Effects of Alloying Elements on the Strength of Friction-bonded Interfaces of Al Alloys to Steel†

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Abstract

The microstructures of the friction-bonded interfaces of mild steel S10C to Al alloys, 5052, 5083 and 6061 have been investigated in nano-scale mainly by TEM observations to explain the effect of the alloying element in the Al alloy on the bond strength of the interface. The bond strength was significantly influenced by the alloying elements; the 5052/S10C joint showed the highest strength, followed by the 6061/S10C joint and 5083/S10C joint. At the interface of the 5052/S10C joint, intermetallic compound(IMC) layers ~1 μm thick that consisted of $FeAl_2$ and Fe_2Al_5 were formed. At the interface of the 5083/S10C joint, the IMC layers observed were 200 nm thick in total, and consisted of Fe_4Al_{13} and $(Fe,Mn)Al_6$. In addition, a layer of $MgSiO_3$ ~50 nm thick was formed between the $(Fe,Mn)Al_6$ layer and the 5083 alloy matrix. At the interface of the 6061/S10C joint, IMC layers ~400 nm thick that consisted of $(Fe,Cr)_4Si_4Al_{13}$, $FeAl_2$ and Fe_4Al_{13} were formed. It is thought that the bond strength of the joints reflected these differences in IMC layers.

KEYWORDS (friction bonding)(dissimilar metal joint)(Al-Mg alloy)(TEM observation)(intermetallic compound)(Oxide layer)

1. Introduction

It is known that IMC(Intermetallic Compound) layers are formed as reaction products during the joining of Al alloy to steel, which in many cases have serious influences on the mechanical properties of the joint obtained. In particular, the conventional fusion welding process is inevitably associated with the formation of abundant IMC layers in the fusion zone, and so has been considered to be unsuitable for the Al alloy/steel joint. On the other hand, friction bonding, a kind of solid-state bonding, can control the formation of the IMC at the joint interface by selecting suitable bonding parameters[1)~5)]. It has been reported by several authors that the joint performance of the Al alloy/steel joint obtained by the friction bonding depends significantly on the chemical composition of the Al alloy[) 6), 7)]. Only limited information, however, has been reported regarding the microstructure in the interfacial region of the friction-bonded joint because of the difficulty in observing it. Therefore, we aimed this investigation at revealing the interfacial microstructure at the nano-scale to obtain a deeper insight into the effects of the alloying element of Al alloys on the bond strength.

2. Experimental Procedure

Round bars of mild steel JIS S10C, Al-Mg series 5052 alloy, Al-Mg series 5083 alloy, and Al-Mg-Si series 6061 alloy were employed for the specimen to be bonded. Their chemical compositions are shown in **Tables 1 and 2**. The dimensions of the specimen are

Table 1 Chemical composition of the S10C steel (mass%).

Material	C	Si	Mn	Cu	P	S	Ni	Cr	Fe
S10C	0.11	0.16	0.33	0.07	0.01	0.02	0.04	0.08	bal.

Table 2 Chemical compositions of the 5052, 5083 and 6061 aluminum alloys (mass%).

Material	Si	Mn	Cu	Cr	Mg	Zn	Ti	Fe	Al
5052	0.07	0.01	0.01	0.26	2.60	0.01	-	0.21	bal.
5083	0.22	0.60	0.07	0.11	4.70	0.01	-	0.13	bal.
6061	0.50	-	0.32	0.06	1.00	0.01	0.01	0.23	bal.

Table 3 Bonding parameters.

P_1(MPa)	t_1(s)	P_2(MPa)	t_2(s)	N(S^{-1})
20	5	250	6	20

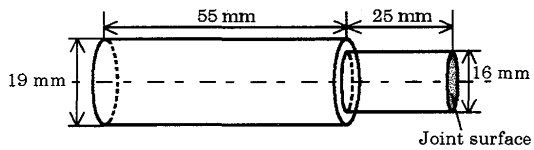

Fig. 1 Dimensions of a specimen.

