Joining phenomena during friction stage of A7075-T6 aluminum alloy friction weld

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

This paper describes the effect of friction welding conditions on joining phenomena during the friction stage of type 7075-T6 aluminum alloy (A7075) friction welds. The friction torque had wear and seizure stages until the initial peak torque when A7075 was welded under high friction speed and low friction pressure, i.e., 27.5 s^{-1} and 30 MPa. Initial seizure and joining began at the central region (centre axis) of the welded interface, and extended toward the peripheral region (outer surface). On the other hand, when A7075 was welded under high friction speed and high friction pressure, i.e., 27.5 s^{-1} and 90 MPa, almost no wear stage existed before the initial peak torque. Initial seizure and joining began at the peripheral region of the welded interface and extended towards the central region. Then, the friction torque reached to the initial peak torque when the welded interface was joined completely and upsetting of both base metals started. As a conclusion, the joining mechanism of A7075 friction welding was similar to that of low carbon steel.

Keywords: Friction welding, A7075-T6 aluminum alloy, Joining phenomena, Central region, Peripheral region

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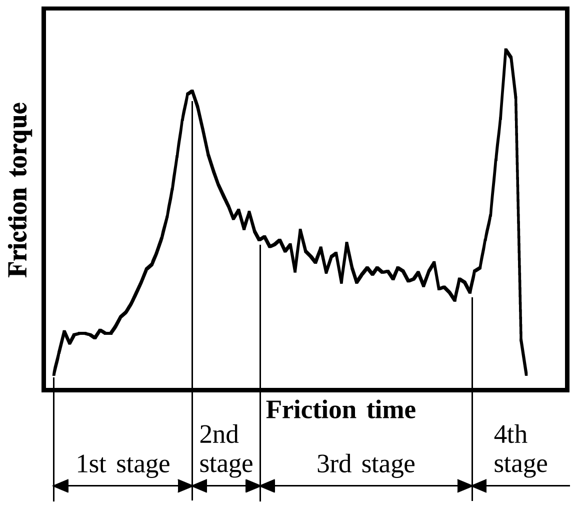
INTRODUCTION

Friction welding is well known amongst solid state joining methods. As this method is very useful for the joining of dissimilar materials, it is widely used in the automobile industry and applied to fabricate important parts such as drive shafts, engine valves, and so on.

Hasui et al.[1] concluded that the friction welding cycle could be divided into four stages on the basis of the friction torque curve for a steel joint, as shown in Fig.1. In the first stage friction torque increases from zero. That is, the faying (contacting) surfaces of both specimens (workpieces) contact each other and friction torque reaches its initial peak torque. The second stage is one in which the friction torque reaches a steady state (steady equilibrium) after the initial peak. The third stage is the steady state equilibrium. The fourth stage is the forge (upset) stage; in this stage friction torque increases when a brake is applied, and then drops to zero when the rotation stops. Many researchers have reported[2-7] on the joining phenomena of the third and fourth stages in the friction welding process, whilst others[8,9] described those of the first and second stages. However, it was difficult to compare these results because the materials, specimen shapes and friction welding conditions were different from each other. In addition, the joining phenomena of the first and second stages are very complicated, and difficult to understand because of their unstable thermal conditions. The joining mechanism of friction welding was not clarified, so that the friction welding conditions for material combinations are determined by trial and error.

In the previous work,[10-13] we clarified the joining mechanism during the friction welding process for carbon steel. Furthermore, we also showed that low carbon steel friction welded joints obtained 100% joint efficiency by using only the first stage (up to the initial peak torque) of the friction welding process without forge pressure.[14-16] We named this friction welding method as "The Low Heat Input Friction Welding Method" (The LHI method).[15,16] LHI method provides more advantages for welded joints than conventional methods, e.g., less axial shortening (burn-off), less flash (burr or collar) and so on. However, the joining mechanism of another materials such as aluminum alloys may differ from that of low carbon steel, because the mechanical properties such as tensile strength and the thermal properties such as thermal conductivity are different. Further investigations are necessary to clarify the joining phenomena of other materials, when the LHI method will be applied to them.

The authors have been research carrying out to clarify the joining mechanism in the friction stage for aluminum alloys. In the present work, we investigated the joining phenomena and mechanism of the friction stage for solution treated and aged an Al-Zn-Mg alloy (hereafter called as A7075) of which the ultimate tensile strength is the highest in



1 Definition of stages on friction torque curve

aluminum alloys.

