

Effect of friction welding conditions on mechanical properties of A5052 aluminium alloy friction welded joint

M. Kimura^{*1}, M. Choji², M. Kusaka¹, K. Seo¹ and A. Fuji³

This paper describes the mechanical properties of Al-Mg aluminum alloy (A5052) friction welded joints. Two types of A5052 with different tensile properties were used. One is H112 base metal with 188 MPa in tensile strength, and the other is H34 one with 259 MPa. They were joined by a continuous drive friction welding machine with an electromagnetic clutch in order to prevent braking deformation. That is, the joints were welded by the "Low Heat Input Friction Welding Method" (LHI method), developed by the authors, in which the heat input is lower than in the conventional method. An A5052-H112 joint, which was made by the condition of a friction speed of 27.5 s^{-1} , a friction pressure of 30 MPa, a friction time of 2.0 s (just after the initial peak torque) and a forge pressure of 60 MPa, had approximately 95% joint efficiency. It fractured at the welded interface and at the A5052-H112 base metal. To improve the joint efficiency, an A5052-H112 joint was made at a forge pressure of 75 MPa, which was the same as the yield strength of the A5052-H112 base metal. It had a 100% joint efficiency and fractured at the A5052-H112 base metal. On the other hand, an A5052-H34 joint was made by the condition of a friction speed of 27.5 s^{-1} , a friction pressure of 90 MPa, a friction time of 0.3 s (just after the initial peak torque) and a forge pressure of 180 MPa. It had approximately 93% joint efficiency and fractured at the A5052-H34 base metal. This joint had also a softened region at the welded interface and its adjacent region. To improve the joint efficiency, an A5052-H34 joint was made at a forge pressure of 260 MPa, which was the same as the ultimate tensile strength of the A5052-H34 base metal. Although this joint had slightly softened region at periphery portion, it had approximately 93% joint efficiency. The fact that the A5052-H34 joint did not achieve 100% joint efficiency is due to a slightly softening at periphery portion and the difference of the anisotropic properties of the A5052-H34 base metal between the longitudinal and radial directions.

Keywords: Friction welding, A5052 aluminium alloy, Joint efficiency, Forge pressure, Soften

Introduction

Aluminium (Al) is one of the most important non-ferrous metals. Al and its alloys are widely used for important structural components in automobiles, aerospace, and so on, because they have good mechanical and metallurgical properties, e.g. high specific strengths and excellent corrosion resistance. Most Al products are assembled by the components of Al alloys that are made by adding various elements such as Mg, Zn, Cu, Mn, etc. to improve the mechanical properties, processability and corrosion resistance. For example, typical Al-Mg alloy AA5052

(referred to as A5052) is a well-known weldable alloy that is widely used in industry, such as transportation machines field. In addition, it is possible to improve the mechanical properties through work hardening or heat treatment for Al alloys. However, the mechanical properties of welded joints are remarkably debased due to heat input when these tempered Al alloys are welded.¹ Hence, it is difficult to weld tempered Al alloys.

A friction welding method, one of solid state joining processes, is suitable for minimizing heat input in the welding of tempered Al alloys. Many researchers have reported that the mechanical properties of a friction welded joint of Al or its alloys show good characteristics.^{2,7} However, it is difficult to achieve 100% joint efficiency for the Al alloys base metal which mechanical properties were improved by work hardening or heat treatment. Incidentally, the authors clarified the joining phenomena during the friction stage of low carbon steel friction welding.^{8,9} We also showed that 100% joint efficiency of low carbon steel welded joints could be obtained by using only the first stage (up to the initial

¹Department of Mechanical and System Engineering, Graduate School of Engineering, University of Hyogo (formerly Himeji Institute of Technology), 2167 Shosha, Himeji, Hyogo 671-2201, Japan

²Himeji Institute of Technology, 2167 Shosha, Himeji, Hyogo 671-2201, Japan

³Department of Mechanical Engineering, National University Corporation–Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido, 090-8507, Japan

