Friction welding of Al-Mg-Si alloy to Ni-Cr-Mo low alloy steel

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ABSTRACT

It is difficult to weld the dissimilar material combinations of aluminium alloys and low alloy steels on account of the formation of brittle interlayer composed with intermetallic compound phases and the wide difference in physical and mechanical properties by fusion welding processes. This study has been carrying out to join them by friction welding method, i.e. one of solid phase joining processes. Especially, this paper will describe the optimization of friction welding parameters so that the intermetallic layer is narrow and the joints of acceptable quality can be produced for the dissimilar joint between Al-Mg-Si alloy (AA6061) and Ni-Cr-Mo low alloy steel by using a design of experiment method. Then, the effect of post-weld heat treatment on the tensile strength of the joints was clarified. As a conclusion, the friction time strongly affects the joint tensile strength, and the strength rapidly decreased with increasing the friction time. The highest one could be achieved with the shortest friction time. The highest joint strength was more than that of AA6061 substrate in as-welded condition. This is due to narrow width of the brittle intermetallic layer that generated from the periphery (outer surface) region to the centerline region of the joint with increasing friction time. The joints in as-welded condition could be bent with no crack by bend test. The joint tensile strength in as-welded condition was increased by heat treatment at 423K (150°C), and then it decreased when the heating temperature exceeded 423K. All joints fractured at AA6061 substrates adjacent to the interface except the joints heated at 773K (500°C). The joints fractured at the interface because of the occurrence of brittle intermetallic compound phase.

INTRODUCTION

Generally speaking, there are several severe problems in dissimilar welding operations [1,2]. One of them occurs in the combinations of ferrous and non-ferrous metals, e.g. steel and aluminium. The dissimilar material combination of aluminium alloy and low alloy steel is difficult to weld on account of the formation of brittle interlayer composed with intermetallic compound phases (hereafter called as IMC) at the joint interface (bondline) and the wide difference in physical and mechanical properties by using fusion welding processes. The layer gives the joints detrimental effects, i.e. decreasing joint tensile strength and toughness, etc. Therefore, the solid phase joining process is usually used for the dissimilar joining in order to reduce the formation of IMC. Friction welding method, one of the solid phase joining processes, offers a viable solution to these problems by virtue of its low and controlled energy input and rapid thermal cycle. That is, the friction welding process can minimize the layer generation [3,4]. Even though using friction welding method it is very difficult to join aluminium alloys and low alloy steels. The performances of the joints are strongly depended on the friction welding parameters.

There were a lot of researches for friction welding of dissimilar joints to the material combinations of pure aluminium/austenitic stainless steel, aluminium alloy/austenitic stainless steel, aluminium alloy/carbon steel, aluminium alloy/pure titanium, etc [5-19]. However, there are very few studies for the material combinations of aluminium alloy and high strength low alloy steels such as Ni-Cr-Mo low alloy steel, e.g. AISI 4340. This combination of the joint will be expected the increase of applications in industrial usages, that is automobile or transportation fields to decrease their mass in order to save energy.

This paper reports the work done to optimize friction welding parameters so that the interlayer is narrow and joints of high joint tensile strength can be produced for Al-Mg-Si alloy (AA6061) to Ni-Cr-Mo low alloy steel dissimilar joint by using a design of experiment method. According to a preliminary study, it could be predicted that friction pressure and friction time strongly affect the joint strength because of producing IMC at the interface of joints during friction welding operation. Therefore, the effects of both factors on the joint tensile strength have been especially clarified. This paper also described the effect of post-weld heat treatment (PWHT) on the joint tensile strength.

EXPERIMENTAL PROCEDURE

Materials used

Commercially Al-Mg-Si alloy (hereafter called as AA6061) and Ni-Cr-Mo low alloy steel (LAS) of 16mm diameter round bar were used throughout this experiment. The AA6061 bar contained 1.21%Mg, 0.72%Si, 0.37%Cu balance Al in mass% (wt.%) was heat treated as T-6 condition by solution-treated at 803K (530^{o}C) for 7.2ks (2H) and age-strengthened at 448K (175^{o}C) for 28.8ks (8H). The ultimate tensile strength of A6061 was 305MPa (31.1kgf/mm^2) and the elongation was 19.4%. The LAS, equivalent to AISI 4340, had the chemical compositions of 0.37%C, 0.64%Mn, 1.64%Ni, 0.62%Cr, 0.16%Mo balance Fe, and was oil-quenched after heating at 1123K (850^{o}C) for 7.2ks (2H) and tempered after heating at 903K (630^{o}C) for 7.2ks (2H). The ultimate tensile strength of LSA was

1040MPa (106kgf/mm^2) and the elongation was 19.5%. All joints were welded with 13mm diameter at the faying surfaces (joining surfaces).

