Effect of friction welding conditions and aging treatment on mechanical properties of A7075-T6 aluminum alloy friction joint

M. Kimura, M. Choji, M. Kusaka, K. Seo and A. Fuji

This paper describes the effect of friction welding conditions and aging treatment on mechanical properties of type 7075-T6 aluminum alloy (A7075) friction welded joint. A7075 was joined by using a continuous drive friction welding machine with an electromagnetic clutch in order to prevent braking deformation during rotation stop. That is, it was welded by using "The Low Heat Input Friction Welding Method (The LHI method)", developed by the authors, of which heat input is lower than that of a conventional method. The maximum joint efficiency by friction pressure of 30 MPa was approximately 25%, and that by 90 MPa was approximately 64%. These joints were made without forge pressure. The low joint efficiency was due to existence of not-joined region at the welded interfaces. However, the welded joint had approximately 82% joint efficiency when friction time was 0.5 s by friction pressure of 90 MPa with forge pressure of 180 MPa. The welded joint softened at the welded interface and its adjacent region. It had approximately 90% joint efficiency by aging for 2 years at room temperature (natural aging). It also had approximately 95% by aged for 48 hours at 393 K (120 ℃), and had no softened region at the welded interface. The heat input of welded joint by the LHI method could be decreased to approximately 50% of that by conventional method. The LHI method has several advantages for A7075 friction welding; less heat input than conventional one, and light post-weld processing (machining, etc.) because the flash can be minimized.

Keywords: Friction welding, A7075-T6 aluminum alloy, Joint efficiency, Forge pressure, Natural aging, Post weld heat treatment

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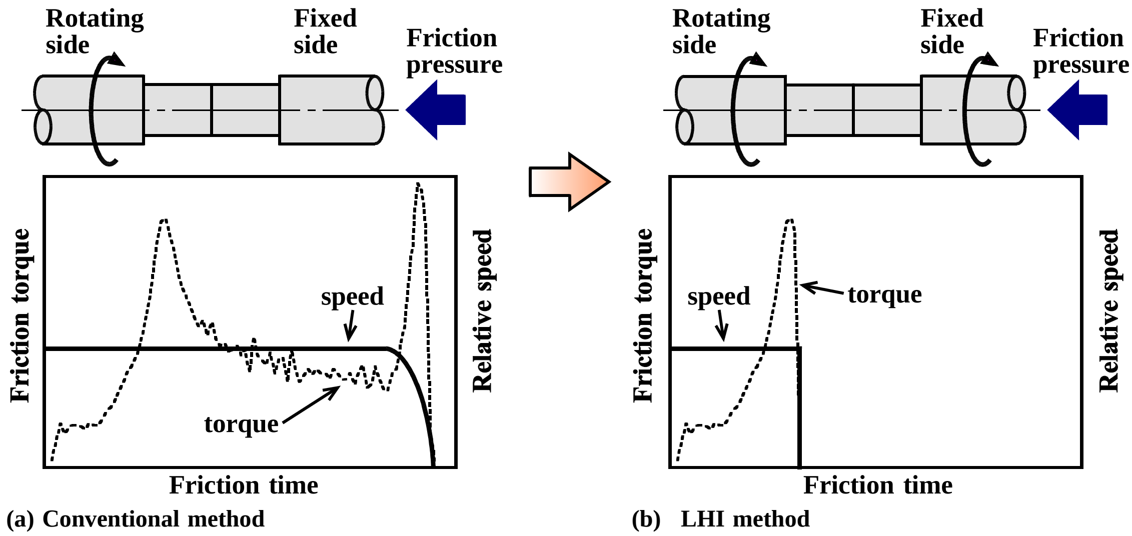
INTRODUCTION

Al-Zn-Mg alloy with T6 treatment (hereafter it is referred to as A7075) has high ultimate tensile strength that is almost similar to that of medium carbon steel. Therefore, it is widely used for important structural components such as frames and bodies for aircraft, and so on. As A7075 is one of heat treated type aluminum alloy, its mechanical properties are improved by heat treatment, such as solution treatment plus artificial aging (T6 treatment). That is, the mechanical properties of the fusion zone and heat affected zones of welded joint are remarkably deteriorated due to the heat input by welding.[1] In particular, the fusion welding process damages the joint properties, so that A7075 is difficult to weld and limited for industrial usage. The welding process that will give less damage of joint mechanical and metallurgical properties is strongly required.

