EFFECTS OF CARBON CONTENT ON INTERMETALLIC COMPOUND LAYER AND JOINT STRENGTH IN FRICTION WELDING OF Al ALLOY TO STEEL




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ABSTRACT

The microstructure and bond strength of the friction-welded interface of Al-Mg alloy A5052 to carbon steel S45C have been investigated, to establish their dependence on C content of steel by comparison with those observed in the joint of A5052 alloy to low C steel S10C. TEM observations revealed that an intermetallic compound layer 100 – 1 000 nm thick was formed at the interface, consisting of Fe_2Al_5 and $Fe_4Al_{13,}$ similar to that observed at the A5052/S10C interface. The thickness of the intermetallic compound layer was increased almost in proportion to friction time in both joints, while that of the A5052/S45C joint grew at a lower rate than that of the A5052/S10C joint. In the intermetallic compound layer, granular Fe_2Al_5 and Fe_4Al_{13} were distributed almost randomly, in contrast to those observed at the interface of the diffusion couple or diffusion-bonded joint, where intermetallic compounds formed as layers distributed in the order of their chemical compositions. This suggests that the formation of the intermetallic compound layer was significantly influenced by a factor other than the diffusion of Al and Fe. In the steel adjacent to the intermetallic compound layer, a very fine grain zone was observed, suggesting that the steel surface underwent heavy plastic deformation during the friction process. The thickness of the fine grain zone was also increased in proportion to friction time. It was found that the thickness of the intermetallic compound layer increased with that of the fine grain zone, obeying a relation almost independent of the C content of the steel and chemical composition of the Al alloy. These results suggest a significant contribution of mechanical intermingling of Fe with Al in the formation of the intermetallic compound layer. On tensile tests using specimens with a circumferential notch at the interface, the A5052/S45C joint was fractured at the interface region, showing higher fracture strengths than the A5052/S10C joint, probably because of the lesser thickness of the intermetallic compound layer.

IIW-Thesaurus keywords: *Aluminium alloys; Dissimilar materials; Friction welding; Intermetallics; Light metals; Reference lists; Steels.*

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Doc. IIW-1943-08 (ex-doc. IX-2290r1-08) recommended for publication by Commission IX “Behaviour of metals subjected to welding”.

1 INTRODUCTION

The solid state welding of Al Alloys to steels has attracted increasing attention, in order to meet the demands for the lightening of vehicles from an ecological point of view. As was indicated by Wallach and Elliot [1, 2], however, a serious reduction in the joint strength occurred when the thickness of the IMC (Intermetallic Compound) layer became greater than about 1 µm. They also suggested that the addition of Si into the Al alloy decreased the growth rate of the IMC layer, while the Mg addition increased the growth rate. Since then, many papers supporting their suggestion have been reported [3-12].

Table 1 – Chemical compositions of the base metals (mass%)

Materials	C	Si	Mn	Cu	P	S	Ni	Cr	Mg	Zn	Fe	Al
S10C	0.11	0.16	0.33	0.07	0.01	0.02	0.04	0.08	–	–	bal.	–
S45C	0.44	0.27	0.71	0.10	0.01	0.01	0.05	0.10	–	–	bal.	–
A5052	–	0.1	0.03	0.04	–	–	–	0.25	2.50	0.01	0.10	bal.

However, recent papers about the friction welding of high-strength Al alloys to steels reported cases where the joint exhibited premature fracture at the interface region, even when the thickness of the IMC layer was undetectable or less than 1 μm [8]. In order to explain the factor controlling the joint strength in these cases, we investigated the effect of the IMC layer on the notched tensile-strength of the joint in friction welding, as well as its growth kinetics, mainly by TEM (Transmission Electron Microscope) observations. Based on these observations, it was revealed that even when the IMC layer was 0.1–1 μm thick, the joint was fractured in the IMC layer and the tensile strength had decreased, with an increase in the thickness of the IMC layer [13]. We also suggested that the growth of the IMC layer was influenced significantly by the mechanical intermingling of Fe with Al alloy during the friction stage, with its growth rate reduced by the addition of Si into the Al alloy, similar to those observed in the diffusion-welded joint [14].