Optimization of friction welding parameters by a design of experiment method (the first experiment)

As the first step, the author produced AA6061/LAS friction joints by using a design of experiment in order to clarify the effect of friction welding parameters, especially, friction pressure and friction time on joint tensile strength (hereafter called as strength). As an intermediate layer is generated during friction stage, friction pressure and time can be thought as important parameter. In this experiment, three levels of each parameter were used in order to clarify the effect of the parameters on the result. Therefore, the orthogonal array table of $L_9\,(3^4)$ was used, and it is shown in Table 1. The friction pressures were 150, 215 and 280MPa, and the friction time were 0.3, 1 and 2s. The friction pressure was arrayed in the first line (No.1), and the friction time was in the second line (No.2), respectively. The factor of "interaction" was arrayed in the third line (No.3), and the experimental error was in the fourth line (No.4), respectively.

The actual friction welding parameters are listed in Table 2. During friction welding operation, upsetting pressure was same as the friction pressure for each welding to eliminate its effect on the strength. Rotational speed and upsetting time were maintained constant at 25s^{-1} (1500rpm) and 6s, respectively. Prior to joining, all contacting surfaces of both substrates were polished with a buff to minimize the effect of surface contamination on the strength. A brake type friction welding machine was used for joining throughout this experiment. All joints in as-welded condition were machined to 12.5mm in diameter and 50mm in parallel length for joint tensile test. The tensile test was carried out at room temperature. After tensile test, fractured surfaces were also observed by scanning electron microscopy (SEM) analysis.

Effect of friction time on joint tensile strength (the second experiment)

As the friction time had strongly affected the strengths from the result of the first experiment that will be discussed later, the effect of friction time on the strength was studied, precisely. The friction joints were produced with friction time from 0.1 to 2s. The upsetting pressures were 220 and 280MPa. The friction pressure, the rotational speed and the upsetting time were maintained constant of 220MPa, 25s-1 and 6s, respectively. All joints in as-welded condition were tensile tested by the same method described before. Some of the interfaces of the completed joints were examined using a combination of SEM analysis and micro-Vickers hardness test. After tensile test, fractured surfaces were also observed by SEM.

Bend test was carried out for the joints of which tensile strength were highest in the previous section. The bend radius was twice of specimen diameter, i.e. 25mm, and it was carried out at room temperature.

Effect of post-weld heat treatment on joint tensile strength

The joints that failed at the AA6061 base metal by tensile test in as-welded condition were post-weld heat treated (PWHT) from 423K (150^{o}C) to 773K (500^{o}C) for 36ks (10H). Succeeding to the PWHT, the joints were tensile tested.

RESULTS AND DISCUSSION

Optimization of friction welding parameters by a design of experiment method (the first experiment)

The tensile test result was listed in Table 2 (allocation table) described before. Figure 1 shows the relationship between friction time and the strength, and Fig.2 shows that between friction pressure and the strength. The strengths broadly varied from 62.5 to 253MPa. The strength decreased as increasing friction time regardless of friction pressure (Fig.1). However the strength was slightly changed when friction pressure increased regardless of friction time (Fig.2). The maximum strength was achieved at the shortest friction time of 0.3s.

Table 3 shows the analysis of the variance as for the strength by a design of experiment. The symbols in Table 3 means that S is sum of square, ϕ is degree of freedom, V is variance and F_0 is ratio of variance. The symbol "**" in the column of F_0 means that the level of significance is more than 99%. It was clarified that the friction time was the most effective parameter on the strength, and the level of significance was more than 99%. However, the friction pressure was not significance in this experiment.

Figure 3 shows the relationship among friction time, tensile strength and appearances of fractured surfaces for the result by a design of experiment. It was clarified that the white circle region on the fractured surface of LAS side in Fig.3 was Al element by SEM-EDS analysis. The area fraction of Al adhered regions decreased as increasing friction time, and it squeezed from the periphery portion to the centerline portion. On the other hand, little Fe could be detected on the fractured surface of AA6061 side. The white region on AA6061 side is the area of ductile fracture showing dimple pattern. That is, the joint with high strength has large Al adhered region and dimple pattern area.

Figure 4 shows the relationship between area fractions of Al adhered on fractured surfaces of LAS side and the rate of the (joint tensile) strength to the tensile strength of AA6061 substrate. The rate increased when the area fraction of Al adhered on LAS side. The area fraction of Al could be divided into two at the friction time of 0.5s. That is, it is more than 70% when the friction time was less than 0.5s. This result indicated that short friction time increases the strength.

