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Joining Phenomena and Tensile Strength of Friction Welded Joint between Pure Aluminum and Pure Copper

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Abstract

This paper describes the joining phenomena and the tensile strength of friction welded joint between type 1070 pure aluminum (CP-Al) and oxygen free copper (OFC). When the joint was made at a friction pressure of 30 MPa with a friction speed of 27.5 s^{-1}, the upsetting (deformation) occurred at the CP-Al side. When the joint was made at a friction time of 2.0 s, the whole weld interface on the OFC side had the transferred CP-Al, and it was obtained approximately 30% joint efficiency. Then, the joint efficiency increased with increasing friction time, and it was obtained approximately 63% joint efficiency at a friction time of 12.0 s. The joint fractured at the weld interface, which had a CP-Al adhering to the weld interface on the OFC side. When the joint was made with friction times of 2.0 s and 6.0 s, the joint efficiency increased with increasing forge pressure and then the joint was obtained the CP-Al side fracture at a forge pressure of 135 MPa or higher. However, the joint did not achieve 100% joint efficiency because the adjacent region of the weld interface at the CP-Al side was softened. In addition, the joint at a friction time of 2.0 s had no intermetallic compound (IMC) layer at the weld interface although the not-joined region was slightly observed. On the other hand, the joint at a friction time of 6.0 s did not have the not-joined region at the weld interface although the IMC layer was slightly observed. In conclusion, to obtain higher joint efficiency with fracture on the CP-Al side, the joint should be made with higher forge pressure, and with the suitable friction time at which the entire weld interface of the OFC side had the transferred CP-Al.

Key words : Friction Welding, Pure Aluminum, Pure Copper, Joining Phenomena, Tensile Strength, Friction Welding Condition, Not-joined Region, Intermetallic Compound

1. Introduction

Because an expansion in the use of dissimilar metal joints (referred to as dissimilar joints) is expected and widely used in various component parts, easily welding method for dissimilar metal joints is required. On the other hand, dissimilar welding operations have several severe problems in industrial usage. One problem will occur when the dissimilar joints are welded by using fusion welding processes which conventionally produce intermediate layer (interlayer) consisting of brittle intermetallic compound (IMC) at the joint interface of both base metals to be joined. The interlayers usually give detrimental damages on mechanical and metallurgical properties of dissimilar joints (For example, American Welding Society, 1982). In particular, fusion welded joints between aluminum or its alloys (referred to as the Al-system material) and copper or its alloys (referred to as the Cu-system material) have also some problems, e.g. the generation of blowholes and cracks at the joint interface (For example, Mizuno et al., 1999). Therefore, a welding process is urgently required, which will reduce the degradation of the mechanical and metallurgical properties of the joints between Al-system material and Cu-system material.

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Generally speaking, solid state joining processes, e.g. diffusion joining or friction joining such as rotary friction welding (referred to as the friction welding) can minimize IMC generation. Many researchers have reported that the mechanical and metallurgical properties of friction welded joints between Al-system material and Cu-system material show desirable characteristics (Ando, et al., 1963; Wang, 1975; Kaga, et al., 1981; Morozumi and Kikuchi, 1982; Dawson, 1983; Hasui, et al., 1986; Aritoshi, et al., 1991; Yilbaş, et al., 1995; Itoh, et al., 1998; Lee, et al., 2005; Ochi, et al., 2007; Ratković, et al., 2009; Sahin, 2010). However, several joints of this combination, which were affected by the IMC that was generated at the weld interface, had brittle fractures themselves in the IMC (Aritoshi, et al., 1991; Itoh, et al., 1998; Lee, et al., 2005). Moreover, the joining mechanism of friction welding between dissimilar materials such as Al-system material and Cu-system material has not been fully clarified, so that the friction welding conditions for material combinations are determined by trial and error. That is, the joining mechanism of friction welding for dissimilar materials was not clarified, and the condition that the joint does not fracture at the weld interface when it will be satisfied with some state was not theoretically displayed. Furthermore, the joining mechanism of friction welding of dissimilar materials differs from that of similar materials, because mechanical properties such as the tensile strength and thermal properties such as the thermal conductivity are different in their combinations. To determine the theoretical friction welding conditions is necessary to clarify the joining phenomena between dissimilar materials in friction welding. In particular, clarifications of the joining mechanism are required concerning the weldability of Al-system material and Cu-system material, because those materials have many kinds of types and an expansion in the use of both materials is expected.