The present investigation has been aimed at revealing the effect of C content of steel on the IMC layer and the tensile strength of the friction-welded joint, since a recent paper about the diffusion welding of Al alloy to steel reported that the increase in C content of steel decreased the thickness of the IMC layer [15].

2 EXPERIMENTAL DETAILS

Round bars of carbon steel S45C, low carbon steel S10C and Al-Mg alloy A5052 were employed for the specimen to be welded. The chemical compositions of these steels and Al alloy are shown in Table 1. The specimen to be welded was a round bar of 19 mm diameter, with a protrusion of 25 mm in length and 16 mm in diameter. The end face of the protrusion was the faying surface, which was finished by machining with a lathe to 1.6 μmRa. The friction welding was carried out with a direct drive machine by pressing an unrotated Al alloy specimen against a rotated low carbon steel specimen. Welding parameters employed are listed in Table 2.

The microstructure of the bond interface was investigated mainly by TEM observations. Specimens for TEM observation were cut with a focused ion beam system from a position ~5 mm away from the centre axis of the joint. This position was selected because SEM observations at lower magnifications indicated that both the IMC layer and fracture morphology of the joint observed at this position dominated almost the whole area of the bond interface.

3 EXPERIMENTAL RESULTS AND DISCUSSION

A typical IMC layer observed in a joint of the A5052 Al alloy to the steel S45C(A5052/S45C) is shown in Figures 1 a), 1 b) and 1 c). As can be seen in these Figures, intermetallic compounds Fe_2Al_5 and Fe_4Al_{13} were formed in the S45C/A5052 joint. Although the thickness of the IMC layer increased with friction pressure and time, the IMCs observed in the layer were identified as Fe_2Al_5 and Fe_4Al_{13}, as shown in Figure 2. Unlike those observed in the diffusion couple of the Al alloy to the steel and the diffusion-bonded joint, none of these IMCs formed a layer lying in the order of the Al/Fe content ratio from the Al alloy to the steel side. However, there were granular particles distributed almost randomly within the IMC layer. In Figure 3, the thickness of the IMC layer (an average of 100 measurements taken at intervals of 100 nm) is plotted against friction time [14]. The thickness of the IMC layer increased almost in proportion to friction time at a rate depending on the friction pressure, but it did not obey the parabolic law believed to be valid when the growth of the IMC layer is controlled by diffusion. Compared with those observed in the friction-welded joint of low carbon steel S10C to A5052 alloy, the growth rates of the IMC layer decreased in the S45C/A5052 joint.

The physical meaning of the relation shown in Figure 3 is rather obscure, because the thickness of the IMC layer was scattered quite widely (± 30 % of the thickness) and the interfacial region was not necessarily maintained at a constant temperature during the friction pressure. The increase in the thickness of the IMC layer with friction pressure, however, suggests that mechanical factors (such as stress and strain applied to the interfacial region) play an important role as controlling factors of the IMC layer growth, since an increase in friction pressure does not bring about a significant rise in temperature at the interface, as suggested by Shinoda *et al*. [12]. The random distribution and granular morphologies of the IMCs (see Figures 1 and 2) also support the conclusion that mechanical factors make significant contributions to the formation of these intermetallic compounds.

Table 2 – Welding parameters employed

Rotation speed, N (s^{-1})	20		
Friction pressure, P_1 (MPa)	20	40	20
Friction time, t_1 (s)	1-5	0-5	5
Forge pressure, P_2 (MPa)	230		0
Forge time, t_2 (s)	6		