Effect of friction time on joint tensile strength (the second experiment)

The effect of friction time on the strength is shown in Fig.5. The strength decreased as increasing the friction time. It drastically decreased when the friction time increased from 0.1 to 0.7s. The strength was almost saturated when the friction time exceeded 1s. The upsetting pressure hardly affected the strength. In Fig.5, the joints that were joined with the friction time of 0.1s and the upsetting pressure of 280MPa fractured at the AA6061 substrate. This means the joint efficiency is more than 100%.

Figure 6 shows the distribution of Al content on fractured surface of LAS side along radial direction of the joints welded with the friction times of (a) 0.3s and (b) 2s. The aluminium adhered region of the joints decreased with decreasing of friction time. The area also decreased from the periphery region to centerline region. The region with high strength, that is, friction time of 0.1s as shown in Fig.6(a), was larger than that with low tensile strength, i.e. 2s (Fig.6(b)). This results proved that short friction time promoted the joint strength of the interface.

The hardness distributions across the interface at the periphery position of the joints welded with friction time of 0.1, 1 and 2s are shown in Fig.7. There was a little scattering among the friction times of 0.1, 1 and 2s. However, the distributions were not so different among them. It is worth note that the harnesses of the AA6061 region adjacent to the interface were approximately 50HV lower than those of AA6061 substrates. This is due to heat cycle during friction welding operation.

Figure 8 shows the distributions of Fe, Al and Si contents by SEM-EDS analysis across interface at (a) the centerline portion and (b) the periphery portion of the joint welded with the friction time of 2s. No plateau region could be observed at the interface of the centerline portion as shown in Fig.8(a). On the other hand, the sub- micron wide plateau region as in Fig.8(b) could be observed at the interface of the periphery portion, and Si was concentrated in front of the plateau region. This silicone concentration is same phenomena as the dissimilar friction joint between pure titanium and pure aluminium [17]. The plateau means IMC occurred at the interface during friction operation. The chemical compositions of the plateau region were composed with Fe-Al system, i.e. approximately 30mol%Fe and 70mol%Al. It was estimated that the plateau region was mainly composed with Fe_2Al_5 from binary phase diagrams [20]. The difference was due to the heat generation during friction operation.

The fracture appearance and distribution of Fe and Al elements on the fractured surface of low alloy steel side is shown in Fig.9. This joint was produced with friction time of 2s, i.e. the lowest strength joint. The fracture surface of low alloy steel side shows dimple patterns at the centerline portion, and aluminium was adhered on its surface. At the periphery portion, however, flat surface could be observed and little aluminium was adhered on the low alloy steel surface. These results indicated that the fracture occurred in the intermetallic compound phase at the periphery portion, and it propagated into aluminium, that is, AA6061 substrate. This result can be coincident with Fig.3.

Figure 10 shows the appearance of bend test specimens in as-welded condition after test. There was no crack observed at the interface regions including both substrates. That is, the joint has good ductility with it.

As a conclusion, short friction time is recommended to join aluminium alloy to low alloy steel by friction welding method in order to minimize the generation of Al-Fe binary intermetallic compound phase.

Effect of post-weld heat treatment on tensile strength of joints

Figure 11 shows the relationship between heating temperature of PWHT and joint tensile strength. The strength increased at 423K (150°C), and then it decreased when the heating temperature exceeded 423K. All joints except the 773K (500°C) heated joints fractured at AA6061 substrate adjacent to the interface. This reason can be thought as follows. AA6061 is precipitated hardening aluminium alloy of which the aging temperature is around 423K. Therefore, the PWHT of 423K increased the strength (hardness) of AA6061 substrate. On the other hand, the strength decreases as increasing of PWHT temperature over 423K because of overaging. Figure 11 also includes the hardness of AA6061 substrate heated at each temperature. The hardness of AA6061 heated after 423K-36ks (150°C-10H) was approximately HV100, and this hardness was higher than that of as-welded condition (as T-6 condition). The hardness descended to about HV40 when the joints heated at 673K for 36ks (400°C-10H) .

The joints heated at 773K (500°C) fractured at the interface immediately after PHWT. This reason can be thought as follows. Generally speaking, the strength of the interface decreases when as the width of intermediate layer (intermetallic compound phase) increases. By the way, thermal stress and plastic-elastic strain occur at the interface region during cooling stage from heating due to the much difference of thermal expansion coefficiency between both substrates for dissimilar weld joint during PWHT. Co-researcher and I reported the residual stress and plastic strain distributions at the interface of Al/Ti friction weld [21]. These phenomena also occur at the interface of A6061/low alloy steel joint. For example, the thermal expansion coefficiency of AA6061 is approximately 24x10-6

[1/K] and that of low alloy steel is 13x10-6 [1/K]. The interface region is stress relieved during heating stage. However, this much difference of thermal expansion coefficiency induces a large thermal stress, i.e. residual stress and plastic strain during cooling stage. Therefore, the wide intermediate layer at the interface region of the joint heated at 773K and a large residual stress induced the crack at the interface region.