*Corresponding author, email mkimura@eng.u-hyogo.ac.jp

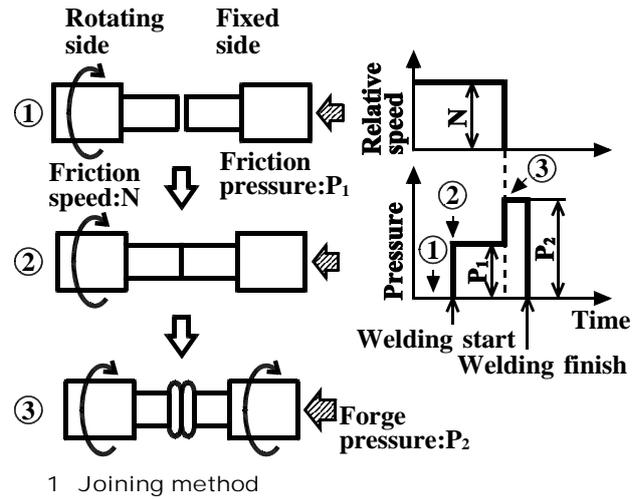
peak torque) of the friction stage.¹⁰⁻¹² We also demonstrated the joining phenomena during the friction stage and the joint properties of Al-Zn-Mg alloy (A7075-T6) friction welding.^{12,13} We named this friction welding method the "Low Heat Input Friction Welding Method" (LHI method).⁹⁻¹¹ The LHI method has several advantages over the conventional method, e.g. less axial shortening (burn-off) and less flash (burr or collar). In addition, the heat input in the LHI method is much lower than that with the conventional method. Furthermore, we also showed that a 780 MPa class high tensile steel welded joint by the LHI method had the same tensile strength as that of the base metal, and it fractured at the base metal.¹⁴ In particular, the high tensile steel welded joint by the conventional method was not able to obtain those results.¹⁴ If Al alloys such as A5052 with the temper conditions of the base metal differed are joined by the LHI method, the joint will have superior properties. In particular, the joint made by the LHI method will have higher joint efficiency than that made by the conventional friction welding method regardless of the temper conditions for base metal.

The authors have been carrying out the work to clarify the joint properties of Al alloys. In this report, we present the joint mechanical properties of an A5052 joint made with the LHI method under various friction welding conditions, especially the relationship between the friction time and the joint efficiency of the welded joint is clarified.

Experimental procedure

The material used was an A5052 rod with a 16 mm diameter. Two types of A5052 having different tensile properties as a result of work hardening treatments denoted by H112 and H34 were used, and are referred to below as H112 and H34, respectively. Chemical composition of the H112 was Al-2.5Mg-0.18Cr-0.05Cu-0.12Si-0.19Fe-0.03Mn-0.02Zn (mass-%) with an ultimate tensile strength of 188 MPa. That of the H34 was Al-2.5Mg-0.23Cr-0.02Cu-0.05Si-0.13Fe-0.01Mn-0.00Zn (mass-%) with 259 MPa. The detail tensile properties of used materials are given in Table 1. Both A5052 rods were cut to 12 mm diameter for the weld faying surface by lathe. Before joining, the weld faying (contacting) surface of the specimen was polished from 0.05 to 0.15 μm in roughness as the centre line average height by a surface grinding machine.

Both base metals were joined by LHI method and conventional friction welding methods with a continuous (direct) drive friction welding machine. Hereafter, we call them the H112 joint and the H34 joint, respectively. The LHI method used an electromagnetic clutch in order to prevent braking deformation during the rotation stop. When the clutch was released, the relative speed between both specimens instantly decreased to zero, as shown in Fig. 1. The detailed characteristics of the LHI method



have been described in the previous reports.⁸⁻¹³ During the friction welding operations, the friction speed and the friction pressure were set to the following combination: 27.5 revolutions per second (s^{-1}) and 30 MPa. Forge pressure was applied to the joint at various values corresponding to the details of the experiment. 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 with a sampling time of 0.015 s. All joint tensile test specimens had been removed their flash, and they were tested. Vickers hardness at the half-radius location (referred to as the half-radius) and at 0.5 mm inward from the outer surface location (referred to as the periphery) of the welded interface regions were measured with a load of 2.94 N (0.3 kgf). The measuring range was 7 mm from the welded interface, and the measuring interval was 200 μm .