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 surfaces were polished from 0.05 to 0.15 μm in roughness as the center line average height.

A continuous (direct) drive friction welding machine was used for the joining. During friction welding operations, the friction speed and pressure were set to the following combinations: 27.5 revolutions per second (s^{-1}) and 30 MPa, and 27.5 s^{-1} and 90 MPa. No forge pressure was applied in order to clarify the joining phenomena of the friction welding process. The joining behavior was recorded by a digital video camera. The torque during the friction stage was measured with a load-cell, and recorded with a personal computer through an A/D converter with a sampling time of 0.05 s. The friction torque measured with the load-cell lacked continuity in the stepwise part as shown in Fig.2(b), because the minimum resolution of the friction torque was approximately 1 Nm. However, sufficient data could be obtained in order to understand the joining phenomena of the friction stage.

Incidentally, the joining phenomena at the welded interface slightly changes during braking (rotation stopping) of a continuous drive friction welding process (conventional method). The rotation of the specimen does not stop instantly when braking force is applied, so that deformation of welded interface occurs during braking. To observe the joining phenomena, it was essential to eliminate this deformation during braking for the friction welded joint. In this study, we performed two types of experiments with using the same methods as in the previous reports.[10-16] Detailed experimental methods are as follows.

(1) The fixing (steady) side chuck was directly connected to a hydraulic cylinder. The fixing side specimen was simultaneously and forcibly separated from the rotating side specimen when the friction time expired. The welded interface was separated at each friction time and observed.

(2) The fixing side specimen was fixed with an electromagnetic clutch. When the clutch was released, the relative speed between both specimens instantly decreased to zero. In this case, the friction pressure could be maintained (loaded), so that the effect of the deformation on the welded joint during braking time could be considered to be negligible. As the braking time was smaller than 0.04 s, i.e., one rotation of the specimen, its effect was negligible.

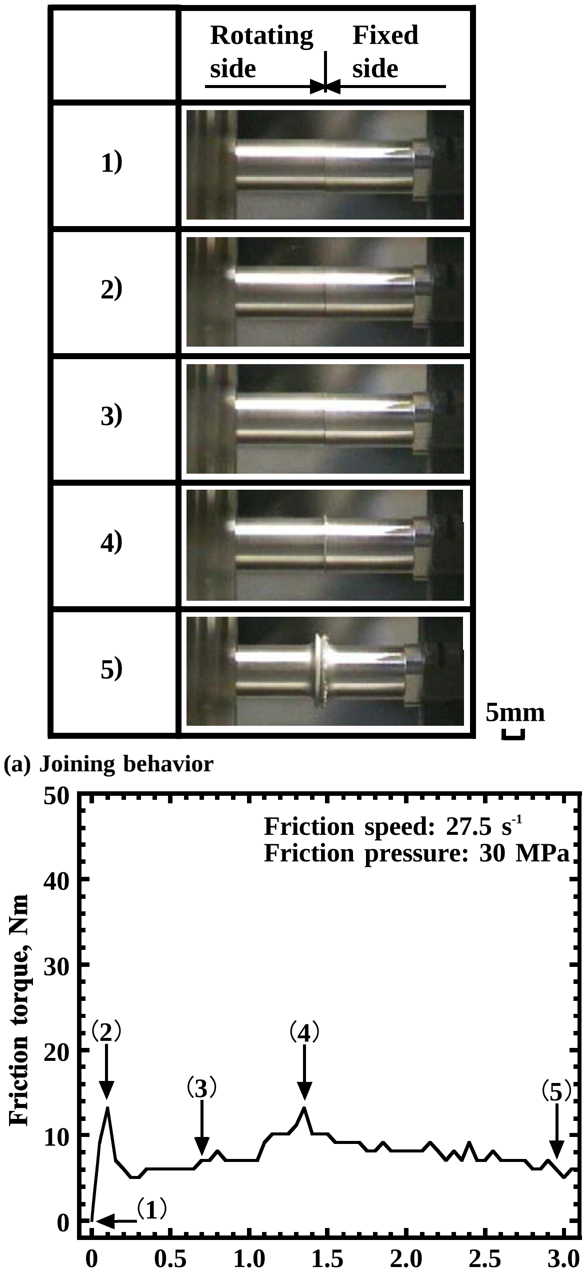
In experimental method (1), the transitional joining phenomena were clarified when the weld faying surfaces contacted each other at each applied friction time. In experimental method (2), the cross-sectional appearances of welded interface regions were observed at each applied friction time. To clarify them, the cross-sections of welded joints were etched with a water based reagent solution of 6% nitric acid and 2% hydrofluoric acid.