In previous works (Kimura, et al., 2002a, 2002b, 2002c, 2003a, 2003b, 2005a, 2005b), the authors clarified the joining mechanism during the friction welding process and the joint mechanical properties (mainly tensile strength) of similar material combinations which were various carbon steels or Al-system materials. Furthermore, the authors also clarified the joining mechanism and the joint mechanical properties of friction welded joint for some dissimilar material joints as following combinations: Al-system materials and low carbon steel (LCS) (Kimura, et al., 2009a, 2009b, 2013), Cu-system materials and LCS (Kimura, et al., 2009c, 2009d), pure Ti and LCS (Kimura, et al., 2014), and pure Cu and pure Ti (Kimura, et al., 2011a, 2011b). If combinations of dissimilar materials such as Al-system materials and Cu-system materials can be joined using the same welding method as that shown in previous reports (Kimura, et al., 2002a, 2002b, 2002c, 2003a, 2003b; 2005a; 2005b, 2009a, 2009b, 2009c, 2009d, 2011a, 2011b, 2013, 2014), the joining mechanism will be clarified. In particular, to clarify the relationship between joining phenomena and tensile strength of that combination joint is strongly important, because that will be estimated for expansion in the use of the electricity industry field.

Based on the above background, the authors have been carrying out research to clarify the joining mechanism between dissimilar materials during the friction process. The present paper focuses on the clarification of the joining phenomena and the joint tensile properties between type 1070 commercially pure Al and oxygen free Cu friction welded joints under various friction welding conditions. The authors demonstrate the results of the joining phenomena during the friction process, and the joint tensile properties under various friction welding conditions, i.e. the effects of friction time and forge pressure on the joint tensile strengths are clarified. In addition, the authors show the friction welding conditions for a joint that had fractured on the pure Al side with no cracks at the weld interface. Furthermore, the authors show the selection guide of friction welding conditions for good joint.

2. Experimental procedures

The materials used were JIS A1070 BD-F commercially pure Al (referred to as CP-Al) and JIS C1020 BD-H oxygen free Cu (referred to as OFC) in rods with a diameter of 16 mm. The chemical composition of the CP-Al was 0.03Si-0.10Fe-0.01Cu-0.00Mn-0.02Mg-0.00Zn-0.01Ti-99.82Al (mass%), the ultimate tensile strength was 120 MPa, the 0.2% yield strength was 118 MPa, and the elongation was 27%. The chemical composition of OFC was 99.99Cu in mass%, the ultimate tensile strength was 326 MPa, the 0.2% yield strength was 311 MPa, and the elongation was 15%. In this connection, used materials had work hardening treated, and its mechanical properties were improved by work hardening. The materials were machined to 12 mm diameters for the weld faying (contacting) surface (referred to as faying surface). All faying surfaces of specimens were polished with a surface grinding machine before joining in order to eliminate the effect of surface roughness on the mechanical properties of dissimilar material joints (Fuji, et al., 1994; Kimura, et al., 2005c, 2011b).

A continuous (direct) drive friction welding machine was used for the joining. This friction welding machine had three kind of welding method as follows.

(1) A conventional friction welding method that have a brake system when the friction time expired, for measuring

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the friction torque.

(2) The welding method that the fixed side specimen is simultaneously and forcibly separated from the rotating side specimen when the friction time expired, for observation of the transitional changes at the weld interface.

(3) The welding method that the relative speed at the weld interface between both specimens simultaneously is decreased to zero when the friction time expired to prevent braking deformation during rotation stop, for observation of the cross-section at the adjacent region of the weld interface and measuring of joint mechanical properties.

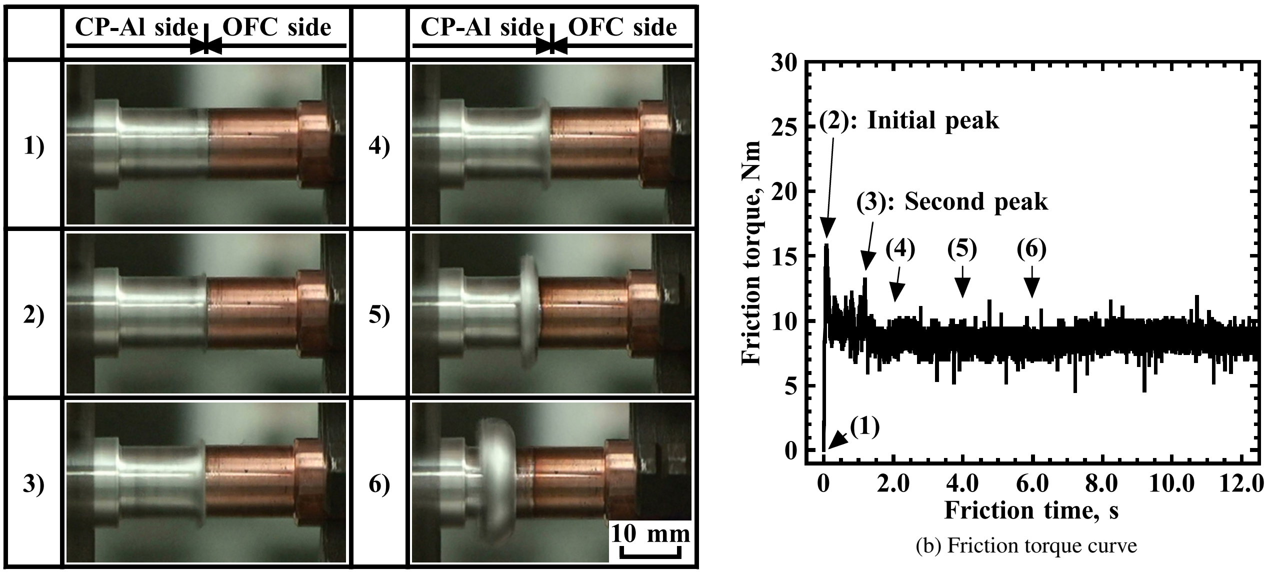
To clarify the joining phenomena during the friction process, the authors carried out three above welding methods. In particular, the experimental methods of (2) and (3) were used to obtain the joint without braking deformation. The details of these methods have been described in previous reports (Kimura, et al., 2002a, 2002b, 2002c, 2003a, 2003b; 2005a; 2005b, 2009a, 2009b, 2009c, 2009d, 2011a, 2011b, 2013, 2014).