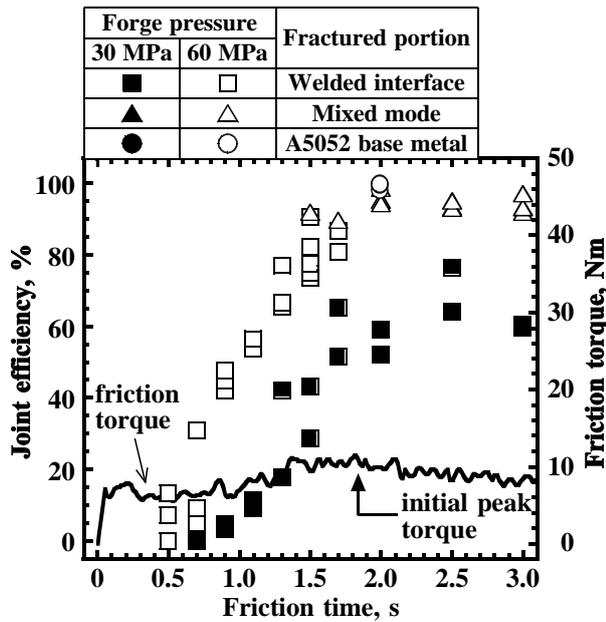
Results

Tensile properties of the A5052-H112 joint

Figure 2 shows the relationship between the friction time and the joint efficiency of the H112 joints plotted on the friction torque curve. The H112 joints were made at a forge pressure of 30 and 60 MPa. The joint efficiency was based on the ratio of joint tensile strength to the ultimate tensile strength of the base metal. Figure 3 shows an example of the appearance of the tensile specimens after tensile testing. The joint efficiency of the H112 joint at a forge pressure of 30 MPa was 0% at a friction time of 0.5 and 0.7 s because sufficient heat quantities could not be produced for welding during these friction times. The joint efficiency increased with increasing friction time. The joints had approximately 55% joint efficiency at 2.0 s, i.e. just after the initial peak torque. This joint fractured at the welded interface, as shown in Fig. 3a. Thereafter, the joint efficiency saturated with increasing friction time. On the other hand, the joint efficiency of the H112 joint by applying a forge pressure of 60 MPa was approximately 10% at a friction time of 0.5 and 0.7 s, as shown in Fig. 2. That is, the joint tensile strength was very low, and the fracture occurred at the welded interface. Some joints at 1.5 and 1.7 s (close to the initial peak torque) had approximately 90% joint efficiency, and fractured at the welded interface and the H112 base metal (a mixed mode fracture), as shown in Fig. 3b. The joint

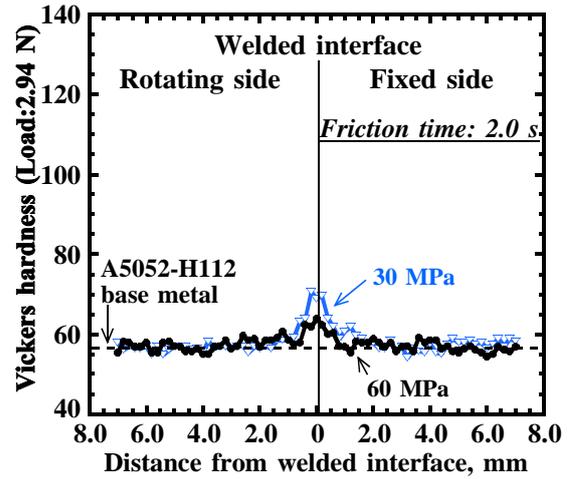
Table 1 Mechanical properties of materials used

Material	T.S., (MPa)	0.2%Y.S., (MPa)	El., (%)	Vickers hardness
A5052-H112	188	73	34.5	58
A5052-H34	259	213	22.3	86



2 Relationship between friction time and joint efficiency of A5052-H112 joint corresponding to friction torque curve: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa

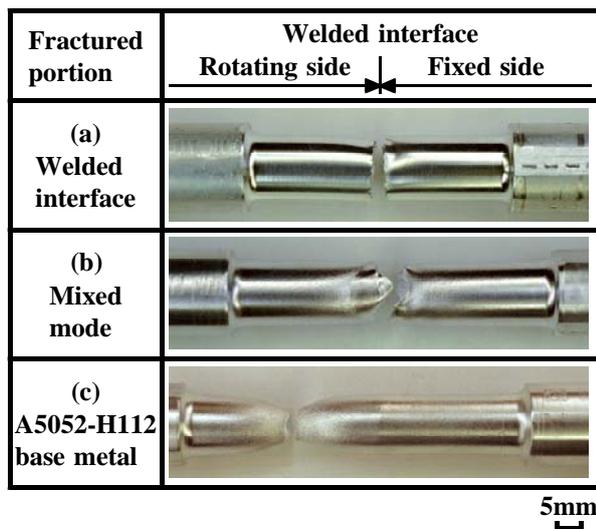
efficiency was approximately 95% at 2.0 s (just after the initial peak torque). In addition, some joints had 100% joint efficiency and fractured from the H112 base metal. However, the joint efficiency was approximately 95% and saturated with increasing friction time, and the joint had a mixed mode fracture. Figure 4 shows the Vickers hardness distribution across the welded interface at the half-radius of the joint at a friction time of 2.0 s. These joints had a hardened region at the welded interface about 1.5 mm in longitudinal direction across the welded interface. These joints did not have a softened region at all.