Generally speaking, the friction welding method is well known as one of the solid state joining methods. Some researchers have reported that A7075 joints made by a continuous (direct) drive friction welding machine showed the good mechanical properties.[2-7] Ogawa et al. showed that A7075 welded joint had maximum joint efficiency of approximately 84%.[4] However, the joint efficiency was evaluated by the joint tensile test specimen that had notch at the welded interface. It will be able to consider that the joint efficiency is lower if the joint tensile test is carried out by using smooth type tensile test specimen. Hazlett et al.[2] and Fuwano et al.[7] investigated the joint efficiency of A7075 friction welded joint by some aging treatment conditions. These welded joints also had not obtained 100% joint efficiency, because they had softened heat affected zone at the welded interface region. The effects of aging treatment on joint properties of A7075 friction welded joint were not yet clarified in details. Thus, it is necessary to clarify the effect of friction welding conditions and aging treatment on the joint properties of A7075 friction welds in order to obtain higher joint efficiency.

Incidentally, the authors clarified the joining phenomena during friction stage of A7075 friction weld in the previous report.[8] We also showed that the welded joints of low carbon steel obtained 100% joint efficiency by using only the first stage (up to the initial peak torque) of the friction stage.[9-11] We named this friction welding method as "The Low Heat Input Friction Welding Method " (The LHI method).[10,11] The LHI method provides more advantages than conventional method, i.e., less axial shortening (burn-off), less flash (burr or collar) and so on. In particular, the heat input of the LHI method is much more lower than that of conventional method. If A7075 joint is made by the LHI method, the welded joint will have superior properties such as high joint efficiency to that of one made by a conventional friction welding method.

The authors have been carrying out to clarify the joining mechanism in the friction stage for aluminum alloy. In this report, we present the joint mechanical properties of A7075 weld by the LHI method under various friction welding conditions, especially, the relationship between friction time and joint strength of welded joint. We also present the mechanical properties of welded joint made with forge



1 Schematic diagram of the conventional and the LHI methods

pressure to improve the joint efficiency, and the effect of aging treatment such as natural aging and post weld heat treatment. We also show the comparative result between conventional and the LHI methods.

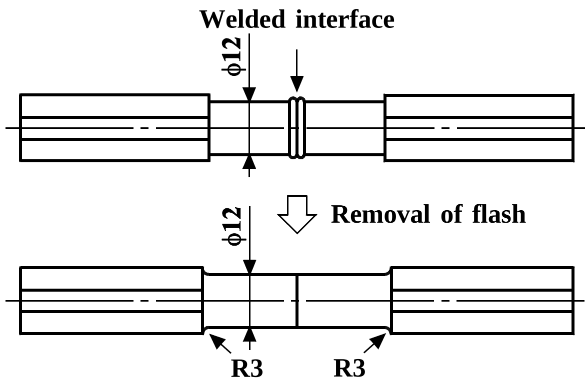
The Low Heat Input Friction Welding Method (The LHI method)

Figure 1 shows the schematic diagram of relationship between friction torque, relative speed and friction time by conventional friction welding and the LHI methods. In case of a continuous (direct) drive friction welding, i.e., conventional method, the rotation of specimen (workpiece) do not stop instantly when braking force is applied. Therefore, the relative speed between both specimens does not instantly decrease to zero as shown in Fig.1(a), and the welded joint is deformed during braking time. In contrast, the LHI method is as follows. The specimens are joined by using an electromagnetic clutch in order to prevent braking deformation during rotation stop. When the clutch is released, the relative speed between both specimens instantly decreases to zero as shown in Fig.1(b). In this case, the friction pressure can be maintained (loaded), so that the effect of braking time on deformation of joint can be negligible. That is, the strength of low carbon steel welded joint by the LHI method was similar to the tensile strength of the base metal. Furthermore, the welded joint by the LHI method had less axial shortening and less flash comparing to those of conventional method. In particular, it was clarified that the heat input of the LHI method was much more less than that of conventional method. The detail characteristics of the LHI method were precisely described in the previous reports.[9-11]

