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ORIGINAL ARTICLE

Friction welding technique and joint properties of thin-walled pipe friction-welded joint between type 6063 aluminum alloy and AISI 304 austenitic stainless steel

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Abstract The joint characteristics of thin-walled pipe friction-welded joint between AA6063 aluminum alloy (A6063) and AISI 304 stainless steel (SUS304) were investigated. The pipe had a thickness of 1.5 mm, and the joint was made with a friction speed of 27.5 rps and a friction pressure of 30 MPa. The joint, which was made by a continuous drive friction welding machine, had heavy deformation on the A6063 side during braking. To prevent deformation until rotation stop with braking, the joint was made by a technique in which the relative speed between both specimens instantly decreased to 0 when the setting friction time was finished, and consequently, the joining could be successfully achieved. The joint with a friction pressure of 30 MPa and a friction time of 0.4 s did not have the intermetallic compound (IMC) layer (interlayer) at the weld interface, although that with a friction time of 1.6 s had it. However, the joint with a forge pressure of 150 MPa had the A6063 side buckling. Moreover, the joint efficiency of the joint with flash was higher than that of the joint without flash because the inner flash of A6063 was stuck to the inner surface of the SUS304 side. Therefore, the joint should be made with the opportune friction time without the IMC interlayer and with the opportune forge pressure without buckling, and the accurate joint efficiency should be evaluated without flash.

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1 Introduction

The circular shape of a pipe or tube (referred to as circular pipe) is mainly used for the piping components of transport equipment for liquid or gas. They are widely used as various components or parts of a plant, pipeline, vacuum vessel, a variety of sensors or actuators, and so on. To produce such components, it is necessary to join two pipe shapes. Generally, the joint of a pipe shape with metallic materials including nonferrous metals is made by fusion welding methods such as shielded metal arc welding, TIG welding, and laser welding. However, the use of fusion welding methods for pipe shape is not convenient because it has some problems for actual welding construction such as sound weld bead formation [1]. In particular, it is difficult to weld a thin-walled circular pipe which has a pipe thickness to outside diameter ratio less than 0.1, since the joint properties will depend on the skill of the welder or working conditions [2]. That is, those welding methods are not easy to use for thin-walled pipe of similar material combinations, although several joints are made by hot isostatic pressing (HIP) which was described by Inoue [3] and Koizumi [4]. In this connection, HIP joint was also demonstrated for the joint of steel [5], Ti-6Al-4V [6], and stainless steel to nimonic superalloy [7]. On the other hand, the joint of a combination of dissimilar materials (referred to as dissimilar combination) has some advantages such as high functionality characteristics for industrial usage. Hence, an expansion for the use of thin-walled circular pipe joints with dissimilar combination is expected and widely used in various component parts. In particular, that joint will be used as pipe components at low temperature condition, wherein some examples of those parts were described by Morii [8], Kakimoto [9], and Aritoshi and Okita [10]. However, the joint of dissimilar combination has several severe problems. That is, the intermediate layer (interlayer) consisting of a brittle intermetallic compound (IMC) will be generated at the interface of both dissimilar metallic materials, so that the IMC interlayer will give fatal damage to equipments [11]. Hence, it is strongly necessary to develop a joining method to mass produce thin-walled circular pipe joints of dissimilar combination with high precision and high reliability, as well as without generating IMC at the interface.

Friction welding is well known among solid-state joining methods. This method is very useful for the joining of dissimilar combination, and the welding process is easily automated. Also, this welding method has several advantages over fusion welding methods such as high energy efficiency, narrower heat affected zone (HAZ), and low welding cost, which were described by Wang [12] and Maalekian [13]. In particular, friction welding is able to easily produce joints with high reliability; it is widely used in the automobile industry and applied to fabricate important parts such as drive shafts and engine valves. Moreover, this welding method can also provide the joint of dissimilar combination as well as the circular pipe. Some researchers have reported that the mechanical and metallurgical properties of the friction-welded joints of circular pipes of dissimilar combination show desirable characteristics. For example, Kawai et al. [14] and Ohkubo et al. [15] showed the results for the joint between various aluminum (Al) alloy and mild carbon steel, which had a wall thickness (referred to as pipe thickness) of 3 mm. However, research on the friction welding of circular pipe of dissimilar combination has been scant in comparison with that of similar combination such as those reports described by Eberhard et al. [16], Ogawa et al. [17], and Kumar and Balasubramanian [18]. Furthermore, those investigations were carried out using relatively thick pipe thickness that was thicker than 1 mm, i.e., the ratio of the pipe thickness to the outside diameter of the pipe was larger than 0.1. In particular, the joint characteristics with the thin-walled pipe such as the ratio of the pipe thickness to the outside diameter of the pipe below 0.1 were not described in detail because friction welding had a difficult point for dissimilar combination as well as a difficult point for thin-walled circular pipe.

In previous works [19], some of the authors obtained the result wherein the joint with the thin-walled circular pipe of austenitic stainless steel was successfully welded. In this case, when the setting friction time was finished, the fixed side specimen was simultaneously rotated in conjunction with the rotating side specimen, i.e., the relative speed at the weld interface was instantly decreased to 0, although the details of this friction welding technique will be described later. In particular, this friction welding technique did not have the final peak torque of the friction torque curve during the welding process. In addition, the joint is able to have less axial shortening (burn-off) and less flash (burr or collar) compared with the conventional method. Hence, if the joint of the thin-walled circular pipe of dissimilar combination is made by this friction welding technique, it will have successful joining.

This study presents further details of the friction-welded joint of thin-walled circular pipe of dissimilar combinations and discusses improvements of a joining method to obtain high joint tensile strength. The present paper focuses on the clarification of the joining phenomena during the friction process of friction welds between type 6063 Al alloy thin-walled pipe and AISI 304 austenitic stainless steel thin-walled pipe. In this report, the authors present the tensile strength of a welded joint with thin-walled circular pipe under various friction welding conditions. The authors also show the results of the joint created with the conventional method in contrast to those created with the friction welding technique developed by the authors. Furthermore, the authors propose that this friction welding technique is also a suitable technique for the welding of thin-walled circular pipe of dissimilar combinations.