RESULTS

Relationship between joining behavior and friction torque

Figure 2 shows the relationship between the joining behavior and the friction torque with a friction pressure of 30 MPa. Photos 1) to 5) in Fig.2(a) are corresponding with in the friction torque of (1) to (5) in Fig.2(b), respectively. Photo 1) shows the state at the weld faying surfaces as they contacted each other; then the friction torque was increased. Photos 2) and 3) were similar to 1), when the friction torque was maintained nearly constant between (2) and (3). Then, the friction torque reached to the initial peak torque of (4), and both base metals were upset as shown in photo 4). However, the initial peak torque was not so clear for the A7075 joint as that of low carbon steel joint with the same friction welding conditions.[10] Thereafter, the friction torque slightly decreased, and the upsetting increased with increasing friction time. In this case, the elapsed time for initial peak torque was almost same as that of low carbon steel one.[10] The friction torque prior to the initial peak torque could be divided into wear and seizure stages, and the initial seizure and joining began at the central region (centre axis) in the friction welding conditions.

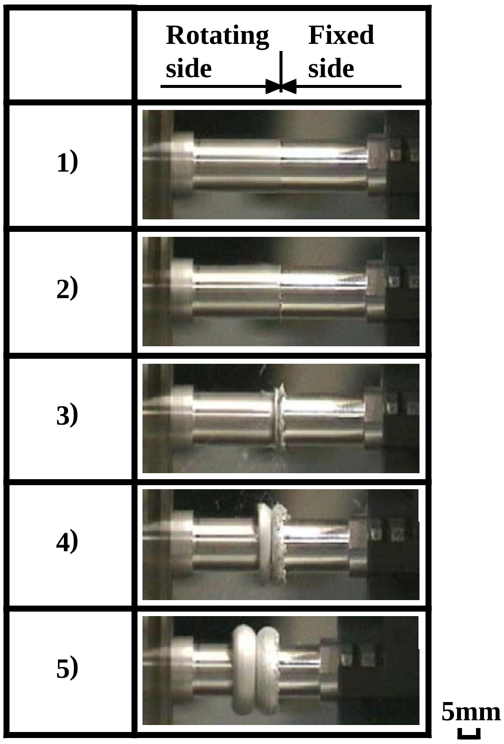
Figure 3 shows the relationship between the joining



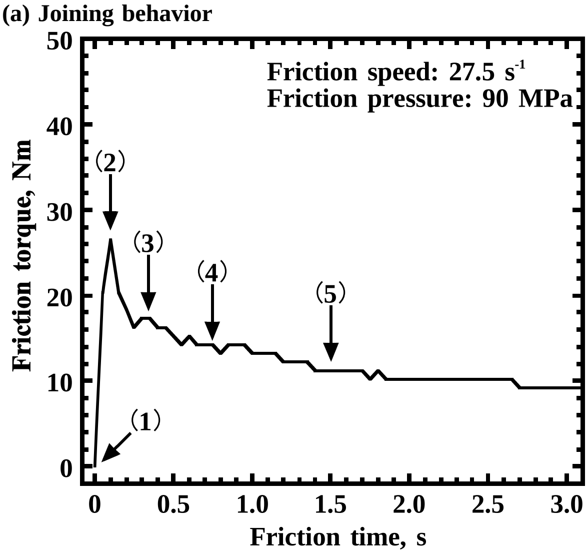
(a) Joining behavior

(b) Friction torque curve

2 Joining behavior and friction torque curve during friction welding process: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa



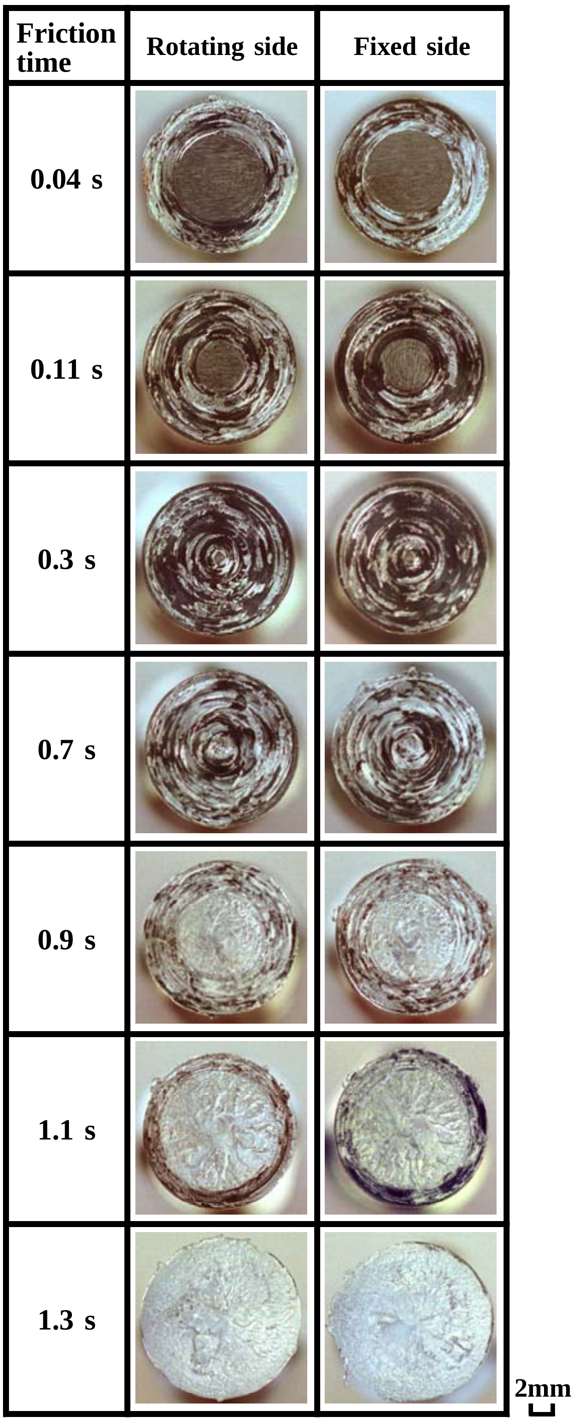
(a) Joining behavior



(b) Friction torque curve

3 Joining behavior and friction torque curve during friction welding process: friction speed of 27.5 s^{-1} and friction pressure of 90 MPa

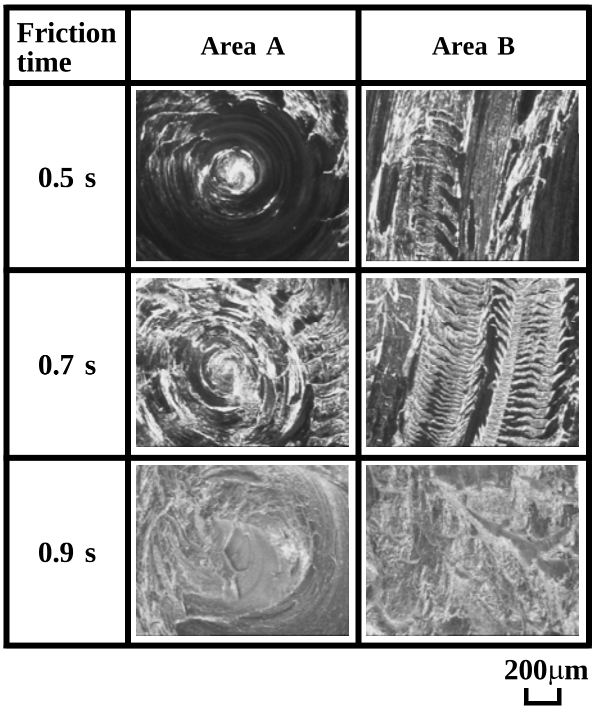
behavior and the friction torque of 90 MPa. Photos 1) to 5) in Fig.3(a) are corresponding with in the friction torque of (1) to (5) in Fig.3(b), respectively. Photo 1) shows when the weld faying surfaces initially contacted each other. When the friction torque reached to the initial peak torque, both base metals were slightly upsetting as shown in photo 2). The initial peak torque was observed clearly and larger than that of 30 MPa as shown in Fig.2(b). The friction torque decreased, and the upsetting increased with increasing friction time. The elapsed time for the initial peak torque of 90 MPa was shorter than that of 30 MPa. The friction torque prior to the initial peak torque included no wear stage, and the initial seizure and joining began at the peripheral region (outer surface) in this set of friction welding conditions.