EXPERIMENTAL PROCEDURE

The material used was a 16 mm diameter A7075 rod with chemical composition of Al-5.7Zn-2.4Mg-1.7Cu-0.10Si-0.24Fe-0.04Mn-0.02Ti in mass%. The ultimate tensile strength was 644 MPa, the 0.2% yield strength was 597 MPa and the elongation was 11%. The diameter of the joining portions was machined to 12 mm, and the faying (contacting) surfaces were polished from 0.05 to 0.15 μm in roughness as the center line average height. The shape and dimensions of this specimen were same of that in the previous report.[8]

A continuous drive friction welding machine was employed for the joining. The specimen was welded by using the LHI method. The friction torque during the friction stage was measured with a load-cell, and was recorded with a personal computer through an A/D converter by sampling time of 0.05 s.



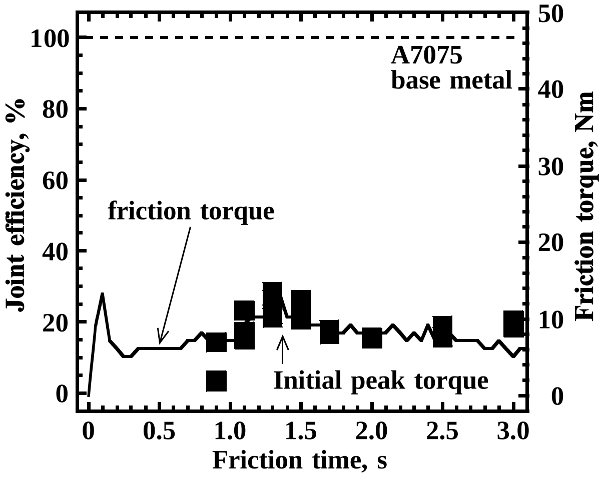
2 Preparation process of joint tensile test specimen

In this study, we performed two kinds of experiments. Detail experimental contents were as follows.

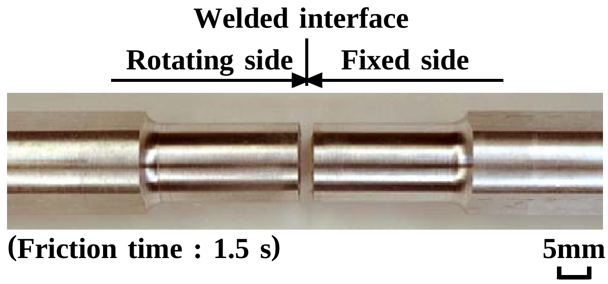
(1) The effect of friction welding conditions, i.e., friction pressure and forge pressure on mechanical properties of welded joints were clarified. Friction speed and friction pressure were set to the following combinations: 27.5 revolutions per second (s^{-1}), 30 MPa, and 27.5s^{-1}, 90 MPa. Joint tensile test and Vickers hardness test were carried out for the welded joints after holding at room temperature for 1 week, because the post weld aging of A7075 is carried out at room temperature (natural aging treatment).[12]

(2) The effects of aging treatment, such as natural aging treatment and post weld heat treatment, on joint properties were clarified. The joints were made under friction speed of 27.5 s^{-1}, friction pressure of 90 MPa and friction time of 0.5 s with forge pressure of 180 MPa. The welded joints were held at room temperature for 0.208 day (5 hours), 1 day, 7 days (1 week), 30 days (1 month), 90 days (3 month), 180 days (half-year), 365 days (1 year), and 730 days (2 years) after welding as for natural aging treatment. On the other hand, the joints were held at 393 K (120℃) for 1, 24, 48, 72 and 96 hours after welding as for post weld heat treatment.

All joint tensile test specimens were removed flash, as shown in Fig.2. In brief, the joint tensile strength was evaluated with smooth type joint tensile test specimen.