2 Experimental procedure

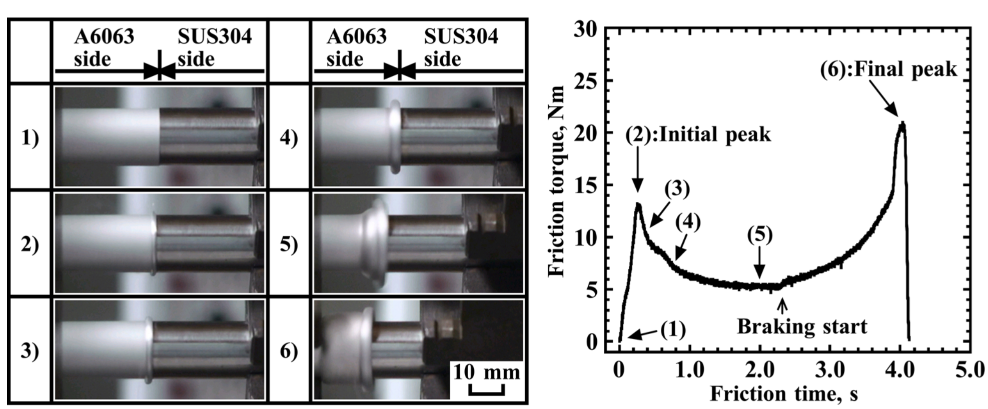
The materials used were AA6063-H18 (JIS A6063TD-H18, referred to as A6063) circular pipe and AISI 304 austenitic stainless steel (JIS SUS304, referred to as SUS304) circular pipe. These pipes had an outer diameter of 16 mm and an inner diameter of 13 mm, i.e., the ratio of the pipe thickness to the outside diameter of the pipes was 0.09375, which was below 0.1. This pipe size is regarded as a difficult combination for welding, as described above. The chemical composition of A6063 was 0.41Si-0.19Fe-0.52Mg-Al in balance (mass%), the ultimate tensile strength was 243 MPa, the 0.2 % yield strength was 225 MPa, and the elongation was 7 %. The chemical composition of SUS304 was 0.043C-0.3Si-0.025P-0.009S-8.04Ni-18.03Cr-Fe in balance (mass%), the ultimate tensile strength was 770 MPa, the 0.2 % yield strength was 596 MPa, and the elongation was 52 %. Both pipes were cut to 75 mm length as the friction welding specimen, and then all weld faying surfaces of the friction welding specimens were polished with a surface grinding machine before joining in order to eliminate the effect of surface roughness on the mechanical properties of the joint of dissimilar combinations [20].

A continuous (direct) drive friction welding machine was used for the joining. During the friction welding operations, the friction welding condition was set to the following combinations: a friction speed of 27.5 rps (1650 rpm), a friction pressure of 30 MPa, a range of friction times from 0.2 to 2.2 s, a range of forge pressures from 30 to 150 MPa, and a forge time of 6.0 s. In the actual experiment, the steel core was inserted into the holding (clamping) part of both friction welding specimens because that part prevents crushing by chucking. The joining behavior was recorded by a digital video camera. The friction torque during welding was measured with a load cell and recorded using a personal computer through an A/D converter with sampling times of 0.001 s.

The joint tensile test was carried out by using two types of joint tensile test specimens for clarification of the influence of flash to the joint strength. That is, one of the joint tensile test specimens had retained the inner and outer flashes that were exhausted from the weld interface, i.e., the flash was not removed. Also, the other joint tensile test specimen had no flash, i.e., only the flash was removed by a lathe. Furthermore, Vickers hardness test at low test force, i.e., the Vickers microhardness (referred to as Vickers hardness), was carried out for clarification of the joint properties. The hardness distribution was measured in a zigzag pattern, and its center line corresponded to the half thickness location of the pipe part on the adjacent region of the weld interface. Measuring load was 2.94 N, the measuring range was about 8.5 mm from the weld interface to both sides, and the measuring interval of the longitudinal direction for the joint was 150 μm and that of the radius direction was 50 μm (amplitude was 100 μm), respectively. This hardness test method was similar to that used in a previous report [21], and the softened and/or hardened region of the joint will be distinguished. That is, it is possible to clarify the softening and/or hardening of the joint by this measuring method. In this connection, as A6063 belongs to the heat-treated type Al alloy, its mechanical properties are improved by heat treatment in general, such as solution treatment plus artificial aging [22]. Actually, the joint, which was made by the solid-state joining methods [23, 24] as well as fusion welding methods [25–27], had changed in joint strength by heat treatment. Furthermore, the friction-welded joints had also changed in strength through heat treatment [28]. However, the material used in this study was A6063, and it had the H18 work hardening treatment. That is, this material was manufactured with work hardening to improve its strength such as tensile strength. Hence, the mechanical properties of the joint were not affected by the natural aging treatment, and it was clarified by preliminary experiments although the data was not shown here. Therefore, the tensile and hardness tests for the joint were carried out in an as-welded condition at room temperature without control of the natural aging time after welding. In addition, analysis via TEM-energy dispersive X-ray spectroscopy (EDS) was carried out to analyze the chemical composition at the adjacent region of the weld interface for the joint.