4 Vickers hardness distribution across welded interface at half radius of A5052-H112 joint: friction speed of 27.5 s^{-1} , friction pressure of 30 MPa and friction time of 2.0 s

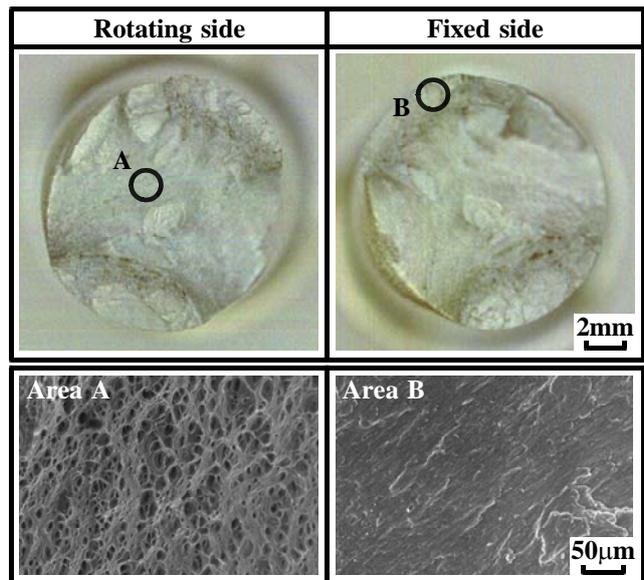
Improving joint properties of the A5052-H112 joint

Figure 5 shows the fractured surfaces and SEM micrographs of the joint with a friction pressure of 30 MPa, a friction time of 2.0 s, and a forge pressure of 60 MPa. The central region of the fractured surface is rough, and the peripheral region is flat. According to SEM observation of the central region of area A, it revealed dimpled pattern. That is, the fracture of the welded joint was a typical ductile fracture. However, in the SEM micrograph of the peripheral region of area B, no dimple surface could be observed. The weld faying surfaces were completely contacted and welded in the central region, but were not welded in the peripheral region under these friction welding conditions. Figure 6 shows the

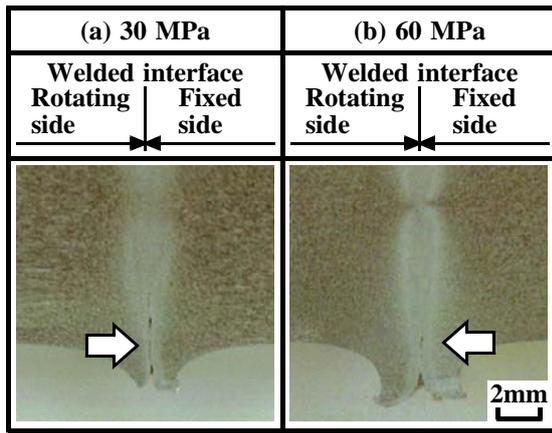


a Welded interface; b Mixed mode; c A5052-H112 base metal

3 Appearances of tensile test specimens of A5052-H112 joint after tensile testing

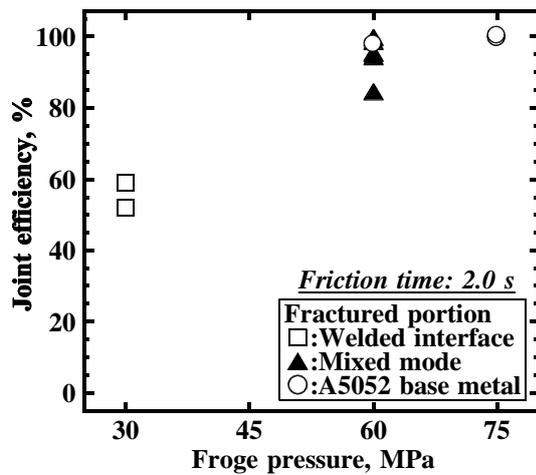


5 Fractured surfaces and SEM micrographs of A5052-H112 joint: friction speed of 27.5 s^{-1} , friction pressure of 30 MPa, friction time of 2.0 s and forge pressure of 60 MPa