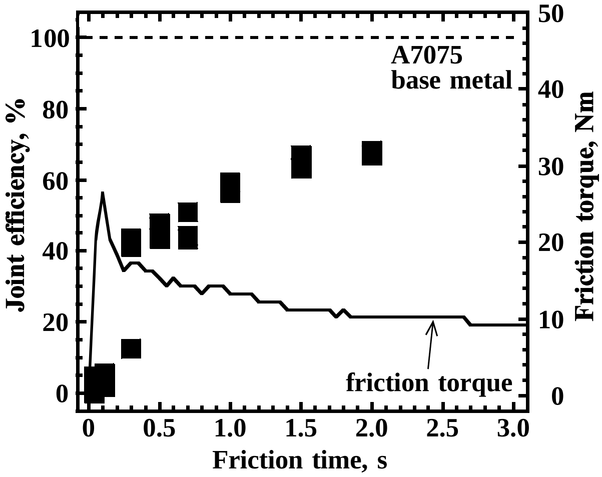


3 Relationship between friction time and joint efficiency of welded joints corresponding to friction torque: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa

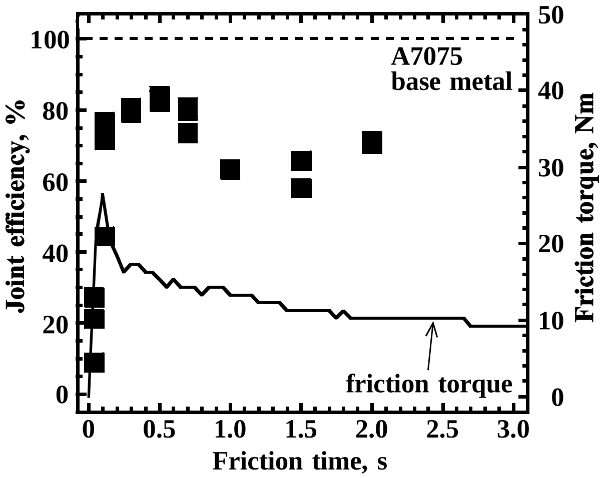


4 Appearance of joint tensile test specimen after tensile testing: friction speed of 27.5 s^{-1}, friction pressure of 30 MPa and friction time of 1.5 s

Vickers hardness distributions at the half-radius location of the welded interface regions were measured with a load of 2.94 N. Measuring range was each 8 mm from the welded interface, and measuring interval was 200 μm.



5 Relationship between friction time and joint efficiency of welded joints corresponding to friction torque: friction speed of 27.5 s^{-1} and friction pressure of 90 MPa



6 Relationship between friction time and joint efficiency of welded joints corresponding to friction torque: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, forge pressure of 180 MPa and forge time of 6.0 s

RESULTS

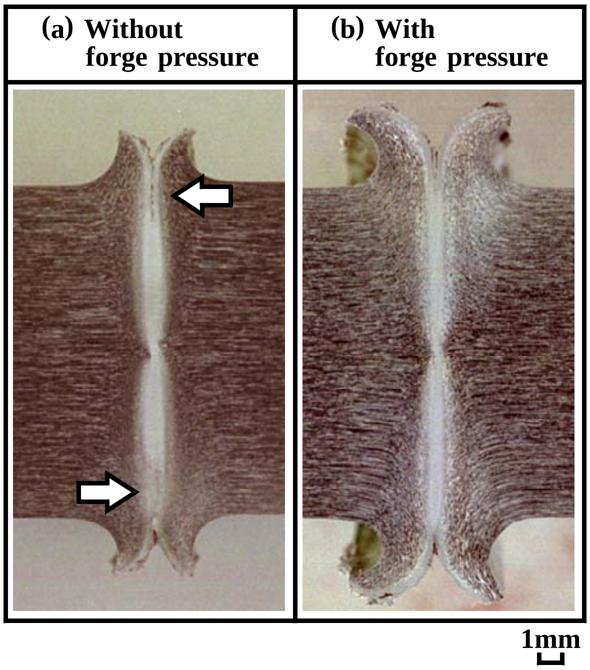
Relationship between friction time and joint tensile strength

Figure 3 shows the relationship between friction time and joint efficiency of welded joints plotted on the friction torque curve by friction pressure of 30 MPa. All welded joints in Fig.3 were made without forge pressure. Figure 4 shows an example of appearance of joint tensile test specimen after tensile testing. The tensile test was carried out after 1 week from welding. The joint efficiency was the ratio between joint tensile strength and ultimate tensile strength of A7075 base metal. The welded joints had approximately 7% joint efficiency at friction time of 0.9 s. That is, the joint tensile strength was very low, and the fracture occurred at the welded interface as shown in Fig.4. The joint efficiency increased with increasing friction time until the initial peak torque. However, the joint efficiency at 1.5 s was still low (approximately 25%), and fracture occurred at the welded interface in all joints.