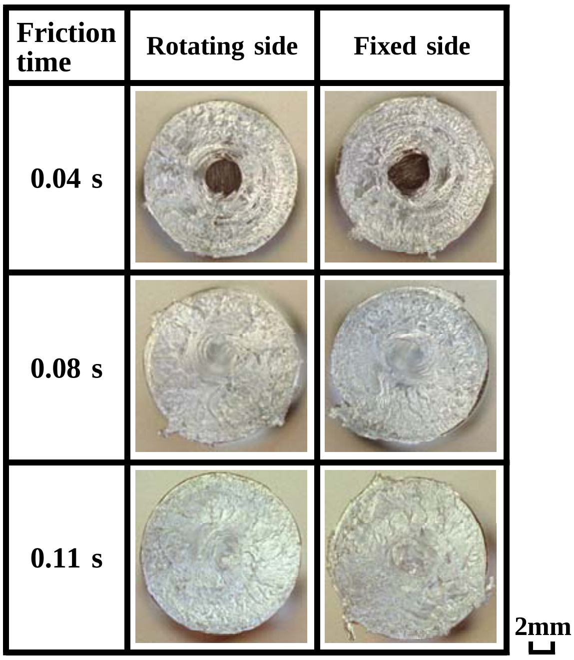
4 Appearances of welded interfaces after welding: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa

Transitional changes of the welded interface

The appearances of the welded interfaces joined by 30 MPa with experimental method (1) are shown in Fig.4. When the friction time was 0.04 s, i.e., the base metals rotated once, concentric rubbing marks were observed at the peripheral region on the fixed and rotating sides. This indicates that wear of both weld faying surfaces started from the periphery. Although the weld faying surfaces were polished before joining, some evidence of wear was observed in the central region of welded interface. The concentric rubbing marks extended from the periphery to the centre at 0.11 s, and spread over almost the whole welded interfaces at 0.3 s. The wear state in the central region changed to a sheared state, as



5 Microstructure of welded interfaces after welding: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa



6 Appearances of welded interfaces after welding: friction speed of 27.5 s^{-1} and friction pressure of 90 MPa

shown by white (see 0.7 s in Fig.4.). The whitish area in the central region extended toward the periphery of the welded interface at 0.9 s, and almost covered the whole welded interfaces at 1.1 s. The whole welded interface changed to a sheared state at 1.3 s, when the colour was entirely white. The sheared state was a seizure state in the case of low carbon steel joints.[10,13] According to this result, the sheared state here, is also the seizure state of the A7075 friction welded joint.

Figure 5 shows the appearances of welded interfaces in the central region (area A) and the peripheral region (area B) for the fixed side of the specimens at 0.5, 0.7 and 0.9 s with an optical microscope. Areas A and B showed that the surface at 0.5 s was rough, i.e., worn state. At 0.7 s, area A changed to the flat plane although area B was still rough. This flat plane of area A showed the state that torsional shear fracture occurred at this area by seizure.[10,13] Consequently, it was determined that the flat plane was the seizure state, and areas A and B were recognized as seizure states at 0.9 s.

Figure 6 shows the appearances of welded interfaces joined by 90 MPa. The welded interface showed the concentric rubbing marks in the sheared state at the peripheral region on the fixed and rotating sides at 0.04 s. The concentric rubbing marks of the sheared state were extended from periphery to the centre of the welded interface at 0.08 s, and spread over the whole welded interface at 0.11 s. These results are identical to those of the low carbon steel joint.[10,12]