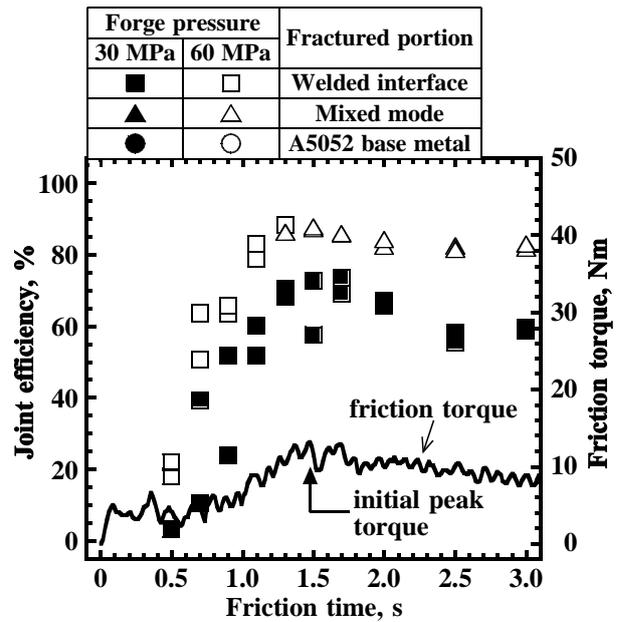


a Forge pressure of 30 MPa; b Forge pressure of 60 MPa
 6 Cross-sectional appearances of welded interface region of A5052-H112 joint: friction speed of 27.5 s⁻¹, friction pressure of 30 MPa and friction time of 3.0 s

cross-sectional appearances of the welded interface with a friction pressure of 30 MPa and a friction time of 3.0 s. One of the joints was made at a forge pressure of 30 MPa (Fig. 6a), and the other was made at 60 MPa (Fig. 6b). Both joints had the not-joined region in the periphery portion, which is indicated by arrows. That is, a flat plane at the peripheral region as shown in Fig. 5 was the not-joined region. Hasui *et al.*¹⁵ clarified the joining and separating behavior of the welded interface after the initial peak torque during friction process. We also observed the not-joined region on a cross-section of a carbon steel friction welded joint.^{10,16} The occurrence of the not-joined region was due to repeated cycle of joining and separating at the welded interface during a steady state in the friction process. In addition, the joining and the separating area at the welded interface increased with increasing friction time. This area was not completely contacted and it was oxidized. The not-joined region could act as a crack, so that it was decided that the crack caused the failure of the joints during the tensile test. Due to this, the joint had a



7 Relationship between forge pressure and joint efficiency of A5052-H112 joint: friction speed of 27.5 s⁻¹, friction pressure of 30 MPa and friction time of 2.0 s



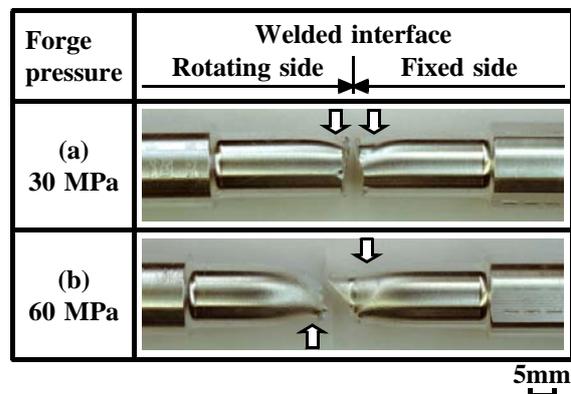
8 Relationship between friction time and joint efficiency of A5052-H34 joint corresponding to friction torque curve: friction speed of 27.5 s⁻¹ and friction pressure of 30 MPa

mixed mode fracture.

In an attempt to improve joint efficiency, the joints were made by applying a higher forge pressure. Figure 7 shows the relationship between the forge pressure and the joint efficiency of the H112 joints at a friction time of 2.0 s. The joint efficiency increased with increasing forge pressure. The joint was made with a forge pressure of the same as the yield strength of the H112 base metal, which had 100% joint efficiency and fractured at the H112 base metal, as shown in Fig. 3c. These results indicate that the H112 joint made under high forge pressure will achieve 100% joint efficiency.

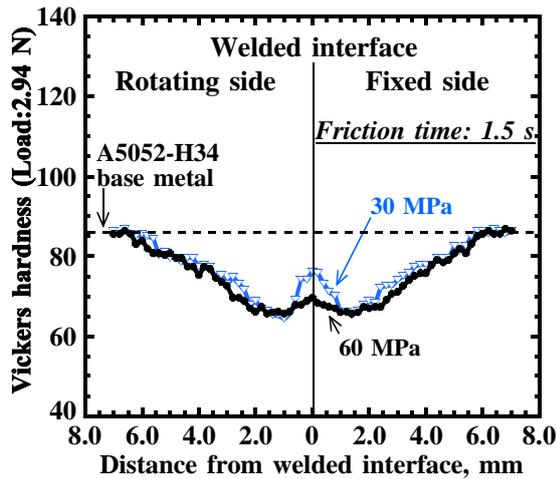
Tensile properties of the A5052-H34 joint