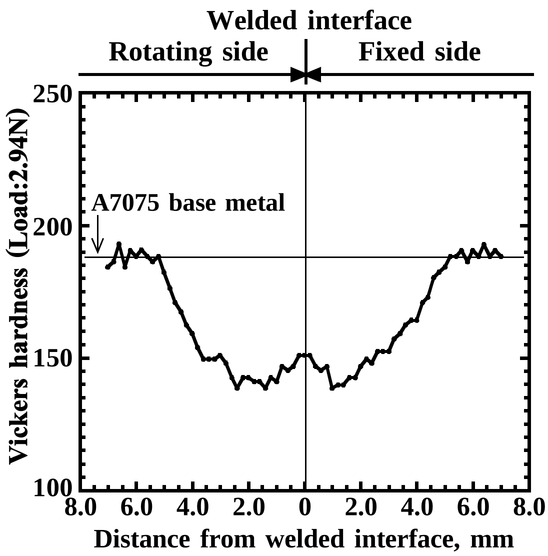
Figure 5 shows the relationship between friction time and joint efficiency plotted on the friction torque curve by 90 MPa. At 0.04 s, the joint efficiency was very low (approximately 2%). The joint efficiency increased with increasing friction time, and that was approximately 64% at 1.5 s. However, the joint tensile strengths were also lower than that of A7075 base metal, and fracture occurred at the welded interface. The fracture originated from the welded interface was due to the not-joined region as shown in Fig.7 (a) that will be described later.

Improving joint properties

In an attempt to improve the joint efficiency, the welded joints were made by applying forge pressure. The welding conditions were friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, forge pressure of 180 MPa and forge time of 6.0 s. Figure 6 shows the relationship between friction time and joint efficiency plotted on the friction torque curve. The joint efficiency increased with increasing friction time, and they had approximately 82% joint efficiency at 0.5 s. Then, the joint efficiency decreased to approximately 62% with increasing friction time, and had been saturated. Figure 7 shows the cross-sectional appearances of the welded interface regions at friction time of 0.5 s by friction pressure of 90 MPa. One of the welded joints was made without forge pressure (Fig.7(a)), and the other was made with forge pressure of 180 MPa (Fig.7(b)). The welded interface of the joint without forge pressure had the not-joined region at the periphery portion indicated by the arrows (Fig.7(a)). The



7 Cross-sectional appearances of welded interface regions: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s

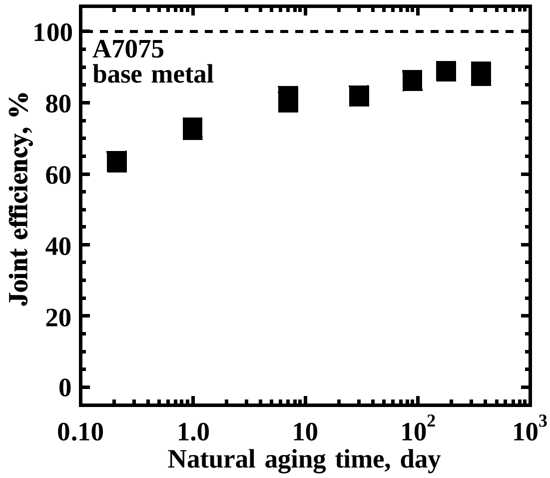


8 Vickers hardness distribution across welded interface at friction time of 0.5 s: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, forge pressure of 180 MPa and forge time of 6.0 s

