMC layer as some barriers to diffusion of Al or Fe, resulting in the improvement of joint strength.

3.2 Effects of Silicon in Aluminum Alloys

Fig.6 shows the variations in cross-tensile strength and nugget size of the dissimilar joints between the specimen A1-A3 and S4 (A1/S4-A3/S4 joints) with welding conditions, in which the surfaces of specimens A1-A2 were polished before spot welding. The higher welding current increased the cross-tensile strength, while the increase in silicon content in aluminum alloys decreased the cross-tensile strength. Fig.7 and 8 show the macrostructure of cross section of spot welds and the thickness distribution of the IMC layer, respectively. As described in the previous paragraph, to improve the joint strength, it is important to form the IMC layer of optimum thickness at a wider area on the border of the nugget. The increase in silicon content in aluminum alloys did not seem to have any effect on the nugget sizes because of the very slight increase in electrical resistivity in comparison with the case in steels. Nevertheless, silicon in aluminum alloys decreased the thickness of the IMC layer of interfaces, resulting in an increase in the area of the thin IMC layer of less than about 1 micron on the border of nuggets. Thus, it is considered that these change in thickness distribution of the IMC layer caused the decrease in joint strength. Fig.9 shows the composition-depth profiles across the IMC layer analyzed by SIMS. From these profiles, silicon was enriched at the steel/aluminum interfaces in either case. Fig.10 shows the HAADF-STEM images of the IMC layer. Silicon was mainly concentrated into the Al_5Fe_2 phases on the steel side, resulting in a decrease in

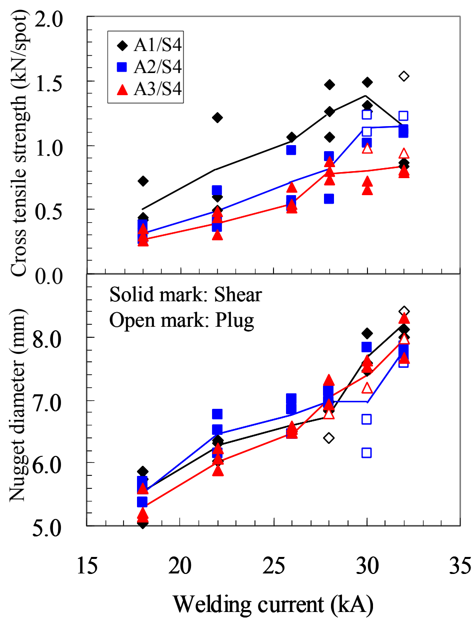

Fig. 6 Variation in the cross tensile strength and nugget diameter with the welding current.

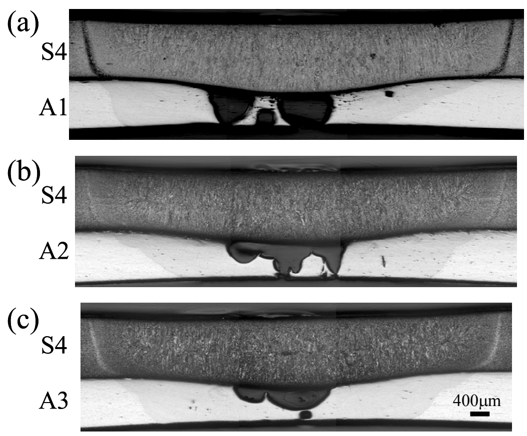

Fig. 7 Macro structures of spot welds (28kA, 40ms): (a) A1/S4, (b) A2/S4, and (c) A3/S4.

thickness of the IMC layer by thinning the Al_5Fe_2 layer, which were the same effects as in the case of silicon in steels. The Al_3Fe layer on the aluminum alloy side, on the other hand, contained little silicon even in the case of high silicon content aluminum alloys. It is reported that a relatively ductile Al-Fe-Si phase was formed instead of a brittle Al_3Fe phase at the aluminum alloy side for dissimilar joints of steels with aluminum alloys including 1 mass% Si or more by diffusion bonding process, resulting in improving the joint strength [2, 12]. However, in the present study, any Al-Fe-Si layer was not detected on the interfacial regions, except for α-AlFeSi ($Al_{8.3}Fe_2Si$) phase distributed in the aluminum matrix, which was considered to have no effect on the joint strength. The reason for the differences in the kinds of IMC phases between these two processes was interpreted from the viewpoint of the temperature dependence of phase stability. Fig.11 shows the equilibrium phase distribution as a function of temperature for the composition of Al-17.6at%Fe-8.8at%Si, which corresponds to the composition of $Al_{8.3}Fe_2Si$, calculated by Thermo-Calc software. The $Al_{8.3}Fe_2Si$ phase is predominantly formed at lower temperatures of the only solid phase region where diffusion bonding process is operated, whereas the Al_3Fe phase develops at higher temperatures of solid/liquid two-phase region where it certainly reaches enough for the RSW process. Moreover, the thermal history of rapid heating and cooling for the RSW process would suppress the formation of the IMC

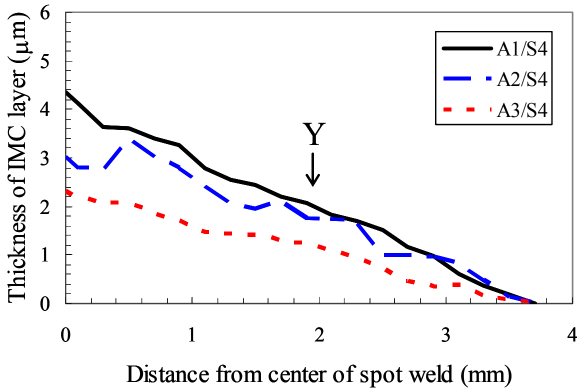

Fig. 8 Effects of Si contents in aluminum alloys on the thickness distribution of IMC layer (30kA, 40ms).