3 Results of the conventional method

To clarify the joining phenomena by using the conventional method, the joining behavior and friction torque during the friction welding process of the joint were investigated in detail. Figure 1 shows the example of the relationship between the joining behavior and the friction torque curve. In this case, the joint was made with a friction time of 2.2 s and a forge pressure of 30 MPa. Photos (1) to (6) in Fig. 1a correspond to the friction torque of (1) to (6) in Fig. 1b, respectively. Photo (1) shows the state at the weld faying surfaces as they contacted each other, and then the friction torque was rapidly increased. When the friction torque reached the initial peak of (2), the A6063 side was slightly upset (deformed) and exhausted the outer flash from the weld interface, which was indicated in photo (2). Thereafter, the friction torque decreased and the outer flash of the A6063 side increased with increasing friction time, as shown in photos (3) to (5). Then, the friction torque was increased by braking for a rotation stop, and it decreased to 0 after reaching the final peak of (6), and the joining was completely finished. The joint had heavy deformation at the A6063 side which was indicated in photos (5) to (6),



(a) Joining behaviour (b) Friction torque curve

Fig. 1 Example of **a** joining behavior and **b** friction torque curve by conventional method: friction time of 2.2 s i.e., the deformation of the joint during the braking process (braking deformation) was much larger than that of the friction process as shown in photos (1) to (4). However, the SUS304 side was hardly deformed during those processes.

In an attempt to reduce the flash on the A6063 side, the joint was made in a short friction time because the flash will be decreased with decreasing friction time. Figure 2 shows an example of the friction torque curve and the cross section of the joint, which was made with a friction time of 0.4 s and a forge pressure of 60 MPa. The friction torque curve before braking was similar to that of a friction time of 2.2 s as shown in Fig. 1b. However, the friction torque had also a large final peak torque by braking, and the outer and inner flashes of this joint were not uniformly generated at the weld interface. That is, the deformation of the A6063 side of the joint even with this friction time was very large, which was indicated in the photo in Fig. 2. In addition, the inner part of the pipe was bunged with flash completely, and the steel core which was inserted to the friction welding specimen of the A6063 side before joining was not removed from the joint. Moreover, the joint, which was made with another friction time or forge pressure, had also a large deformation (data not shown due to space limitations). In particular, the braking deformation of the A6063 side was much larger than that during the friction process as shown in Fig. 1. However, the SUS304 side did not have remarkable deformation. Hence, the large deformation of the A6063 side seems to be caused by the increase of the friction torque by braking, as shown by the friction torque curve in Fig. 2.

4 Improving the joining method

4.1 Suggestions for the friction welding technique

Based on the results of the conventional method, it is necessary to reduce the braking deformation during the rotation stop from the joint to obtain successful joining of the thin-walled circular pipe. As described in Section 1, some of the authors suggested the friction welding technique, and the thin-walled circular pipe of austenitic stainless steel made by this technique had less axial shortening and less flash compared to the conventional method [19]. Figure 3 shows the general view of a part of the friction welding machine. The fixed side chuck had an electromagnetic clutch, and the fixed side specimen was fixed with another chuck, which was connected with an electromagnetic clutch. When the clutch was released, the fixed side specimen was simultaneously rotated in conjunction with the rotating side specimen, i.e., the relative speed at the weld interface was instantly decreased to 0. Therefore, the braking time had a negligible effect on the joining phenomena, and the braking deformation of the joint during the rotation stop was extremely small. The detailed characteristics of this friction welding technique have been described in previous reports [19, 29]. If the thin-walled circular pipe joint of dissimilar combination is made by this technique, it will have less axial shortening and less flash being generated.

Figure 4 shows an example of the friction torque curve and the cross section of the joint, which was made by this friction welding technique. In this case, the joint was made with a friction time of 0.4 s and a forge pressure of 30 MPa. The

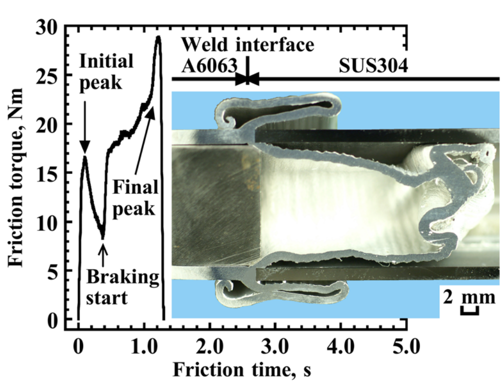


Fig. 2 Example of friction torque curve and cross section of joint by conventional method: friction time of 0.4 s and forge pressure of 60 MPa

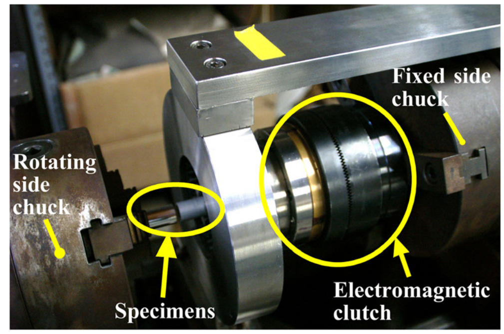


Fig. 3 General view of a part of the friction welding machine

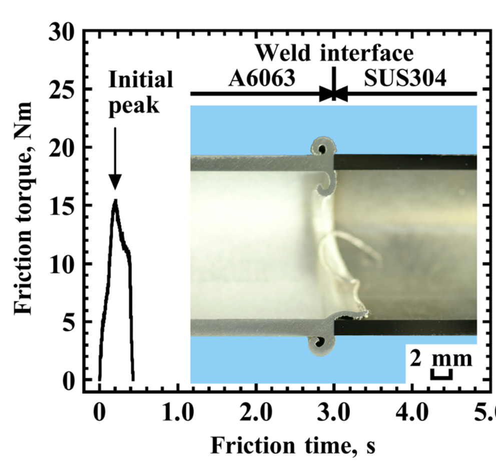


Fig. 4 Example of friction torque curve and cross section of joint by our friction welding technique: friction time of 0.4 s and forge pressure of 30 MPa