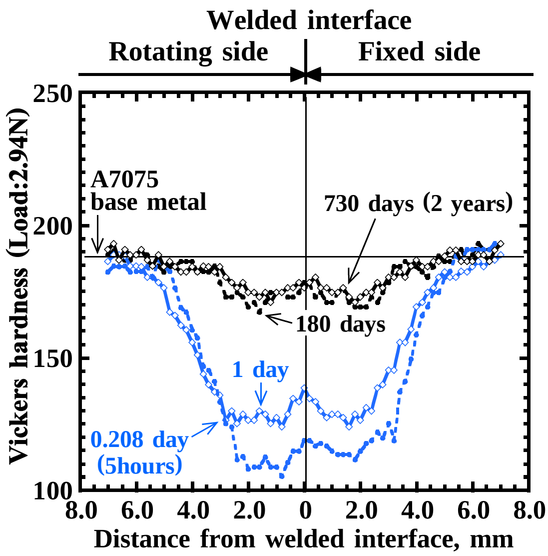
joint with forge pressure of 180 MPa was joined completely, and did not have the not-joined region (Fig.7(b)). However, the joint with forge pressure had not obtained same ultimate tensile strength of A7075 base metal as shown in Fig.6. Figure 8 shows the Vickers hardness distribution across the welded interface at 0.5 s by 90 MPa with forge pressure of 180 MPa. The welded interface and its adjacent region were softened. As a result, it was difficult that the welded joints are completely upset by adding forge pressure.

Results of joint properties by natural aging

The softened region of A7075 welds recovers by aging treatment.[19] Figure 9 shows the relationship between natural aging time and joint efficiency. These joints were welded by friction pressure of 90 MPa and friction time of 0.5 s with

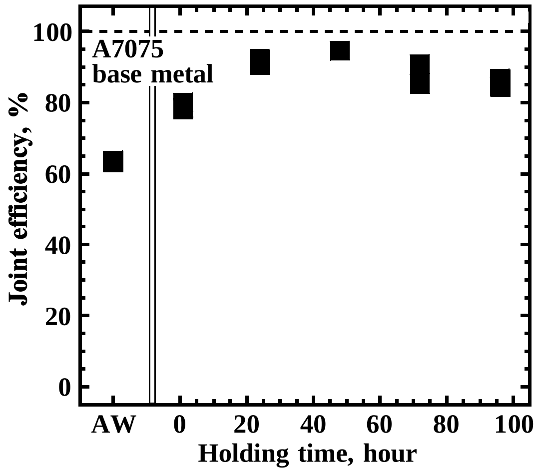


9 Relationship between natural aging time and joint efficiency of welded joints: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s

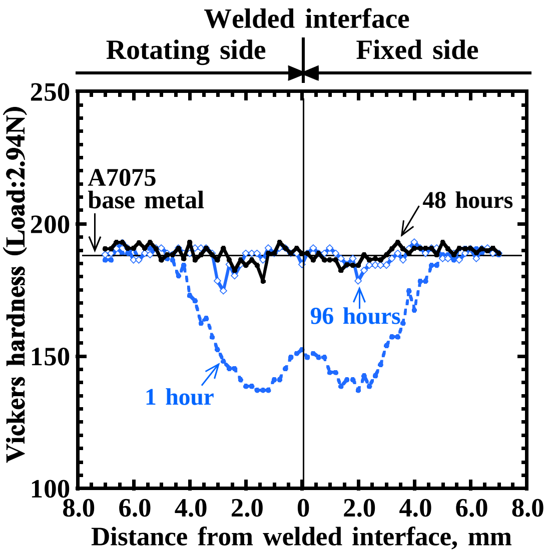


10 Vickers hardness distributions across welded interfaces on various natural aging times: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s

forge pressure of 180 MPa. When natural aging time was 0.208 day (5 hours), the welded joints had approximately 63% joint efficiency. The joint efficiency increased with increasing natural aging time. The welded joints had approximately 90% joint efficiency at 730 days (2 years) after welding. Figure 10 shows the Vickers hardness distribution across the welded interface regions at 0.208, 1, 180 and 730 days. The welded interface and its adjacent region were softened at all natural aging times. The joint of 0.208 day had softened region at about 10 mm in the longitudinal direction and that was approximately 55% hardness of A7075 base metal. The welded interface and its adjacent region recovered the hardness with increasing natural aging time. However, they were not completely recovered to the hardness of A7075 after 730 days. The recovery of softened region and aging behavior of A7075 friction welded joints were similar to those of Al-Zn-Mg alloy joint by fusion welding.[13-18] According to this result, the recovery of hardness at the welded interface was due to precipitation which is called as G.P. zone.[13-18]