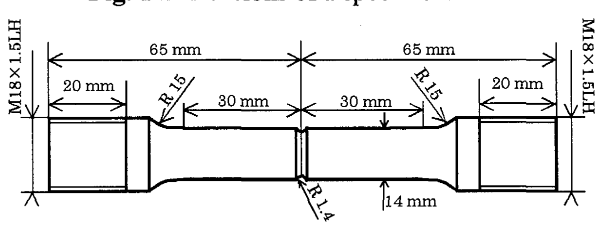

Fig. 2 Dimensions of tensile test-piece.

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illustrated in **Fig. 1**. The faying surface was finished by machining. The friction bonding has been carried out with a direct drive machine by pressing a rotated Al alloy specimen against a stational specimen of S10C steel. Bonding parameters employed are shown in **Table 3**. These parameters were determined through preliminary experiments so that joint performance comparative to the Al alloy base metal was obtained for the 5052 alloy/S10C steel joint. The bond strength of the joint interfaces was estimated from tensile strength of a specimen with a notch at the interface as shown in **Fig. 2**. The microstructure around the bond interface was investigated by TEM observations.

3. Results and Discussion

Results from the tensile test are shown in **Fig. 3**. Five specimens were tested for each combination. All the tested specimens were fractured near the joint interface. The maximal, minimal and average values of the joint efficiency((the joint tensile strength) / (the tensile strength of the notched specimen of the Al alloys)) are indicated in Fig. 3. The average joint efficiency of 5052/S10C joints was slightly higher than that for the 6061/S10C, while that of 5083/S10C joints presented much lower strengths. The joint efficiency of the 5052/S10C joints showed a much smaller dispersion than those of the others.

In **Fig. 4** are shown the axial hardness distributions for the joints. For all the joints, a softened heat-affected-zone was observed in the Al alloy adjacent to the bond interface. These decreases in the hardness of the Al alloys can be attributed to the solution of precipitates and/or over-aging caused by the thermal cycle during the bonding [8]. The hardness of the heat-affected-zone of the 5083/S10C joint was higher than those of the other joints, although it showed the lowest bond strength. This suggests that the controlling factor of the joint efficiency was not the hardness of the heat-affected zone of the Al alloy, but the microstructure closer to the interface. In order to investigate this controlling factor, the fractured surface of the joint subjected to the tensile test was observed. In **Fig. 5** are shown the appearances of the fractured surfaces of all the joints. The fractured surfaces of the 5052/S10C and 6061/S10C joints can be divided into

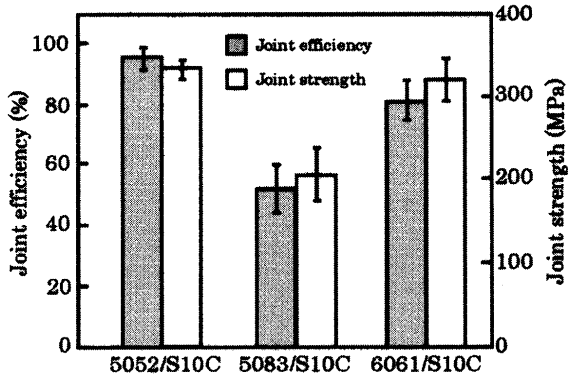

Fig. 3 Joint efficiency and joint strength of the friction bonding of S10C to various Al alloys.

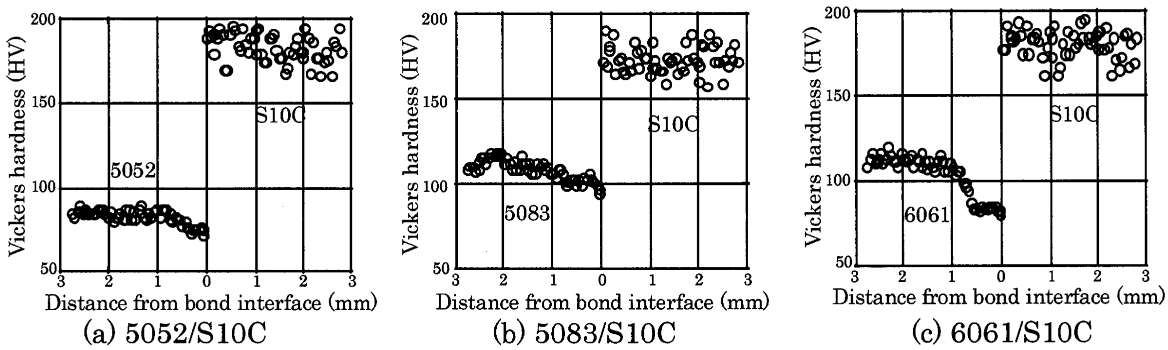

Fig. 4 Vickers hardness distribution in cross section of 5052/S10C joint(a), 5083/S10C joint (b) and 6061/S10C joint (c).