Figure 8 shows the relationship between the friction time

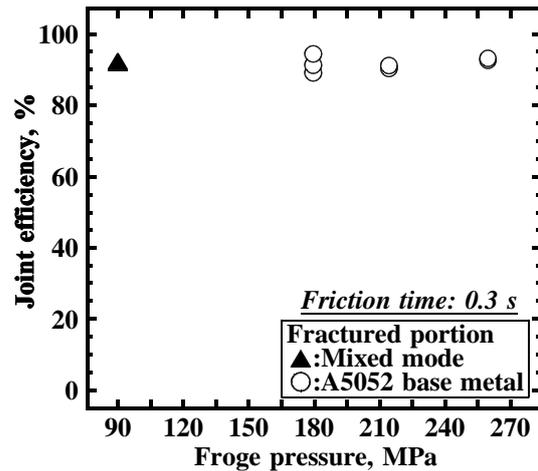


a Forge pressure of 30 MPa; b Forge pressure of 60 MPa

9 Appearances of tensile test specimens of A5052-H34 joint after tensile testing: friction speed of 27.5 s⁻¹, friction pressure of 30 MPa and friction time of 1.5 s



10 Vickers hardness distribution across welded interface at half radius of A5052-H34 joint: friction speed of 27.5 s^{-1} , friction pressure of 30 MPa and friction time of 1.5 s



12 Relationship between forge pressure and joint efficiency of A5052-H34 joint: friction speed of 27.5 s^{-1} , friction pressure of 90 MPa and friction time of 0.3 s

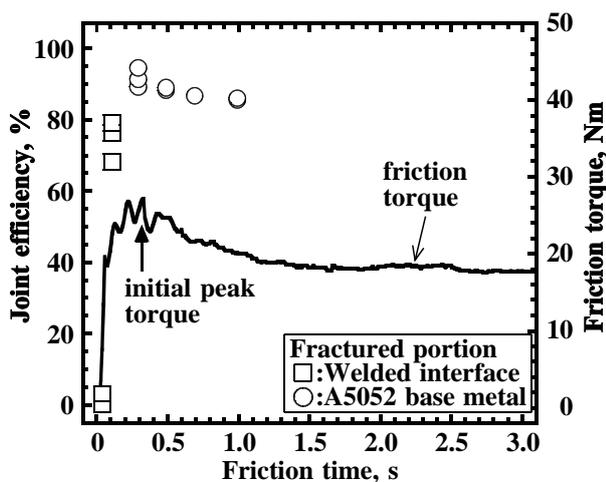
and the joint efficiency of the H34 joints that were plotted on the friction torque curve. Figure 9 shows an example of the appearance of the tensile specimens at a friction time of 1.5 s after tensile testing. The joint efficiency of the H34 joint at a forge pressure of 30 MPa was approximately 3% at a friction time of 0.5 s. The joint efficiency increased with increasing friction time up to the initial peak torque. The joints at a friction time of 1.5 s, i.e. just after the initial peak torque, had approximately 65% joint efficiency. This joint fractured at the welded interface, as shown in Fig. 9a. Thereafter, the joint efficiency slightly decreased with increasing friction time. On the other hand, the joint efficiency of the H34 joint by the applying a forge pressure of 60 MPa was approximately 20% at a friction time of 0.5 s, as shown in Fig. 8. The joint efficiency increased with increasing friction time. The joint efficiency was approximately 88% at 1.5 s, and all the joints fractured at the welded interface

and the H34 base metal (a mixed mode fracture), as shown in Fig. 9b. Thereafter, the joint efficiency decreased with increasing friction time. The tensile specimens under both friction welding conditions had a necking in the welded interface region, which is indicated by arrows (Fig. 9). The appearance of these joints differed from the H112 joints (Fig. 3). Figure 10 shows the Vickers hardness distribution across the welded interface at the half-radius of the joint at a friction time of 2.0 s. These joints had a softened region of about 12 mm in longitudinal direction across the welded interface. The minimum hardness of the softened region was approximately 75% of the hardness of the H34 base metal. Thus, the H34 joint did not achieve 100% joint efficiency at a friction pressure of 30 MPa.