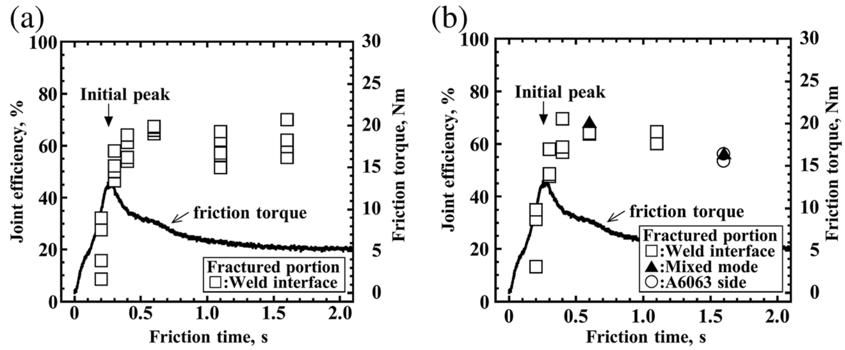


Fig. 5 Relationship between friction time and joint efficiency of joint, in relation to friction torque with forge pressure of 30 MPa at various joint tensile test specimens: **a** result of joint efficiency for joint tensile test specimen with flash and **b** result of joint efficiency for joint tensile test specimen without flash

friction torque curve before a setting friction time of 0.4 s was similar to that of the conventional method as shown in Fig. 2. However, the friction torque simultaneously decreased to 0 at a friction time of 0.4 s, i.e., when the friction process was finished. Thus, this friction torque did not have the final peak. In addition, the joining could be successfully achieved, which was indicated in the photo in Fig. 4. The flash of the joint was almost uniformly generated to the radial direction at the weld interface, and it was extremely smaller than that using the conventional method (see Fig. 2). Therefore, it is considered that the friction welding technique, in which the relative speed at the weld interface decreased to 0 when the friction process was finished, would be suitable for the joining of thin-walled circular pipes of dissimilar combination.

4.2 Joint tensile strength

Figure 5 shows the relationship between friction time and joint efficiency of the joints at various joint tensile test specimens. The joint efficiency was defined as the ratio of joint tensile strength to the ultimate tensile strength of the A6063 base metal. Figure 6 shows an example of the appearance of the joint tensile-tested specimen that had flash. Figure 7 shows those appearances without flash. In this case, a forge pressure was applied at an identical friction pressure, i.e., 30 MPa. When the joint was tested with flash using A6063 as shown in Fig. 5a, the joint efficiency was approximately 21 % at a friction time of 0.2 s (before the initial peak) and it had scattering. The joint efficiency increased with increasing friction time, and it was approximately 59 % at a friction time of 0.4 s, i.e., the friction torque was reached just after the initial peak. However, the joint efficiency was maintained with the range of 51 to 70 % in spite of increasing friction time, and all joints fractured from the weld interface as shown in Fig. 6. On the other hand, when the joint was tested without flash using A6063 as shown in Fig. 5b, the joint efficiency was approximately 27 % at a friction time of 0.2 s and it had scattering. The joint efficiency also increased with increasing friction time, and it was approximately 62 % at a friction time of 0.4 s. Then, the joint efficiency slightly decreased with increasing friction time, and it was approximately 55 % joint efficiency at a friction time of 1.6 s. Some joints fractured between the weld interface and the A6063 side (referred to as mixed mode fracture) as shown in Fig. 7b, although all joints before a friction time of 0.4 s fractured from the weld interface as shown in Fig. 7a. In addition, some joints at a friction time of 1.6 s fractured from the A6063 side as shown in Fig. 7c. However, the joint efficiency of 100 % was not achieved. Hence, the joint should be made by applying forge pressure that was higher than the applied friction pressure to obtain high joint efficiency.

4.3 Improving joint efficiency

To improve the joint efficiency, the effect of forge pressure on joint efficiency was investigated. Figures 8 and 9 show the relationship between the forge pressure and the joint efficiency of the joints at various joint tensile test specimens. Figure 10 shows examples of the appearances of the joint tensile-tested specimens that had flash. In this case, a friction time was set to 0.4 and 1.6 s, respectively. When the joint was made with a friction time of 0.4 s and a tensile test was carried out with flash using A6063 as shown in Fig. 8a, the joint efficiency slightly increased with increasing forge pressure and it was approximately 65 % at a forge pressure of 105 MPa. Then, the joint efficiency was approximately 75 % at forge pressures of 120 and 135 MPa. Some joints had mixed mode fracture as

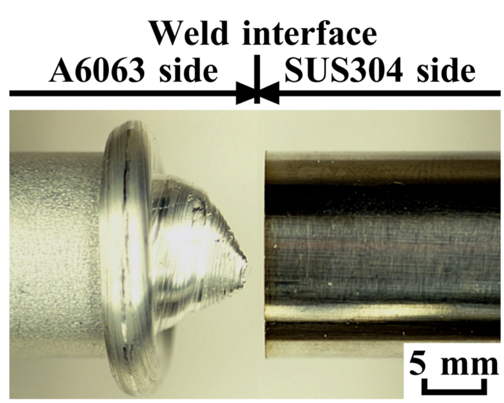


Fig. 6 Example of appearance of joint tensile-tested specimen with flash: weld interface fracture

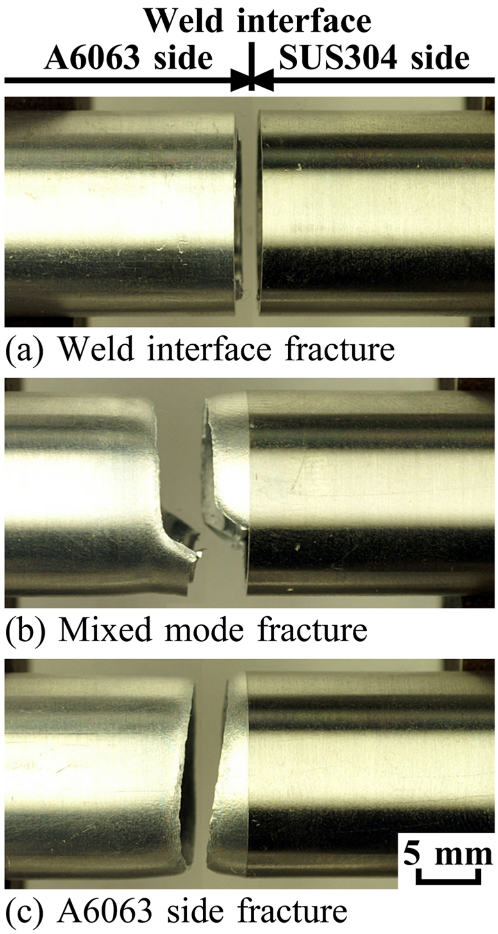


Fig. 7 Examples of appearances of joint tensile-tested specimens without flash: **a** weld interface fracture, **b** mixed mode fracture, and **c** A6063 side fracture