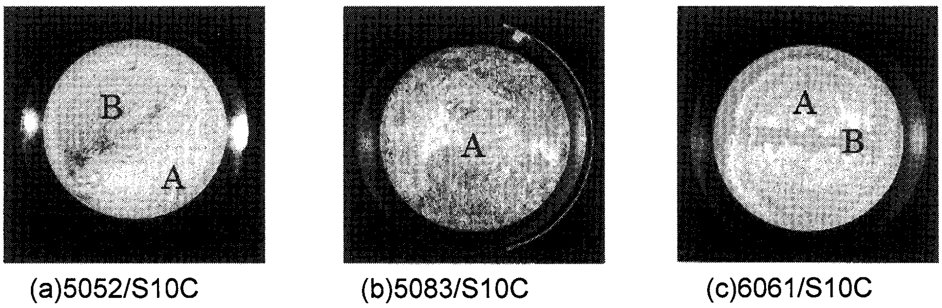

Fig. 5 Fractured surfaces of the steel side of the friction-bonded joints after the tensile test. Flat areas are indicated by letters 'A' and ductile areas 'B'.

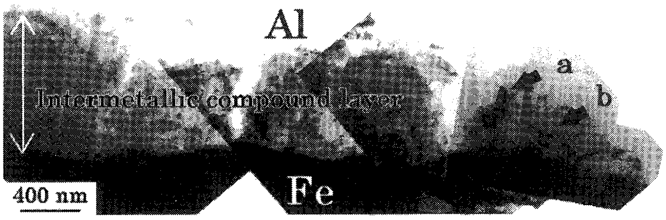

Fig. 6 Reaction layer at the bond interface in the 5052/S10C joint.

two characteristic areas: rather flat and smooth areas where the crack propagated along a path close to the bond interface, and ductile areas where the crack path deviated into the Al alloy, probably into the heat-affected zone. On the other hand, only flat and smooth areas were observed on the fractured surface of the 5083/S10C joint. These results also support the view that the properties of the interfacial region are responsible for the lower joint efficiency of 5083/S10C joint than the 5052/S10C and 6061/S10C joints.

Therefore, closer observations by transmission electron microscopy have been carried out for the interfacial regions. As is shown in **Fig. 6**, polycrystalline layers 500-1000 nm thick were observed between the 5052 alloy and S10C steel. The intermetallic compounds formed in 'a' and 'b' layers shown in Fig. 6 were identified as Fe_2Al_5 and $FeAl_2$ on the basis of SAD patterns and EDS analyses, respectively. The bond interface of the 5083/S10C joint was also observed with a TEM. As is shown in **Fig. 7**, a continuous layer of intermetallic compounds was observed. The thickness of this layer was 200~250 nm. It consisted of three layers. The intermetallic compounds formed in 'a', 'b' and 'c' layers shown in Fig. 7 were identified as Fe_4Al_{13}, $(Fe,Mn)Al_6$ and $MgSiO_3$, respectively. A TEM micrograph of the bond interface of the 6061/S10C joint is shown in **Fig. 8**. A continuous layer of an intermetallic compound was observed. Its thickness was ~400 nm. The intermetallic compounds formed in this layer shown in Fig. 8 was identified as $(Fe,Cr)_4Si_4Al_{13}$. In this joint, granular IMC were also. They were identified respectively as Fe_4Al_{13} and $FeAl_2$.

Thus intermetallic compounds formed at the bond interface were strongly influenced by the alloying elements of the Al alloy. Therefore, it can be concluded that this difference in the intermetallic compounds at the bond interface was responsible for the effect of the alloying elements on the bond strength of the joint interface.