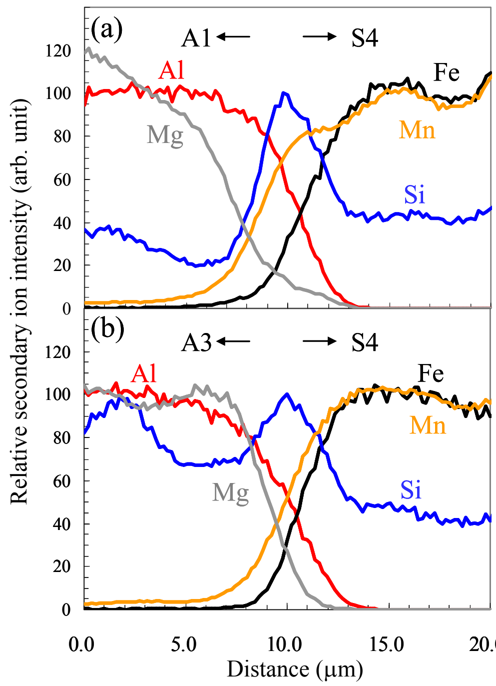

Fig. 9 Composition-depth profile analyzed by SIMS across the IMC layer at the position Y in Fig. 8: (a) A1/S4, (b) A3/S4.

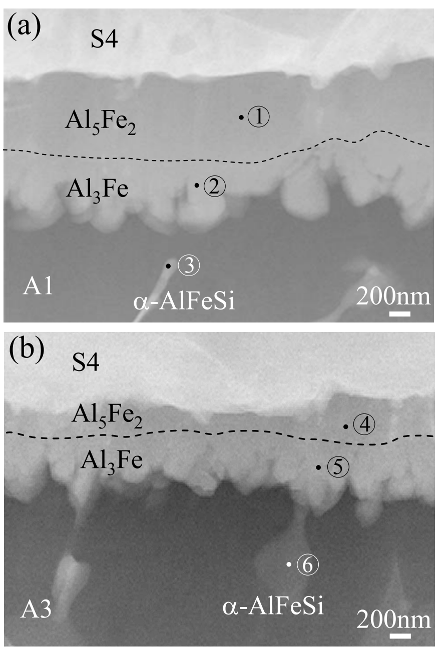

Fig. 10 HAADF-STEM images of IMC layer at the position Y in Fig. 8: (a) A1/S4, (b) A3/S4.

Table 5 EDX and diffraction pattern analysis of each selected point in Fig.10.

Joint designation	Point	Composition of detected element by EDX semi-quantitative analysis (at%)			Identified structure from diffraction pattern
		Al	Fe	Si	
A1/S4	①	71.4	27.3	1.3	Al_5Fe_2
	②	76.8	22.9	0.3	Al_3Fe
	③	81.2	13.6	5.2	α-AlFeSi ($Al_{8.3}Fe_2Si$)
A3/S4	④	71.4	26.8	1.8	Al_5Fe_2
	⑤	76.8	22.6	0.6	Al_3Fe
	⑥	80.7	13.4	5.9	α-AlFeSi ($Al_{8.3}Fe_2Si$)

phase at lower temperatures. These differences in temperature dependence of phase stability are supposed to hinder the formation of $Al_{8.3}Fe_2Si$ phase for the RSW process

Thus, the joint strength of Al-Mg-Si alloy sheets with cold rolled high tensile strength steel sheets by RSW process was proved to be dominantly influenced by the thickness distribution of the IMC layer, especially Al_5Fe_2 phases. Moreover, as the thickness distribution of the IMC layer was affected by silicon content in both materials, improvement of the joint strength to control the thickness of the IMC layer needs control of the silicon content in both materials synthetically, as well as the process conditions.

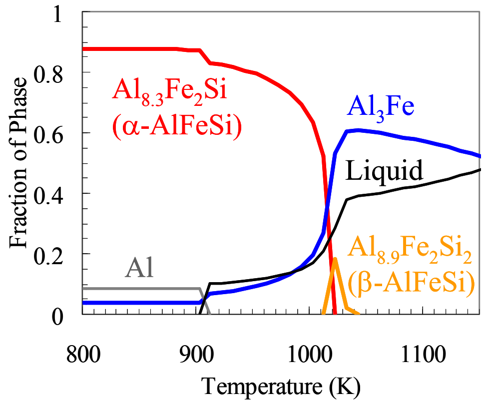

Fig. 11 Equilibrium phase distribution as a function of temperature for the composition of Al-17.6at%Fe-8.8at%Si calculated by Thermo-Calc software.

4. Summary

Effects of silicon alloying on joint properties of Al-Mg-Si alloy sheets with cold rolled high tensile strength steel sheets by the RSW process were investigated, focusing on the existing state of silicon in each material. The following results were obtained.

(1)The joint strength was improved by control of silicon contents in both materials as well as process conditions.

(2)Microstructural analysis revealed that the joint strength was dominantly influenced by the thickness distribution of the IMC layer at steel/aluminum alloy joint interface.

(3)Silicon played an important role on the formation behavior of the IMC layer, where silicon was enriched in solid solution or distributed as submicron oxides.

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