shown in Fig. 10a and the others had fracture on the A6063 side as shown in Fig. 10b. However, the joint efficiency had large scattering, and the suitable value of the forge pressure for all joints with fracture on the A6063 side was not obtained in this study. On the other hand, the joint efficiency was maintained with the range of 52 to 70 % in spite of increasing forge pressure when the joint was made at a friction time of 0.4 s and a tensile test was also carried out without flash as shown in Fig. 8b. In addition, all joints with a forge pressure of 135 MPa had fracture on the A6063 side as shown in Fig. 7c. That is, when the joint was made with a forge pressure of 135 MPa, all joints fractured from the A6063 side as shown in Fig. 7c. Furthermore, when the joint was made at a friction time of 1.6 s as shown in Fig. 9, its joint efficiency with flash was 55 to 76 % and that without flash was 53 to 65 %, respectively. Almost all joints with flash had fracture on the weld interface as shown in Fig. 6, and almost all joints without flash had the mixed mode fracture as shown in Fig. 7b. That is, the result at a friction time of 1.6 s resembled that of a friction time of 0.4 s, although the joint strength at that friction time (1.6 s) was not measured because it had heavily deformed. Furthermore, although those joints were welded at the same friction welding condition, the joint efficiency of the joint with flash was higher than that of the joint without flash. The reason of those results will be described later.

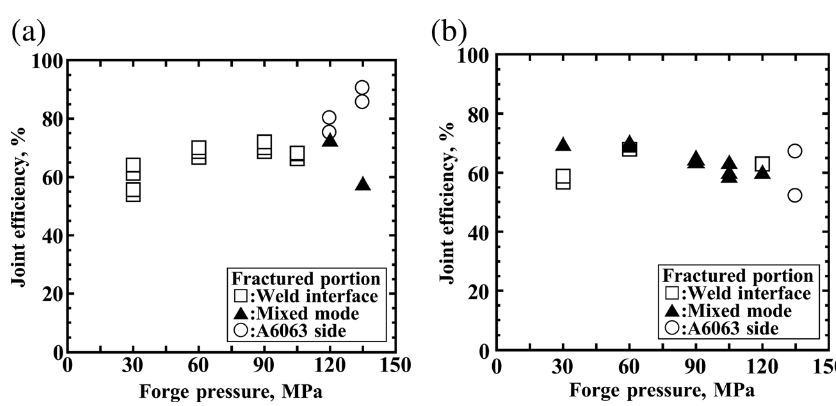
5 Discussion

Based on the above results, it was clarified that the joint without flash had fracture on the A6063 side at a friction time of 0.4 s with a forge pressure of 135 MPa. However, the joint efficiency of 100 % was not achieved, and the joint strength differed regardless of the presence or absence of flash. To clarify the opportune friction welding condition and the influence of the flash for joint strength, those parameters were investigated as follows.

5.1 Influence of friction time

To clarify the influence of friction time on joint strength, the cross section of the joint in detail was investigated. Figure 11 shows the TEM images and EDS analysis results of the adjacent region of the weld interface of the joint. In this case, a forge pressure was applied at an identical friction pressure (30 MPa). The distribution lines corresponding to Al, Cr, Fe, and Si by EDS analysis of the joint with a friction time of 0.4 s

Fig. 8 Relationship between forge pressure and joint efficiency of joint with friction time of 0.4 s at various joint tensile test specimens: **a** result of joint efficiency for joint tensile test specimen with flash and **b** result of joint efficiency for joint tensile test specimen without flash



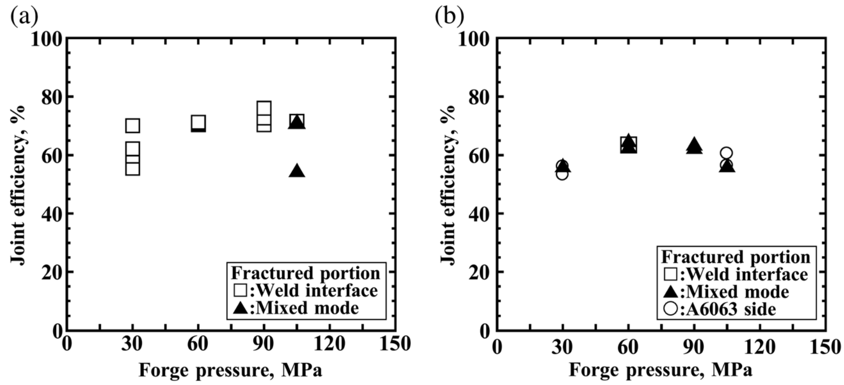


Fig. 9 Relationship between forge pressure and joint efficiency of joint with friction time of 1.6 s at various joint tensile test specimens: **a** result of joint efficiency for joint tensile test specimen with flash and **b** result of joint efficiency for joint tensile test specimen without flash