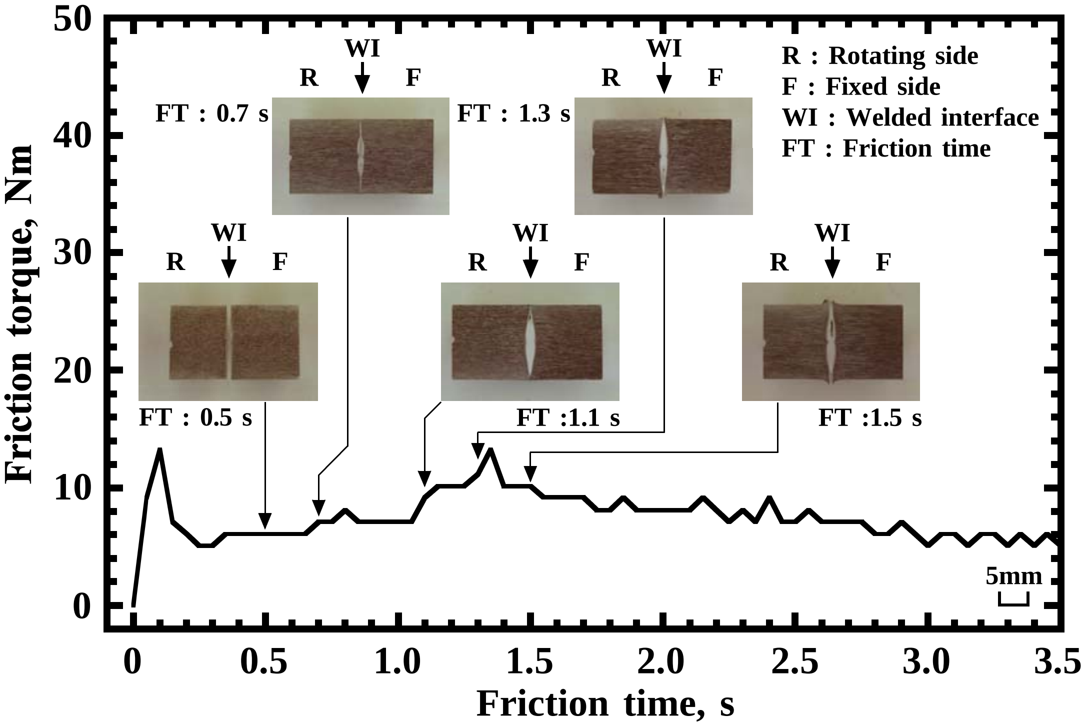
Relationships between friction time, friction torque and the cross sectional appearance of the welded interface region

Figure 7 shows the relationship between friction time, friction torque, and the cross-sectional appearance of the welded interface region joined by 30 MPa through the experimental method (2). To clarify the joining process, each cross-sectional appearance corresponds to the friction torque curve. When the friction time was 0.5 s, the welded interface of the central region was white, which showed that the zone was affected by friction heat. However, neither base metal was joined. At 0.7 s, the whole welded interface was white. The boundary interfaces of both base metals at the central region were not clear, i.e., they were joined. The joined region extended from the centre to the periphery at 1.1 s, and the flash began to generate on the outer surface at 1.3 s. The friction torque increased from 0.7 s, at which time joining had started at the centre portion of welded interface. The friction torque reached the initial peak when the whole welded interface was joined and upsetting of both base metals started. However, the welded interface included a not-joined region, i.e., the dark gray region at half-radius position as shown in the photo of 1.5 s in Fig.7. Then, the friction torque decreased with increasing friction time after the initial peak torque.