Since the joints heated at 773K fractured immediately after PWHT, it could not be measured and analyzed the intermetallic compound phase. The phase width of the joints heated at 673K was approximately several microns. The chemical compositions were about (68-75)mol%Fe and (32-25)mol%Al, so that the phase could be estimated mainly Fe_2Al_5.

CONCLUSIONS

This paper described the effect of friction welding parameter on the joint tensile strength of Al-Mg-Si alloy (AA6061) and Ni-Cr-Mo low alloy steel dissimilar joint by using a design of experiment method, and the effect of post-weld heat treatment up to 773K (500^{o}C) on the joint and bend ductility of the joints. The following conclusions were reached.

(1) Friction time strongly affected the joint tensile strength, and the strength decreased as increasing friction time. The highest strength could be achieved at the shortest friction time. The strength was approximately equal to that of AA6061 substrate.

(2) Fe-Al binary intermetallic compound phase, mainly Fe_2Al_5, occurred from periphery side (outer surface) of joints to center axis portion when friction time increased. This intermetallic compound phase decreased the join tensile strength.

(3) The fracture during joint tensile test propagated from AA6061 side to the interface as increasing friction time of the joints in as-welded condition.

(4) The as-welded joint joined by the shortest friction time could be bent to 180degrees with no crack. That is, the joint has good ductility with it.

(5) The joints heated up to 673K (400^{o}C) after welding fractured at AA6061 substrate in joint tensile test. However, the joints heated at 773K (500^{o}C) fractured at the interface because of much intermetallic compound phase.

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Table 1 Orthogonal array table: L_9 (3^4).

Line / No.	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1
	a	b	ab	ab^2

Table 2 Allocation of friction welding condition by design of experiment and tensile test result.

Line	1	2	—
Condition / Test No.	Friction pressure, MPa	Friction time, s	Tensile strength, MPa
1-1, 1-2	150	0.3	247, 220
2-1, 2-2	150	1.0	125, 115
3-1, 3-2	150	2.0	135, 80.3
4-1, 4-2	215	0.3	253, 226
5-1, 5-2	215	1.0	149, 116
6-1, 6-2	215	2.0	141, 147
7-1, 7-2	280	0.3	245, 237
8-1, 8-2	280	1.0	173, 148
9-1, 9-2	280	2.0	62.5, 96.0

Other friction welding conditions;

* Rotating speed: 25s^{-1} (1500rpm)
* Upsetting pressure: same as each friction pressure
* Upsetting time: 6s

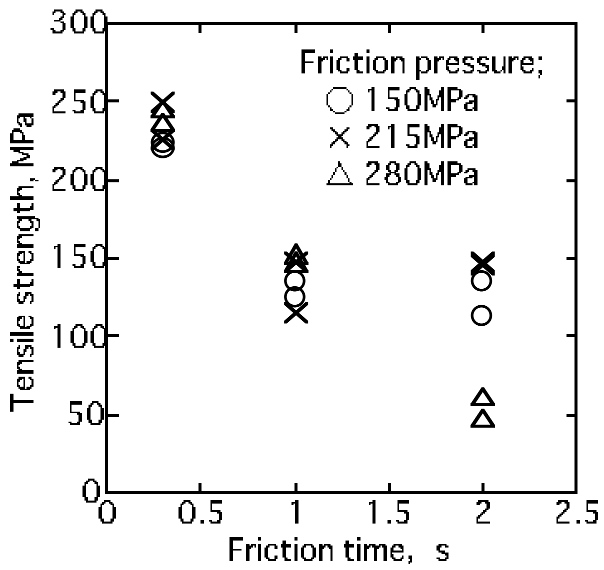


Fig.1 Relationship between friction time and tensile strength.