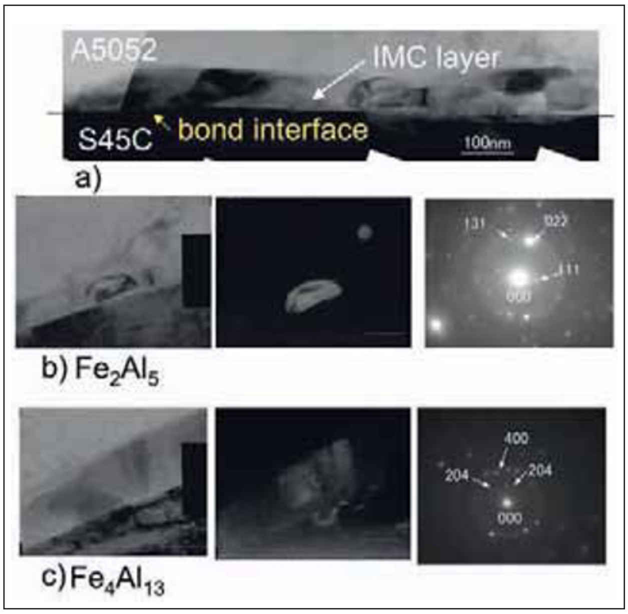

Figure 1 – TEM micrographs of an A5052/S45C joint interface (P_1 = 20 MPa, t_1 = 1 s)
a) IMC layer
b) B.F. (Bright Field) image, D.F. (Dark Field) image and SAD (Selected Area Diffraction) pattern of Fe_2Al_5
c) those of Fe_4Al_{13}.

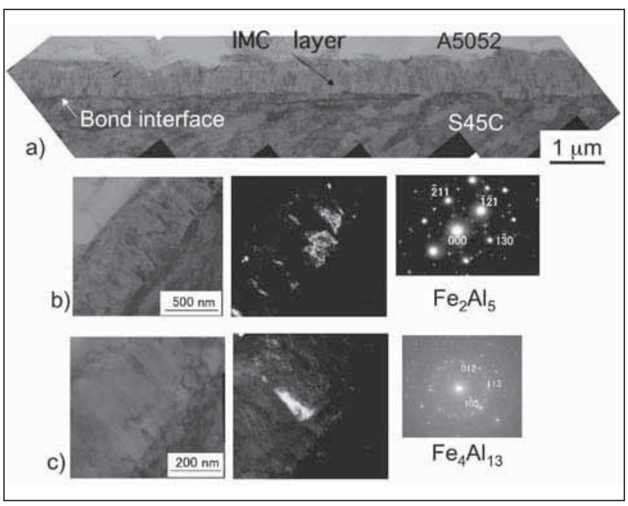

Figure 2 – TEM micrographs of an A5052/S45C joint interface (P_1 = 40 MPa, t_1 = 3.5 s)
a) IMC layer
b) B.F. image, D.F. image and SAD pattern of Fe_2Al_5
c) those of Fe_4Al_{13}

In relation to the effect of the mechanical factor, it should be noted that the steel substrate adjacent to the bond interface seems to be heavily deformed, as suggested by the cementite lamellae that were bent and became indiscernible in closer proximity to the interface (see Figure 4). TEM micrographs shown in Figure 5 indicate that a fine grain zone of 500~1 000 nm thickness was formed in the steel substrate adjacent to the IMC layer and its thickness increased with friction time and pressure. SAD patterns and dark field images indicated that this zone consisted of α-Fe grains a few 100 nm in size.

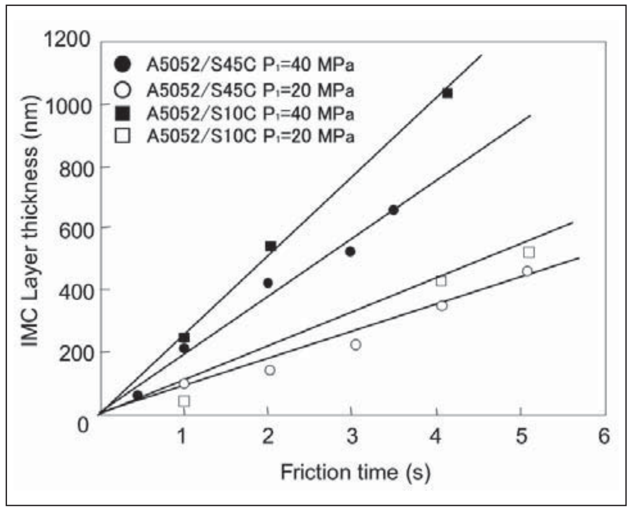

Figure 3 – Thickness of the IMC layer vs. friction time

EDX analyses did not detect any significant amount of Al from this zone, suggesting that the alloying with Al did not make any contribution to the formation of the fine grain zone.