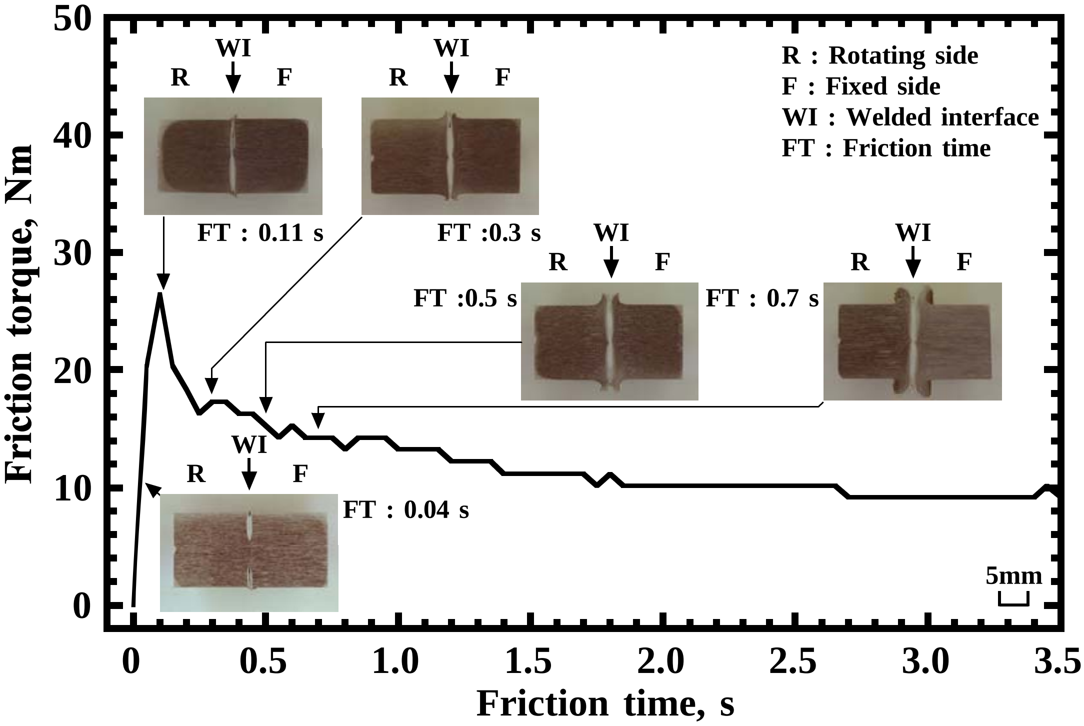
Figure 8 shows the relationship between friction time, friction torque, and cross-sectional appearance of welded interface region joined by 90 MPa. When the friction time was 0.04 s, the peripheral region of the welded interface was white, and the boundary interfaces of both base metals were not clear. The friction torque rapidly increased when joining started at the peripheral region of the welded interface. When the friction torque reached the initial peak torque at 0.11 s, the whole welded interface was joined and upsetting of both base metals started. The friction torque subsequently decreased with increasing friction time after the initial peak torque and flash also increased.

DISCUSSION

According to the results described above, the joining mechanism of A7075 friction welds is identical to that of low carbon steel.[10,12] Both weld faying surfaces of the base metals are rubbed against each other from those contacting. When the base metals are welded by high friction speed and low friction pressure, a fresh surface can be repeatedly created from the periphery toward the central region of the welded interface. Therefore, the heat generation is considered to be small in this stage. The initial seizure and



7 Relationship between friction time, friction torque, and cross-sectional appearance of welded interface region: friction speed of 27.5 s^{-1} and friction pressure of 30 MPa



8 Relationship between friction time, friction torque, and cross-sectional appearance of welded interface region: friction speed of 27.5 s^{-1} and friction pressure of 90 MPa

joining generates from the central region where the relative speed of both welded interfaces is slow, and the temperature of the fresh surface is high enough to generate seizure. Then, the joined region (seizure region) extends from the central region toward the periphery with increasing friction torque. On the other hand, the initial seizure and joining can be repeatedly created from the periphery to the central region of the welded interface when the base metals are welded by high friction speed and high friction pressure. The friction torque reaches the initial peak torque, when a fresh surface generated the seizure to the whole of the welded interface, regardless of friction pressure. Then, the friction torque decreases with reducing yield strength of base metals due to the increasing temperature of the welded interface.

CONCLUSIONS

This paper described the joining phenomena during the friction stage of 7075-T6 aluminum alloy friction welds. The following conclusions are provided.

1. Friction torque had wear and seizure stages until the initial peak torque when the base metals were welded with of high friction speed and low friction pressure, i.e., 27.5 s^{-1} and 30 MPa.

2. When the base metals were welded under high friction speed and high friction pressure, i.e., 27.5 s^{-1} and 90 MPa, almost no wear existed until the initial peak torque. The friction torque rapidly increased and reached the initial peak immediately after both weld faying surfaces contacted each other.

3. The wearing of both weld faying surfaces started at the peripheral region, and extended toward the central region of the welded interface. When the base metals were welded by high friction speed and low friction pressure, the initial seizure and the joining began at the central region and extended toward the peripheral region. In case of high friction speed and high friction pressure, the initial seizure and the joining began at the periphery and they extended toward the centre.

4. The results of joining of with for A7075 friction welds were similar to those of low carbon steel at the same friction welding conditions. That is, the joining mechanism of A7075 friction welding is the same as that of low carbon steel one.

ACKNOWLEDGMENTS

The authors wish to thank the staff members of the Machine and Workshop Engineering of Graduate School of Engineering of University of Hyogo (former, Himeji Institute of Technology). We also wish to thank the alumnus of Mr. Yasutomo Takeuchi for his devoted contribution to this research project.

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