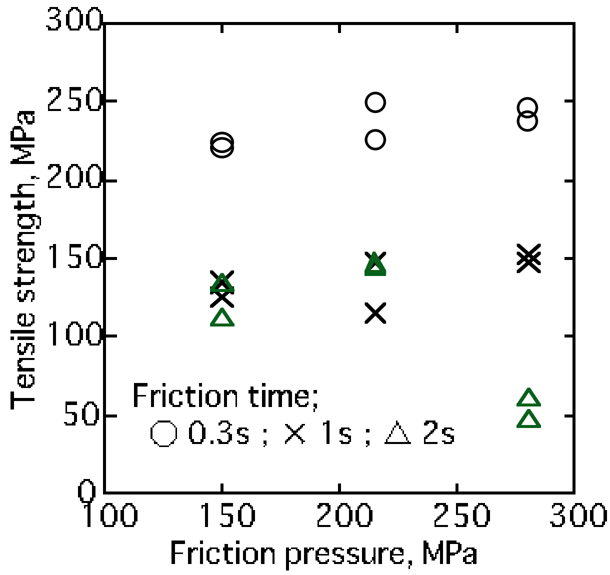


Fig.2 Relationship between friction pressure and tensile strength.

Table 3 Analysis of variance for joint tensile strength by design of experiment.

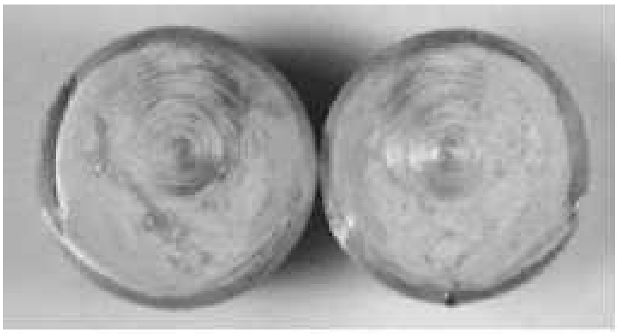
Factor	S	ϕ	V	F_0
Friction pressure [a]	14.93	2	7.46	2.02
Friction time [b]	502.64	2	251.32	68.1**
Interaction [a×b]	48.91	4	12.23	3.32
Error [*e*]	33.19	9	3.69	
Total	599.67	17		

Note:

(1) S: Sum of square; ϕ: degree of freedom;
V: Variance; F0: Ratio of variance

(2) F^2_9 (0.05) = 4.26; F^2_9 (0.01) = 8.02; F^4_9 (0.05) = 3.63; F^4_9 (0.01) = 6.42

(3) ** Level of significance is more than 99%.

Friction time, s	Joint tensile strength, MPa	Fractured surface	
		Low alloy steel side	AA6061 side
0.3	244		
1.0	172		
2.0	96		

10mm |---------------------|

Fig.3 Relationship among friction time, joint tensile strength and appearances of fractured surfaces of joints made by design of experiment.

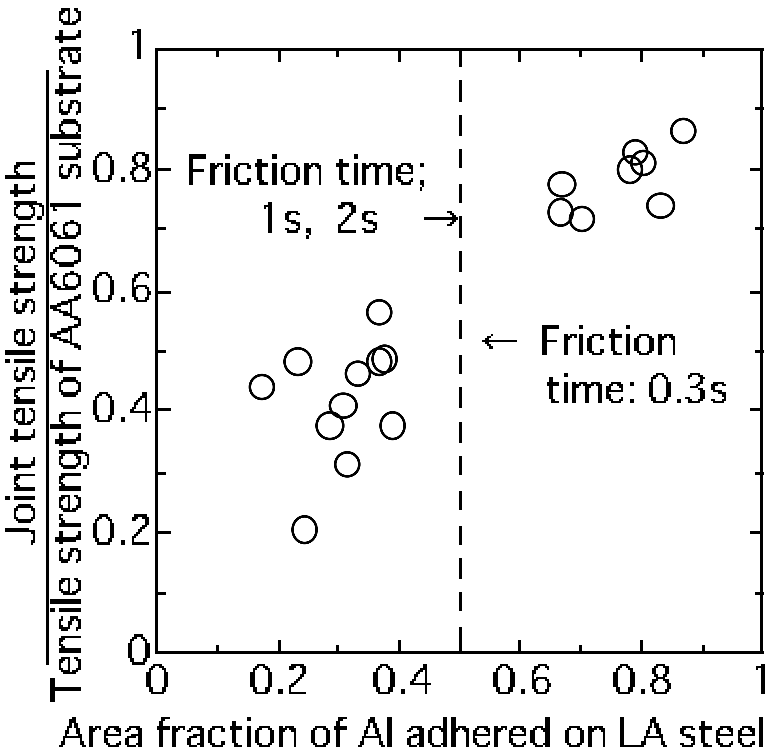


Fig.4 Relationship between area fraction of Al adhered on fractured surfaces of low alloy steel side and rate of joint tensile strength to tensile strength of AA6061 substrate.