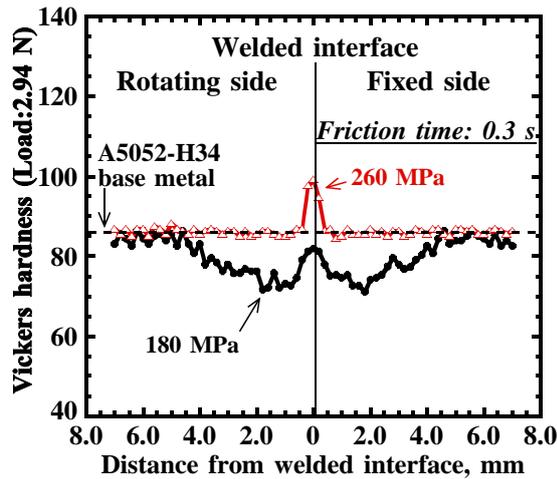
Improving joint properties of the A5052-H34 joint

In the previous reports, we showed that the temperature at the welded interface was able to be lower by increasing friction pressure.^{16,17} To improve the joint efficiency, we tried to weld the H34 joint at a friction pressure of 90 MPa. Figure 11 shows the relationship between the friction time and the joint efficiency of the H34 joints at a forge pressure of 180 MPa, plotted on the friction torque curve. The joints had approximately 93% joint efficiency at a friction time of 0.3 s, and it fractured in the H34 base metal. This joint efficiency was the maximum value obtained in our experiment.

Figure 12 shows the relationship between the forge pressure and the joint efficiency by the condition of a friction pressure of 90 MPa, and a friction time of 0.3 s. The joints had approximately 93% joint efficiency regardless of an increase in forge pressure. That is, the H34 joint did not achieve 100% joint efficiency, and the joints fractured at the H34 base metal. Figure 13 shows the Vickers hardness distribution across the welded interface at the half-radius of these joints. The joint at 180 MPa had a softened region, which was about 8 mm in longitudinal direction from the welded interface. The joint at 260 MPa had hardly any softened region. However, this



11 Relationship between friction time and joint efficiency of A5052-H34 joint corresponding to friction torque curve: friction speed of 27.5 s^{-1} , friction pressure of 90 MPa and forge pressure of 180 MPa

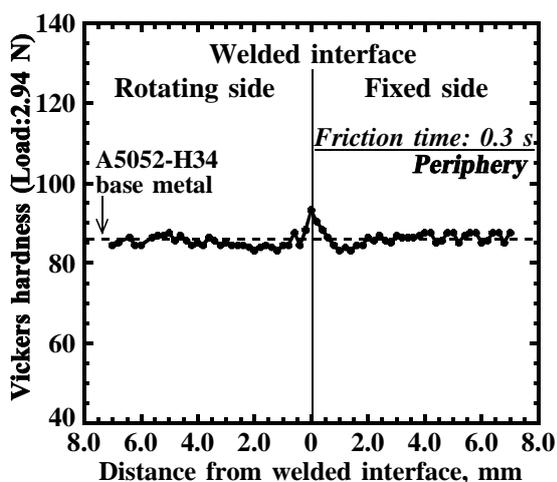


13 Vickers hardness distribution across welded interface at half radius of A5052-H34 joint: friction speed of 27.5 s^{-1} , friction pressure of 90 MPa and friction time of 0.3 s

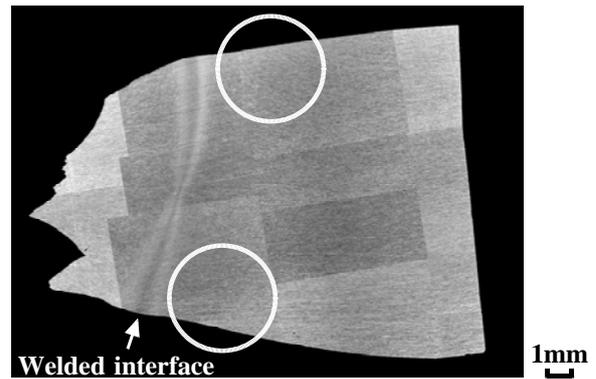
joint did not achieve 100% joint efficiency.