as shown in Fig. 11a had no plateau part at the weld interface although those lines were slightly varied. That is, this joint did not have an IMC interlayer at the weld interface, and that with a forge pressure of 135 MPa was fractured at the A6063 side as shown in Fig. 7c. On the other hand, the distribution lines corresponding to Al, Cr, and Fe had a plateau part at the weld interface of the joint with a friction time of 1.6 s as shown in Fig. 11b, although the weld interface was also slightly unclear. That is, this joint had an IMC interlayer and its width was about 25 nm. The composition of the IMC interlayer was approximately 77Al-14Fe-3Cr in atomic percent. Moreover, the distribution corresponding to Si had a plateau part at the weld interface of this joint. Hence, when the joint was made with a long friction time such as 1.6 s, an IMC interlayer was generated at the weld interface. In this connection, the joint strength of the joint with a friction time of 1.6 s and high forge pressure was not measured. However, the joint will be able to estimate that the joint fractured portion will be affected by the IMC interlayer, since it was reported that the IMC interlayer was not decreased by adding high forge pressure [21]. Furthermore, many researchers such as Fukumoto et al. [30], Reddy et al. [31], Sahin [32], Shubhavardhan et al. [33], and Ashfaq et al. [34] have reported that the IMC interlayer was observed in similar material combinations in their studies. Then, the interlayer affected the joint strength, and the joint was fractured from the weld interface. In those reports, the IMC interlayer was described as Fe_2Al_5 or $FeAl_3$ though detailed compositions of its interlayer differed [30, 31, 34]. Hence, the IMC interlayer as shown in Fig. 11b was considered as mainly Fe_2Al_5 or $FeAl_3$, although further investigation will be needed to elucidate the detailed characteristics of this IMC interlayer. Those layers were also observed with other welding methods such as friction stir spot welding [35], resistance spot welding [36, 37], laser welding [38, 39], and gas metal arc welding [40]. Hence, because those layers are brittle materials [41], the IMC interlayer will give fatal damage to equipments [11] if the joint will be used. Thus, it is desirable that the joint does not have an IMC interlayer at the weld interface. Therefore, the joint should be made with the opportune friction time for the joint not having the IMC interlayer, although the joint strength as shown in Figs. 8 and 9 had similar results. In this study, it is desirable that friction time is set to 0.4 s.

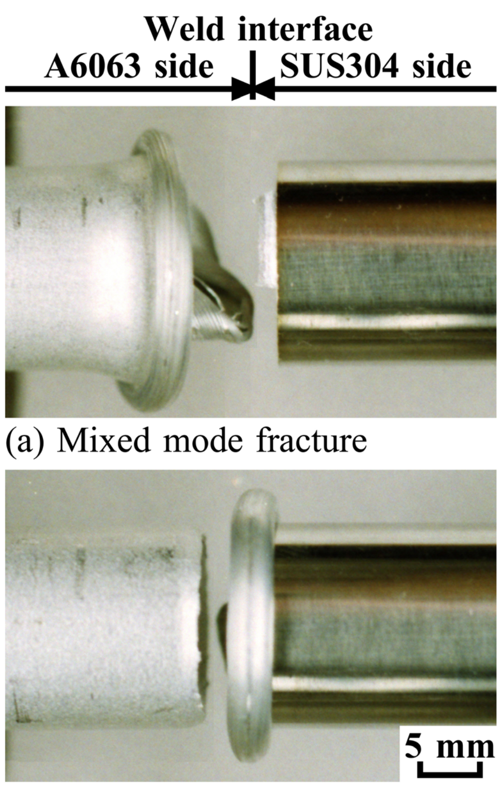


Fig. 10 Examples of appearances of joint tensile-tested specimens with flash: **a** mixed mode fracture and **b** A6063 side fracture

5.2 Influence of forge pressure

To clarify the influence of forge pressure on the fractured portion of the joint, the hardness distribution of the adjacent region of the weld interface and the deformation of the joint were investigated, since the fractured portion of the joint differed regardless of increasing forge pressure although the joint efficiency was maintained approximately 60 % as shown in

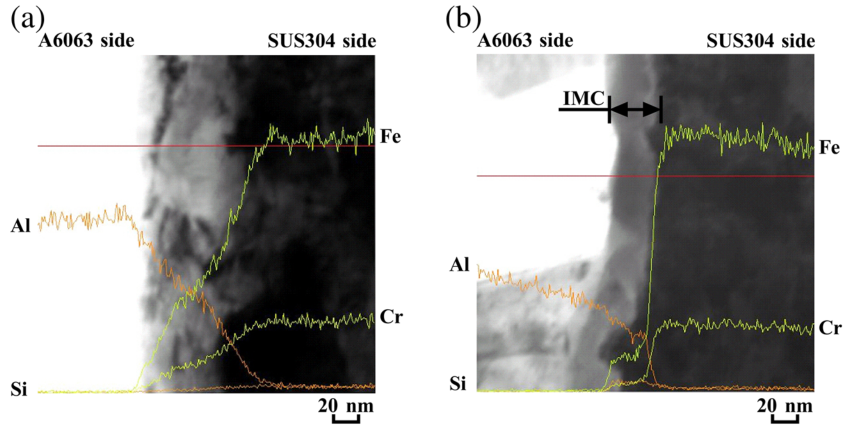


Fig. 11 TEM images and EDS analysis results of adjacent region of weld interface for joint at various friction times: **a** 0.4 s and **b** 1.6 s

Fig. 8. Figure 12 shows examples of Vickers hardness distributions across the adjacent region of the weld interface for the joints at various forge pressures. Those graphs also showed the results of hardness for both base metals, which was measured with the same method. When the joint was made with a forge pressure of 30 MPa as shown in Fig. 12a, it had a softened region that extended about 5.5 mm in the longitudinal direction from the weld interface on the A6063 side. The minimum hardness of that region was approximately 68 % of the A6063 base metal. In addition, the hardness distribution of the SUS304 side did not have the softened and/or hardened regions, although it had scattering. Therefore, it was considered that a softened region at the adjacent region of the weld interface of the joint was generated because A6063 base metal had work hardening treatments. That is, the softened region was generated at the adjacent region of the weld interface of the A6063 side, and it was produced with annealing and recrystallization by friction heat and deformation [32, 42]. The softened region of the friction-welded joint was also observed which was made with another Al alloy [34, 43, 44] as well as type 6000 series of Al alloy [32, 45, 46]. Incidentally, the joint had also a similar softened region, which was made by fusion welding methods such as MIG welding [25, 26] and laser welding [27]. On the other hand, when the joint was made with a forge pressure of 135 MPa as shown in Fig. 12b, it had also a softened region that extended about 2.6 mm in the longitudinal direction from the weld interface on the A6063 side, and the minimum hardness was of the same value