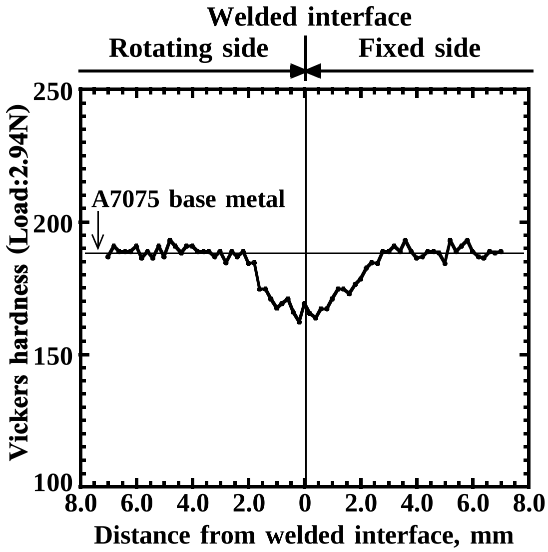
11 **Relationship between holding time and joint efficiency of welded joints in heating temperature of 393 K: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s**



12 **Vickers hardness distribution across welded interface region on various holding times at heating temperature of 393 K: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s**

Results of joint properties by post weld heat treatment

Figure 11 shows the relationship between holding time at heating temperature of 393 K and joint efficiency. These joints were welded by friction pressure of 90 MPa and friction time of 0.5 s with forge pressure of 180 MPa. 393 K was same as the final aging temperature of T6 treatment.[19] As-welded (AW) joints were also plotted in Fig.11, which were same data of natural aging at 0.208 day. The welded joints had approximately 79% joint efficiency when holding time was 1 hour. The joint efficiency increased with increasing holding time, and that had approximately 95% at 48 hours. Then, the joint efficiency slightly decreased with increasing holding time, and that had approximately 85% at 96 hours. Figure 12 shows the Vickers hardness distributions across the welded interfaces at 1, 48 and 96 hours. The welded interface and its adjacent region at 1 hour had softened and that was approximately 75% hardness of A7075



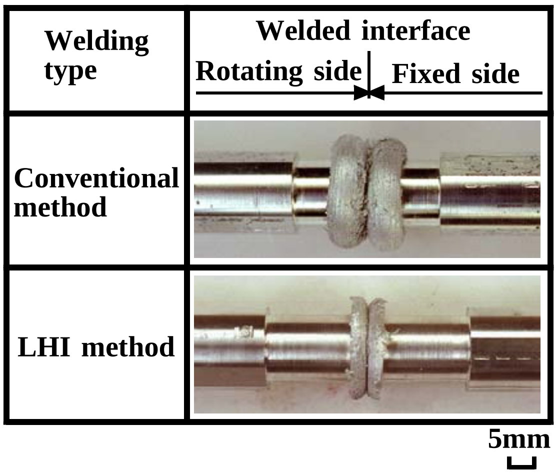
13 **Vickers hardness distribution across welded interface by friction pressure of 500 MPa through conventional method: friction speed of 27.5 s^{-1} and friction time of 0.1 s**

base metal. They did not have almost the softened region at 48 hours or longer. However, the joint efficiency at 96 hours was lower than that of 48 hours as shown in Fig.11. The fiber structure at the welded interface flowed perpendicularly to longitudinal direction of A7075 base metal as shown in Fig.7. The joint tensile strength was affected by flow direction of fiber structure of A7075 base metal. Although the consideration was not clarified in detail, further investigation is necessary to clarify the effect of heat treatment on welded joint.

DISCUSSION

Results of joint properties by high friction pressure

According to the results described above, it was difficult to obtain 100% joint efficiency in A7075 friction welded joint without aging treatment. To clarify the joint properties without aging treatment, we investigated the joint mechanical properties by another friction pressure. Generally speaking, A7075 joint softens in heat affected zone when the maximum welding temperature is approximately 413 K (140 ℃) or over.[13] The friction pressure should be 460 MPa or over to keep the welding temperatures below 413 K, because the temperature can be decreased by increasing friction pressure.[20] This friction pressure was able to be decided by the relationship between temperatures and yield strength of A7075 base metal.[21] Figure 13 shows the Vickers hardness distribution across the welded interface by friction pressure of 500 MPa. This joint had the joining portions diameter of 11 mm, and was made at friction time of 0.1 s without forge pressure by conventional method. This result was also evaluated with the joint that had been held at room temperature for 1 week after welding. The welded interface and its adjacent region were softened as shown in Fig.13, and joint efficiency was approximately 82%. This joint efficiency was equivalent to that of the joint at friction time of 0.5 s by friction pressure of 90 MPa with forge pressure of 180 MPa (Fig.6). The welded joints by 500 MPa had lower (ultimate) tensile strength than that of A7075 base metal, because those had softened region at the welded interface. Moreover, this friction pressure was not practical one, because friction pressure of 500 MPa was higher than the 0.2% yield strength of A7075 base metal. Even though we had selected other friction welding conditions, it was difficult to obtain approximately 82% or over for joint