4. Concluions

The nano-scale microstructures of the friction-bonded interfaces of a mild steel S10C to Al alloys, 5052, 5083 and 6061 have been investigated mainly by TEM observation to discuss the effect of the alloying element of the Al alloy on the bond strength. The results obtained can be summarized as follows:

(1) The bond strength estimated from tensile strength of a specimen with a circumferential notch at the interface depended significantly on the chemical composition; the 5052/S10C joint showed a tensile strength comparable to the 5052 base metal, the 6061/S10C joint ~80%

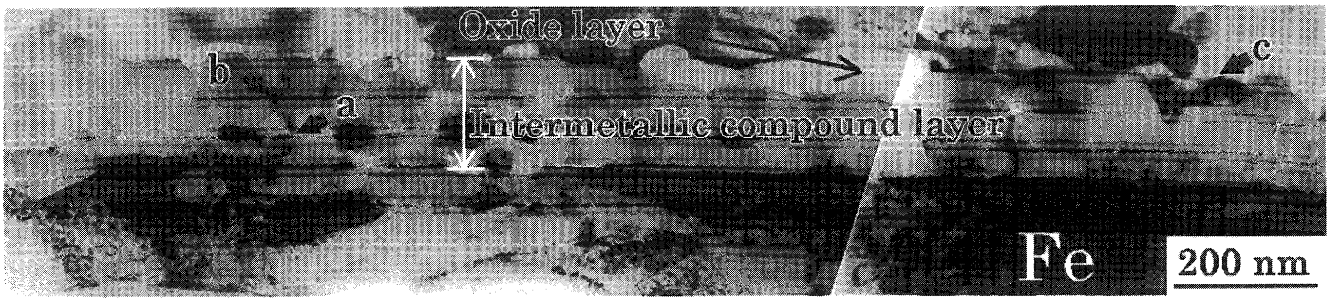

Fig. 7 Reaction layer at the bond interface in the 5083/S10C joint.

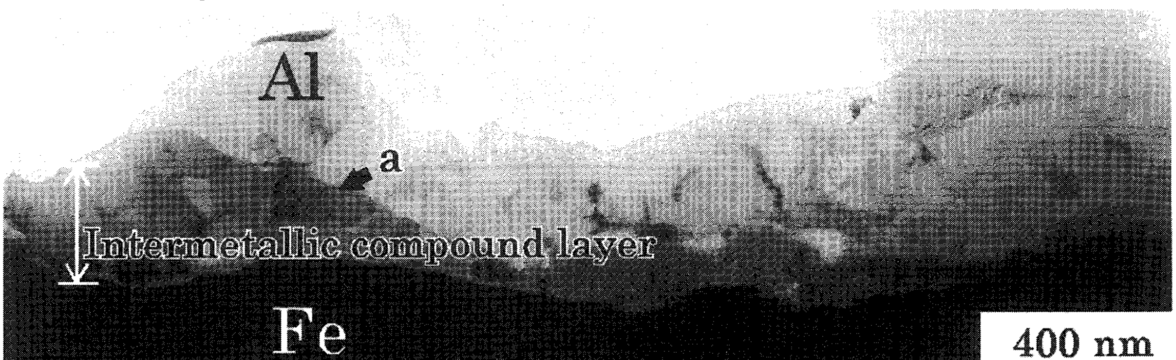

Fig. 8 Reaction layer at the bond interface in the 6061/S10C joint.

tensile strength of the 6061 base metal, and the 5083/S10C joint only ~50% tensile strength of the 5083 base metal.

(2) All the joints tested in this investigation were fractured mainly at the interface of the tensile test. Areas where fracture occurred at the Al alloys were also observed with their fraction depending on the Al alloy.

(3) Layers of intermetallic compounds, $FeAl_2$ and Fe_2Al_5, were found at the bond interface in the 5052/S10C joint. Layers of intermetallic compounds of $(Fe,Mn)Al_6$ and Fe_4Al_{13}, and oxide of $MgSiO_3$ were found at the bond interface in the 5083/S10C joint. Layers of intermetallic compounds, $(Fe,Cr)_4Si_4Al_{13}$, $FeAl_2$ and Fe_4Al_{13}, were found at the bond interface in the 6061/S10C joint.

(4) It can be considered that the effects of the alloying elements on the joint efficiency mentioned in (1) are caused by the difference in the intermetallic compound layer formed at the interface.

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