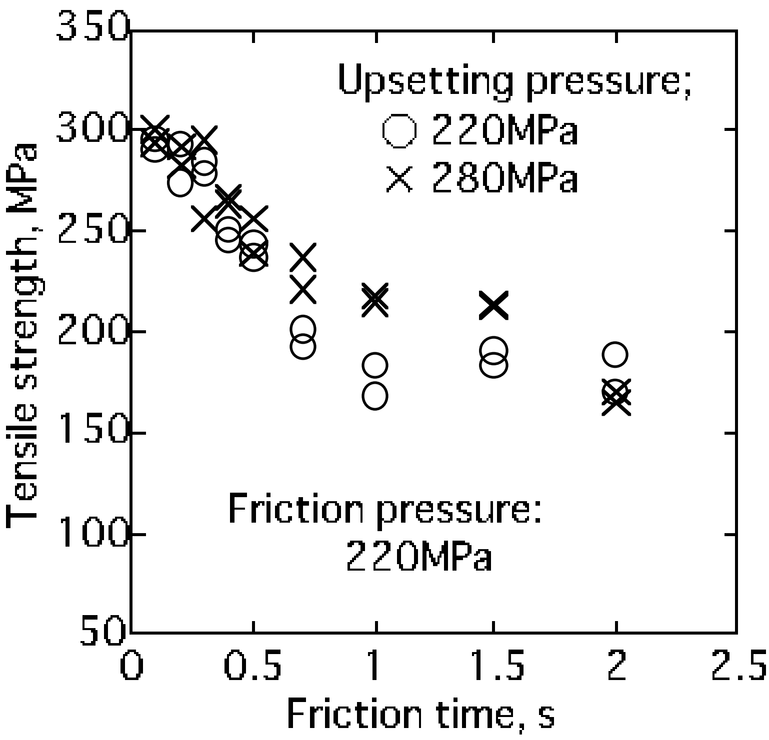


Fig.5 Effect of friction time on joint tensile strength.

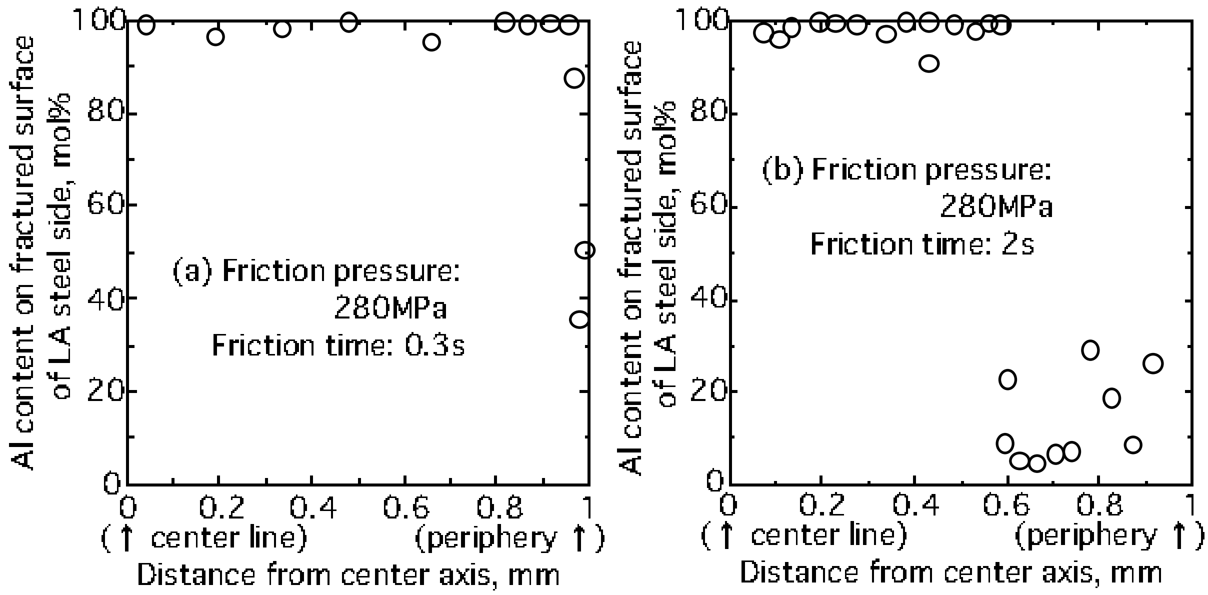


Fig.6 Distribution of Al content on fractured surface of low alloy steel side along radial direction of joints welded with friction time of (a) 0.3s and (b) 2s.