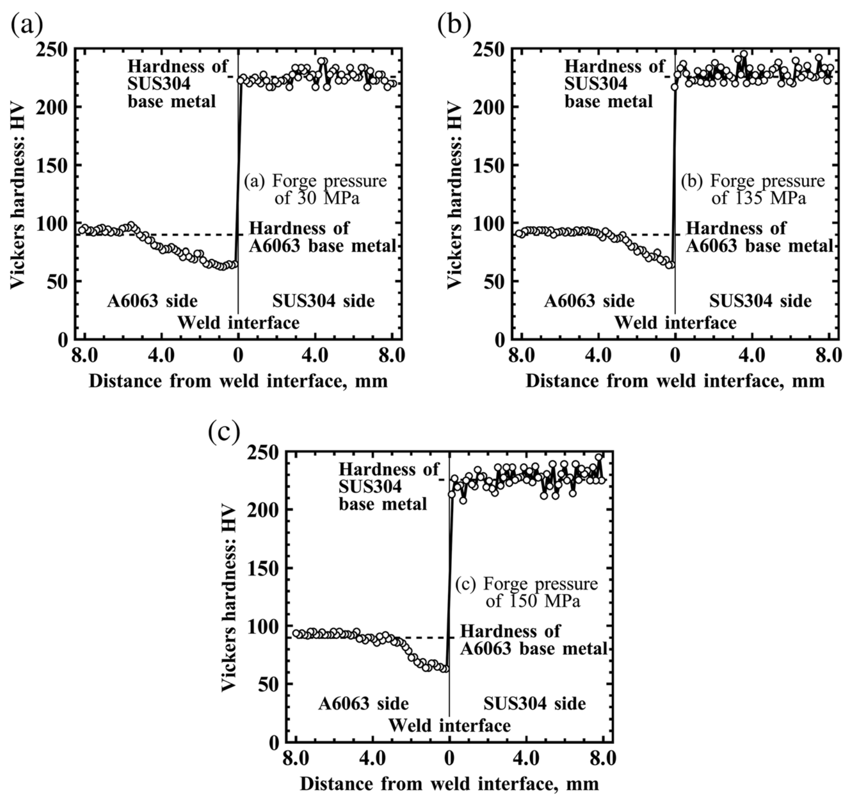


Fig. 12 Vickers hardness distributions across adjacent region of weld interface of joints with friction time of 0.4 s at various forge pressures: **a** 30 MPa, **b** 135 MPa, and **c** 150 MPa

as with the joint with a forge pressure of 30 MPa. That is, the area of the softened region was decreased at a forge pressure of 135 MPa. Therefore, it was clarified that the joint at a forge pressure of 135 MPa was fractured from the A6063 side, although the joint efficiency of 100 % was not achieved. However, the hardness distribution of the joint with a forge pressure of 150 MPa as shown in Fig. 12c resembled that of 135 MPa, i.e., the softened region was not decreased with increasing forge pressure. Hence, it is estimated that joint efficiency will be not able to increase by a forge pressure of 150 MPa or higher. In this connection, the softened region was not decreased with increasing forge pressure as shown in Fig. 12b, c. Hence, one of the reasons for the softened region in the A6063 side was that the joint was accompanied by annealing and recrystallization during the cooling stage after welding by friction heat which was kept into the exhausted flash from the weld interface, although further investigation will be needed to elucidate the detailed characteristics of the joint.

Figure 13 shows the appearances of the joints at various forge pressures. When the joint was made with a forge pressure of 30 MPa as shown in Fig. 13a, it had the outer flash which was uniformly generated to the radial direction at the weld interface. The appearance of the joint with a forge pressure of 135 MPa as shown in Fig. 13b resembled that of 30 MPa, although the flash was increased. However, when the joint was made with a forge pressure of 150 MPa as shown in Fig. 13c, it had buckling at the adjacent region of the weld interface on the A6063 side which was indicated by an arrow. That is, the joining could not be successfully achieved at this forge pressure. A similar result was obtained in a similar combination of stainless steel thin-walled pipes [19]. Hence, the joint without buckling should be made with the opportune forge pressure. In this study, it is desirable that a forge pressure is set to 135 MPa.

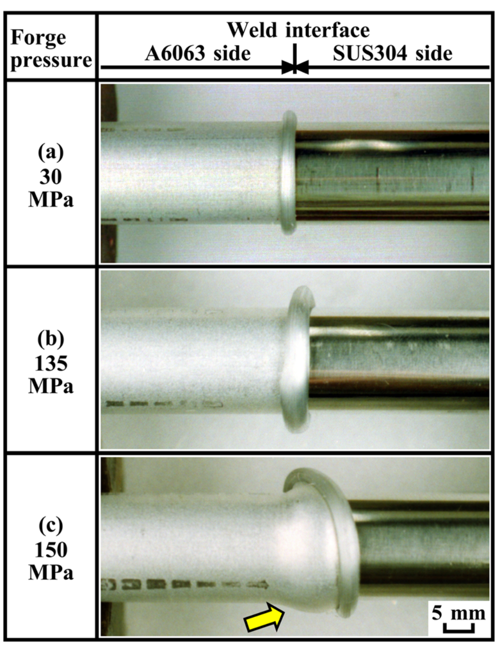


Fig. 13 Appearances of joints with friction time of 0.4 s at various forge pressures: **a** 30 MPa, **b** 135 MPa, and **c** 150 MPa