It is also inconceivable that the grain-refining effect of α↔γ transformation of the steel contributed to the formation of the fine grain zone, since the transformation temperatures of A_1 and A_3 points are much higher than the melting points of the Al alloys. Consequently, it can be concluded that the fine grain zone was formed as a result of heavy plastic deformation during the friction welding. Since its thickness increased with friction time and friction pressure (see Figure 5), the heavy plastic deformation can be considered to have occurred during the friction process.

Though the mechanism causing such heavy plastic deformation in the steel surface region cannot be fully explained, as shown in Figure 6 [14], the thickness of the IMC layer increased with the thickness of the fine grain zone, obeying a relation that was almost independent of welding parameters, the C content of the steel

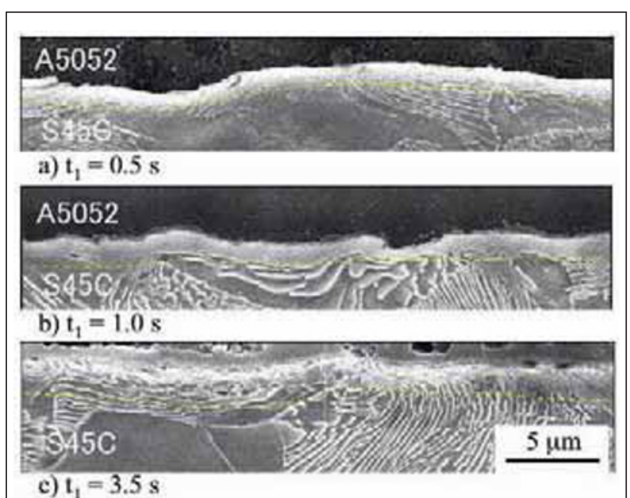

Figure 4 – SEM micrographs of steel microstructures next to the IMC layers (P_1 = 40 MPa)

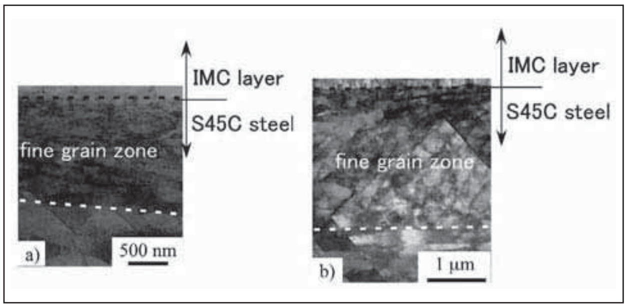

Figure 5 – TEM micrographs of fine grain zones observed in steel substrates next to the IMC layers: a) t_1 = 1.0 s and b) t_1 = 3.5 s

and the kind of Al alloy. This suggests that the growth of the IMC layer was in close relation with that of the fine grain zone, *viz.*, the plastic deformation undergone by the steel surface. Therefore, the lower growth rate of the IMC layer observed in the S45C/A5052 joint can be explained as a result of the smaller amount of plastic deformation of the steel surface region, perhaps owing to the increased hardness due to the higher C content. It seems that the strong shear force that could bring about such heavy plastic deformation produces small fragments from the steel surface, which are incorporated into the Al alloy through the complicated materials flow during the friction stage, forming the intermetallic compounds.