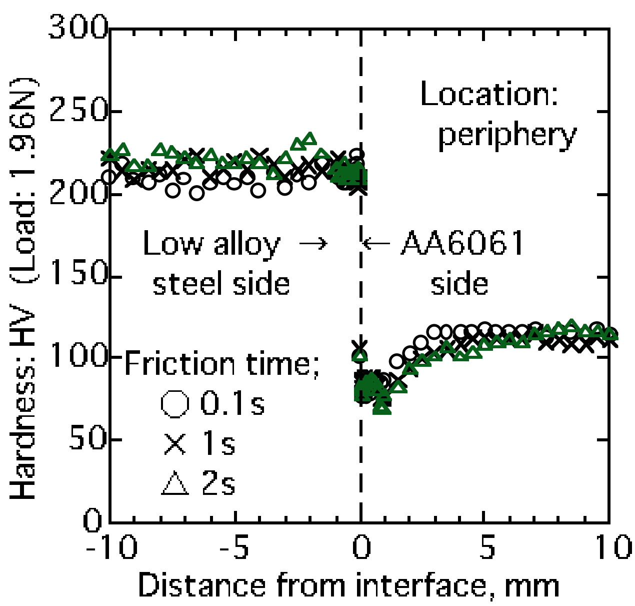


Fig.7 Hardness distributions across interface at center position of joints welded with friction time of 0.1s, 1s and 2s.

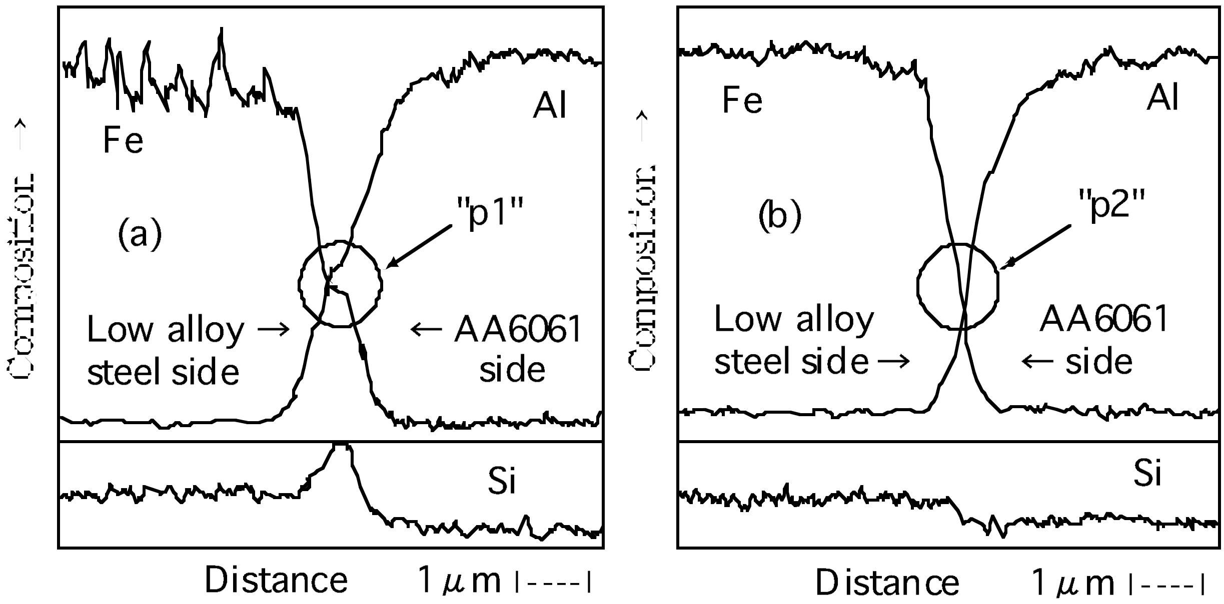


Fig.8 Distribution of Fe, Al and Si contents by SEM-EDS analysis across interface at (a) centerline portion and (b) periphery portion of joint welded with friction time of 2s.