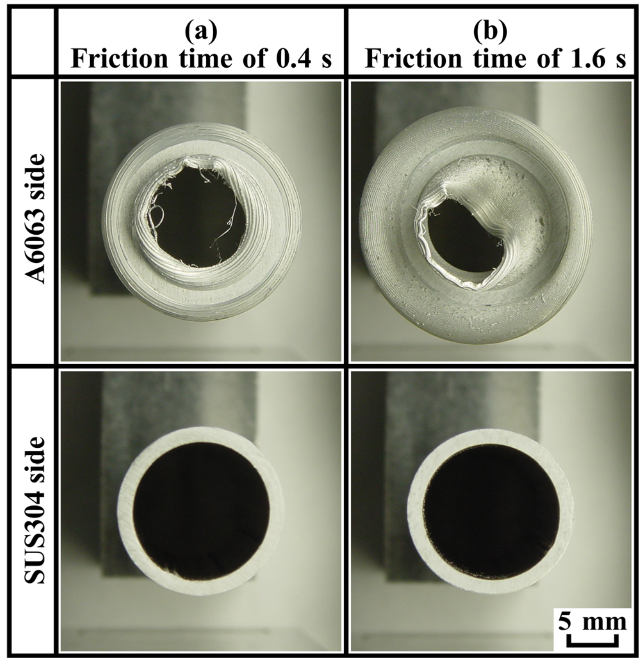


Fig. 14 Examples of fractured surfaces of tensile-tested specimens of joints with flash at various friction times: **a** 0.4 s and **b** 1.6 s

5.3 Influence of flash

To clarify the difference of the joint strength for the joint with or without flash as shown in Figs. 5, 8, and 9, the tensile-tested specimen was observed. Figure 14 shows the fractured surfaces of the tensile-tested specimens of the joints with flash at various friction times. In this case, a forge pressure was also applied at an identical friction pressure (30 MPa). When the joint was made at a friction time of 0.4 s as shown in Fig. 14a, the A6063 side had outer and inner flashes of A6063, and the SUS304 side hardly had flash. The fractured surfaces of the joint at a friction time of 1.6 s as shown in Fig. 14b resembled that of a friction time of 0.4 s. However, the exhausted flash of the A6063 side of this joint was larger than that of a friction time of 0.4 s, i.e., the flash was increased with increasing forge pressure. In particular, this joint had a large inner flash, and the inner diameter part was mostly bunged by that flash. Of course, the joint with high forge pressure had also a large inner flash as well as a large outer flash although those data were not shown due to space limitations. Hence, it was considered that the inner flash was stuck to the inner surface of the SUS304 side, i.e., it affected the joint strength. That is, the joint efficiency of the joint with flash increased with increasing forge pressure as shown in Fig. 8a was able to estimate. However, the result of the joint efficiency of the joint with flash was not an accurate result because the joint strength was affected by flash. On the other hand, the accurate result of the joint efficiency is shown in Fig. 8b, and the data was evaluated by using the joint without flash. Therefore, the accurate joint efficiency must be evaluated by the joint without flash.

Based on the above results, the thin-walled circular pipe joint between A6063 and SUS304 should be made by the friction welding technique in this study. Then, the joint with fracture on the A6063 side should be made with opportune friction welding condition as follows: the opportune friction time should be 0.4 s for the joint not to have the IMC interlayer and the opportune forge pressure should be 135 MPa to avoid buckling. In addition, the joint strength must be evaluated by the joint without flash because the inner flash of A6063 was stuck to the inner surface of the SUS304 side. In particular, the opportune friction time was almost the same just after the initial peak of the friction torque (see Fig. 5b). Hence, this friction welding technique, which will be carried out with a friction time just after the initial peak of the friction torque, is similar to the low heat input (LHI) friction welding method (referred to as LHI method) that was named by the authors in previous reports [29, 47]. The LHI method has several advantages such as less heat input [29] and less softening area [47, 48], and the conventional method has some of these characteristics as discussed in Section 1. Although further investigation will be needed to elucidate the detailed joint properties such as a leak test, this technique is one of the suitable methods for the joint of thin-walled circular pipes of dissimilar combination because the low heat input during the welding process can restrain buckling at the adjacent region of the weld interface.

6 Conclusions

This paper described the joint characteristics of the friction-welded joint between type 6063 aluminum alloy (A6063) thin-walled pipe and AISI 304 austenitic stainless steel (SUS304) thin-walled pipe. The pipe had the thickness of 1.5 mm, and the joint was made with a friction speed of 27.5 rps and a friction pressure of 30 MPa. The following conclusions are drawn:

1. When the joint was made by a continuous drive friction welding machine (conventional method), it had heavy deformation on the A6063 side during braking. This result was due to the deformation of the A6063 side, which was caused by the increase of friction torque during braking, in spite of the setting friction time.
2. To prevent deformation until rotation stop with braking, the joint was made by the technique where the relative speed between both specimens instantly decreased to 0 when the setting friction time was finished. The joining with a short friction time could be successfully achieved by this friction welding technique, and the joint had no deformation on the A6063 side during braking.
3. The joint at a friction time of 0.4 s obtained approximately 60 % joint efficiency, and it did not vary with a long friction time such as 1.6 s. In addition, the joint with a friction time of 0.4 s did not have the intermediate layer consisting of the IMC interlayer at the weld interface, although that with a friction time of 1.6 s had its interlayer.
4. The joint efficiency of 100 % was not achieved because the joint had a softened region in the A6063 side. The softened region was not reduced from the joint regardless of increasing forge pressure. However, when the joint was made at a friction time of 0.4 s with a forge pressure of 135 MPa, it had fracture on the A6063 side. On the other hand, when the joint was made with high forge pressure such as 150 MPa, it had buckling at the adjacent region of the weld interface on the A6063 side.
5. The joint efficiency of the joint with flash was higher than that of the joint without flash. The reason for this result was due to the exhausted inner flash of A6063.

In conclusion, the joint should be made with the opportune friction time for the joint not having the IMC interlayer with the opportune forge pressure to avoid buckling. Moreover, the accurate joint efficiency should be evaluated by the joint without flash because the inner flash of A6063 was stuck to the inner surface of the SUS304 side.

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