Discussion

Figure 14 shows the Vickers hardness distribution across the welded interface at the periphery of the joint at a friction time of 0.3 s and a forge pressure of 260 MPa. This joint had a slightly softened region at the periphery, which differed to that of the half-radius. The minimum hardness at the softened region was approximately 97% of the H34 base metal hardness. Figure 15 shows the cross-sectional appearance of the fractured specimen of the H34 joint after tensile testing at a forge pressure of 260 MPa. The welded interface did not have the not-joined region or defect after tensile testing at all. The fiber structure at the region corresponding to the fractured position flowed from the longitudinal direction to the outer surface of the H34 base metal, as indicated by the

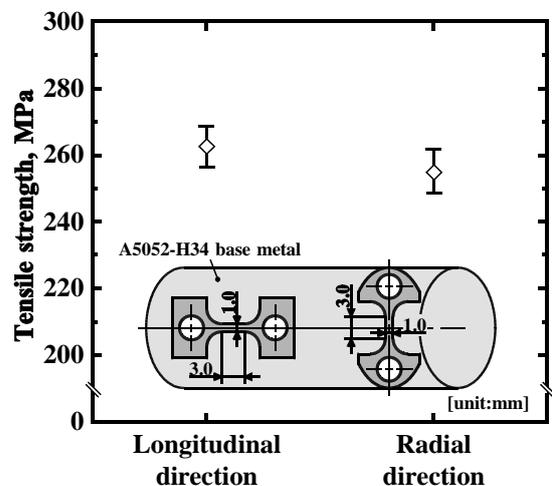


14 Vickers hardness distribution across welded interface at periphery portion of A5052-H34 joint: friction speed of 27.5 s^{-1} , friction pressure of 90 MPa, friction time of 0.3 s and forge pressure of 260 MPa



15 Cross-sectional appearance of fractured specimen of A5052-H34 joint after tensile testing: friction speed of 27.5 s^{-1} , friction pressure of 90 MPa, friction time of 0.3 s and forge pressure of 260 MPa

circles in Fig. 15. Generally, when the tensile test was carried out by using a circular rod specimen of the H34 base metal, the fiber structures flowed from the longitudinal direction to the centre axis of the tensile direction. The fiber structure flow of the friction welded joint differed from that of the H34 base metal. In the case of friction welding, the flow of the fiber structure at the welded interface and its adjacent region of the welded joint are turned perpendicularly to the outer surface from the longitudinal direction. That is, the fiber structure flow was not parallel to the outer surface of joint specimens. Figure 16 shows the tensile strength of the H34 base metal at both the longitudinal and radial directions. This experiment was carried out with the tensile specimens, which were cut along the longitudinal and radial directions from the H34 base metal by machining. The width, the length and the thickness of the parallel part were 1.0, 3.0, and 1.0 mm, respectively. The tensile strength of the longitudinal direction was approximately 263 MPa, and that at the radial direction was approximately 255 MPa. That is, the tensile strength along the radial direction was lower than that of the longitudinal direction. Hence, the H34 joint did not achieve 100% joint efficiency because it had the slightly softened region



16 Tensile strength of A5052-H34 base metal at both longitudinal and radial directions

at its periphery portion and the anisotropic properties between the longitudinal and radial directions. Although the further investigation is necessary to clarify the detail mechanical properties of the welded joints, it was clarified that the LHI method can tightly weld the H34 base metal.

Conclusions

This report described the mechanical properties of Al-Mg aluminium alloy (A5052) friction welded joints using the "Low Heat Input Friction Welding Method" (LHI method), developed by the authors. In particular, we investigated the mechanical properties of A5052 welded joints under various friction welding conditions. The following conclusions are provided.

1. For A5052-H112 base metal with 188 MPa in tensile strength;

(1) The joint, which was made by the condition of a friction speed of 27.5 s^{-1} , a friction pressure of 30 MPa, a friction time of 2.0 s (just after the initial peak torque) and a forge pressure of 60 MPa, had approximately 95% joint efficiency. It fractured at the welded interface and the base metal.

(2) To improve the joint efficiency, a joint was made with a forge pressure of 75 MPa which was the same as the yield strength of the A5052-H112 base metal. The joint had 100% joint efficiency and fractured at the base metal.

2. For A5052-H34 base metal with 259 MPa in tensile strength;

(1) A joint, made by the condition of a friction speed of 27.5 s^{-1} , a friction pressure of 90 MPa, a friction time of 0.3 s (just after the initial peak torque) and a forge pressure of 180 MPa, had approximately 93% joint efficiency and it fractured at the base metal. However, this joint had a softened region.

(2) A joint at a forge pressure of 260 MPa, which was the same as the ultimate tensile strength of the base metal, had hardly any softened region and it fractured at the base metal. However, the joint efficiency of this joint was approximately 93%.

(3) The fiber structure at the welded interface and its adjacent region of the joint after tensile testing was turned perpendicularly to the outer surface from the longitudinal direction of the base metal.

(4) The joint did not achieve 100% joint efficiency, because of a slightly softening at periphery portion and the difference of the anisotropic properties of the base metal between the longitudinal and radial directions.

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