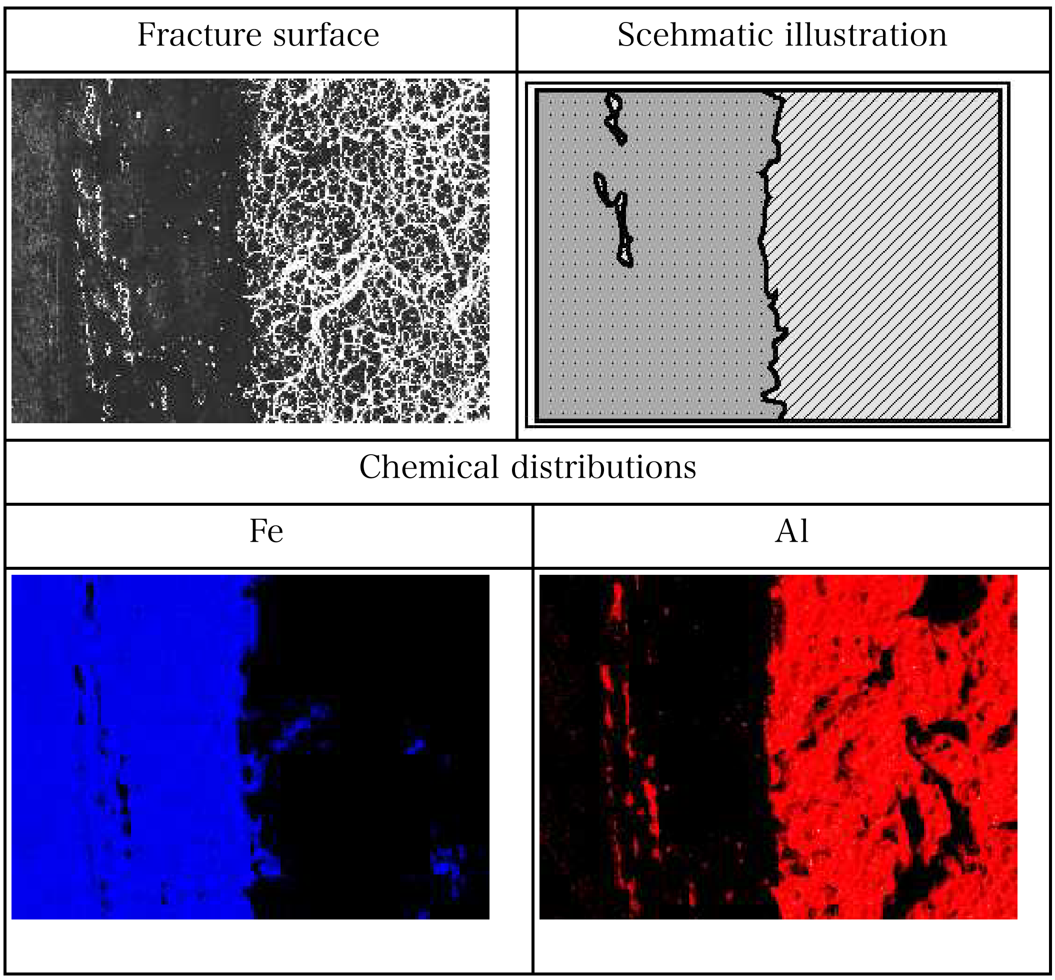


Fig.9 Fracture appearance and distribution of Fe and Al contents on fractured surface of low alloy steel side (friction time is 2s).

AA6061 side

Low alloy steel side |----------| 10mm

Fig.10 Appearance of bend test specimens in as-welded condition after test.

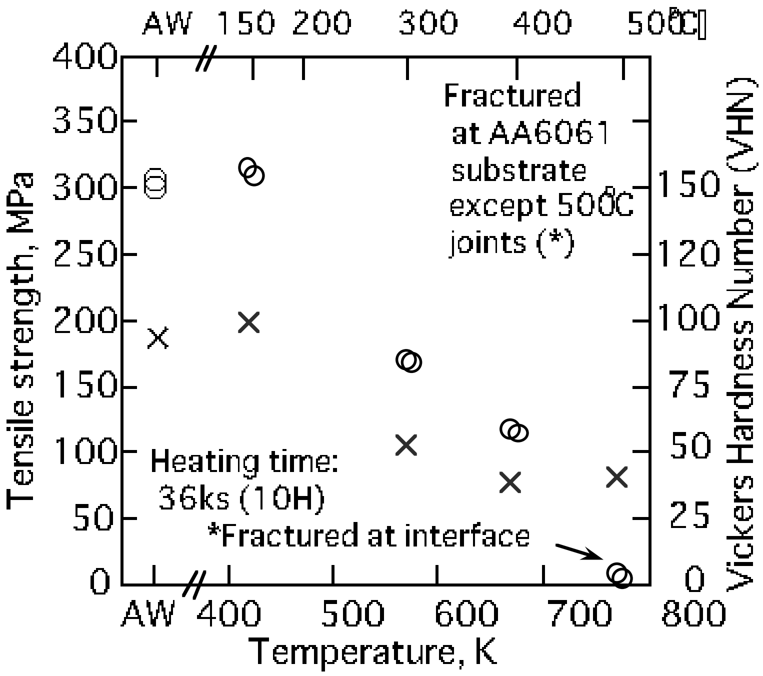


Fig.11 Relationship between heating temperature of PWHT, joint tensile strength and hardness of AA6061 substrate.