14 Appearances of welded joints by conventional and the LHI methods: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s

Table 1 Comparative result of axial shortening, joint tensile strength, joint efficiency and heat input of welded joint between conventional and the LHI methods: friction speed of 27.5 s^{-1}, friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s

Welding type	Conventional method	LHI method
Axial shortening, mm	13.5	4.8
Joint tensile strength, MPa	522	535
Joint efficiency, %	81	82
Heat input, kJ	3.6	1.5

efficiency. As a conclusion, A7075 friction welded joint had obtained approximately 95% joint efficiency by aging treatment.

Comparison between conventional and LHI methods

The relative speed at the welded interface did not instantly decrease to zero and a braking time was approximately 0.4 s when the specimens were joined by conventional method. Otherwise, by using the LHI method, the relative speed between both specimens could be instantly decreased to zero. We investigated the characteristics of A7075 joint by conventional and the LHI methods. Figure 14 shows the appearance of welded joints by conventional and the LHI methods. These joints were welded by the following friction welding conditions: friction pressure of 90 MPa, friction time of 0.5 s, forge pressure of 180 MPa and forge time of 6.0 s. We hereafter called as conventional joint and LHI joint, respectively. In conventional method, A7075 base metal softened by the friction heat generated at the welded interface during braking time. Thus, the flash made by conventional method was larger than the LHI joint as shown in Fig.14. In contrast, the relative speed between both specimens instantly decreased to zero after the friction torque reaches the initial peak for the LHI method. In addition, the softened regions were decreased by applying forge pressure when the relative speed instantly decreased to zero. The LHI joint could decrease the softened region and flash as shown in Fig.14.

Table 1 summarizes the axial shortening (burn-off), the joint tensile strength, the joint efficiency and the heat input of the welded joints by conventional and the LHI methods. Each heat input was calculated from the friction torque curve.[22] The joint tensile strength was measured by natural aging for 1 week. The joint tensile strength and joint efficiency of the LHI joint were about 535 MPa and approximately 82%, respectively. Those of the conventional joint were about 522 MPa and approximately 81%, respectively. Both joints had similar joint strength and joint efficiency. However, the axial shortening of the LHI joint was about 4.8 mm, and less than that of the conventional joint (about 13.5 mm). The heat input of the LHI joint could be decreased to approximately 50% of the conventional joint. The LHI method has several advantages for A7075 friction welding; less heat input than conventional one, and light post-weld processing (machining, etc.) because the flash can be minimized.

CONCLUSIONS

This paper described the effect of friction welding conditions and aging treatment on mechanical properties of A7075-T6 aluminum alloy (A7075) friction welded joints. The following conclusions are provided.

1. The maximum joint efficiency by friction pressure of 30 MPa without forge pressure was approximately 25%, and that by 90 MPa was approximately 64%. The low joint efficiency was due to existence of not-joined region at the welded interfaces.
2. The welded joint had approximately 82% joint efficiency by friction time of 0.5 s, friction pressure of 90 MPa and forge pressure of 180 MPa. However, they had softened region at the welded interface and its adjacent region.
3. The joint efficiency of the joint described in the conclusion 2 reached approximately 90% when the joint had been held for 2 years at room temperature (natural aging). They also had softened region at the welded interface and its adjacent region.
4. The joint efficiency of the joint described in the conclusion 2 reached approximately 95% when the joint had been held at 393 K (120℃) for 48 hours after welding. The welded joint had no softened region at the welded interface.
5. The heat input of the LHI joint could be decreased to approximately 50% of the conventional joint. The LHI method has several advantages for A7075 friction welding; less heat input than conventional one, and light post-weld processing (machining, etc.) because the flash can be minimized.

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