The tensile strength of S45C/A5052 joints and S10C/A5052 joints increased with friction time and reached maximum values at friction times, depending on the friction pressure and the C content of steels as shown in Figure 7 [13]. The further increase in friction time, however, brought about the decrease in the joint strength, presumably due to the growth of the IMC layers as suggested in a previous paper [13]. The S45C/A5052 joint exhibited higher tensile strength than the S10C/A5052, at longer friction times than those required to obtain maximum strength. The lower growth rate of the

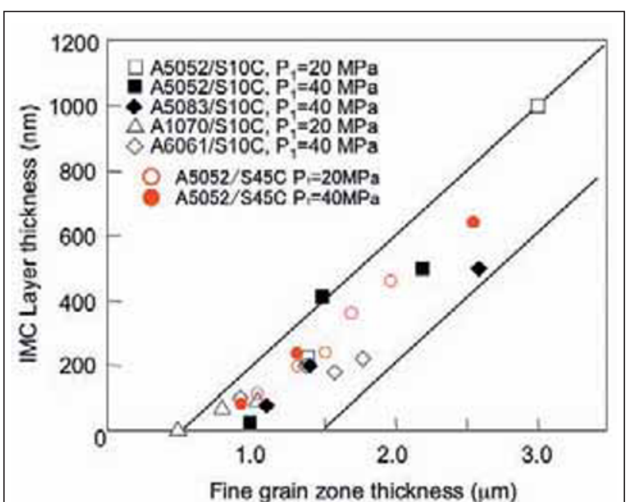

Figure 6 – Thickness of the IMC layer vs. thickness of the fine grain zone in steel substrate next to the IMC layers observed in joints of various Al alloys to steel S10C and steel S45C

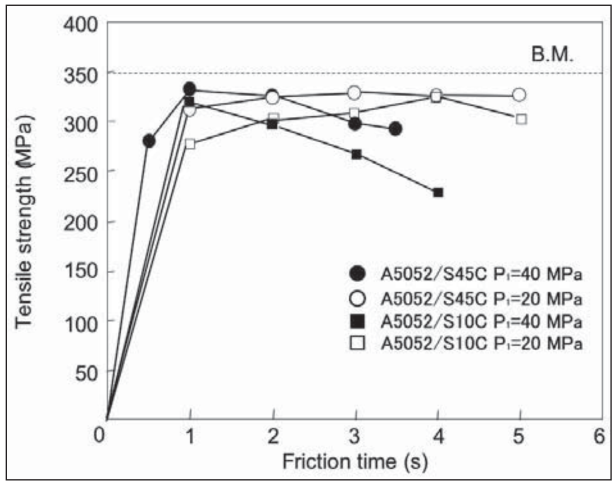

Figure 7 – Tensile strength of A5052/S45C and A5052/S10C joints vs. friction time

IMC layer in the S45C/A5052 joint probably accounts for this difference in the joint strength. Similarly, the effects of the friction pressure on the joint strength at longer friction times can also be explained as resulting from the enhancement of the growth rate of the IMC layer with the increase of the friction pressure.

4 CONCLUSIONS

The effects of the C content of the steel on the growth of the intermetallic compound layer and tensile strength of the friction-welded joint of Al alloy to steel have been investigated, by comparing those observed in the A5052/S45C joint with those in the A5052/S10C joint. Results obtained can be summarized as follows:

1) TEM observations revealed that an intermetallic compound layer 100–1 000 nm thick was formed at the interface in the A5052/S45C joint and it consisted of Fe_2Al_5 and Fe_4Al_{13}, similar to those observed at the A5052/S10C interface.

2) The thickness of the intermetallic compound layer was increased almost in proportion to friction time in both joints, while that of the A5052/S45C joint grew at a lower rate than that of the A5052/S10C joint. In the intermetallic compound layer, granular Fe_2Al_5 and Fe_4Al_{13} were distributed almost randomly.

3) In the steel adjacent to the intermetallic compound layer, a very fine grain zone was observed, suggesting that the steel surface had undergone heavy plastic deformation during the friction process. The thickness of the fine grain zone had also increased in proportion to friction time. It was found that the thickness of the intermetallic compound layer had increased like that of the fine grain zone, obeying a relation almost independent of the C content of the steel and chemical composition of the Al alloy.

4) On tensile tests using specimens with a circumferential notch at the interface, the A5052/S45C joint was fractured at the interface region, showing higher

fracture strengths than the A5052/S10C joint, probably because of the lesser thickness of the intermetallic compound layer.

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