During the friction welding operations, the friction welding condition was set to the following combinations: a friction speed of 27.5 s^{-1} (1650 rpm), a friction pressure of 30 MPa, the range of a friction time from 0.04 to 6.0 s, the range of a forge pressure from 30 to 150 MPa, and a forge time of 6.0 s. The joining behavior was recorded by a digital video camera. The friction torque was measured with a load-cell, and was recorded with a personal computer through an A/D converter with sampling times of 0.001 s. In this case, the sufficient data could be obtained in order to understand the joining phenomena of the friction stage although the friction torque measured with the load-cell lacked continuity in the stepwise part will be showed later. All joint tensile test specimens were machined to 12 mm in diameter and 60 mm in parallel length. That is, all flash (burr or collar), which was exhausted from the weld interface during the friction welding process, were removed from the joint for joint tensile test specimen. Then, the joint tensile test was carried out with as-welded condition at room temperature. Vickers hardness distribution at 0.5 mm from the outer surface (referred to as the periphery) of the adjacent region of the weld interface was measured with a load of 2.94 N (0.3 kgf). The measuring range was about 8 mm from the weld interface, and the measuring interval was 150 μm. Furthermore, analysis via SEM-EDS was carried out to analyze the chemical composition in the adjacent region on the weld interface.

3. Results

3.1. Relationship between joining behavior and friction torque

Figure 1 shows the relationship between the joining behavior and the friction torque. 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 faying surfaces as they contacted each other, then the friction torque was increased. The CP-Al side was slightly upset (deformed) as shown in photo 2), and then the friction torque reached to the initial peak of (2), although it was unclear in comparison with other combination at the same friction pressure. The initial peak torque was approximately 15 Nm, and the elapsed time for the initial peak was about 0.1 s. The friction torque decreased and then re-increased to approximately 14 Nm of (3) at a



(a) Joining behavior

(b) Friction torque curve

Fig. 1 Joining behavior and friction torque curve during friction process.

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friction time of about 1.3 s, and the flash of the CP-Al side was increased as shown in photo 3). Then, the friction torque was re-decreased and it was maintained nearly constant from (4). The upsetting and the flash of CP-Al increased with increasing friction time although the OFC side was not upset, as shown in photos 4) to 6). It was clarified that the friction torque curve had two peaks as the initial and second peak torques, and this result differed from between CP-Al and LCS under the same friction pressures (Kimura, et al., 2009a). In addition, the second peak torque was almost similar value of the initial peak torque. The details in the friction torque will be described later. The deformation of the CP-Al side resembled those with that combination of the friction welded joint, although the change of the friction torque varied.

3.2. Transitional changes of weld interface

Figure 2 shows the examples of the appearances of the weld interfaces at various friction times. When a friction time was 0.04 s, i.e. both specimens had been rotated once, the concentric rubbing marks were observed at whole weld interface on the CP-Al side, and the CP-Al sparsely transferred the weld interface on the OFC side (Fig. 2a). When a friction time of 0.1 s, i.e. the friction torque just reached the initial peak, the entire weld interface on the OFC side did not have transferred CP-Al completely, although the flash of CP-Al increased (Fig. 2b). The quantity of the transferred CP-Al on the OFC side was repeatedly increased and/or decreased, and was extended toward the whole weld interface on the OFC side. Then, the CP-Al side roughened and the flash was exhausted at a friction time of 0.8 s (Fig. 2c). When a friction time was 2.0 s, i.e. the friction torque reached after the second peak, the peripheral portion of the weld interface on the OFC side did not have transferred CP-Al (Fig. 2d). That is, the CP-Al was not transferred completely on the OFC side at this friction time. When a friction time was 3.0 s (Fig. 2e), almost entire weld interface on the OFC side had

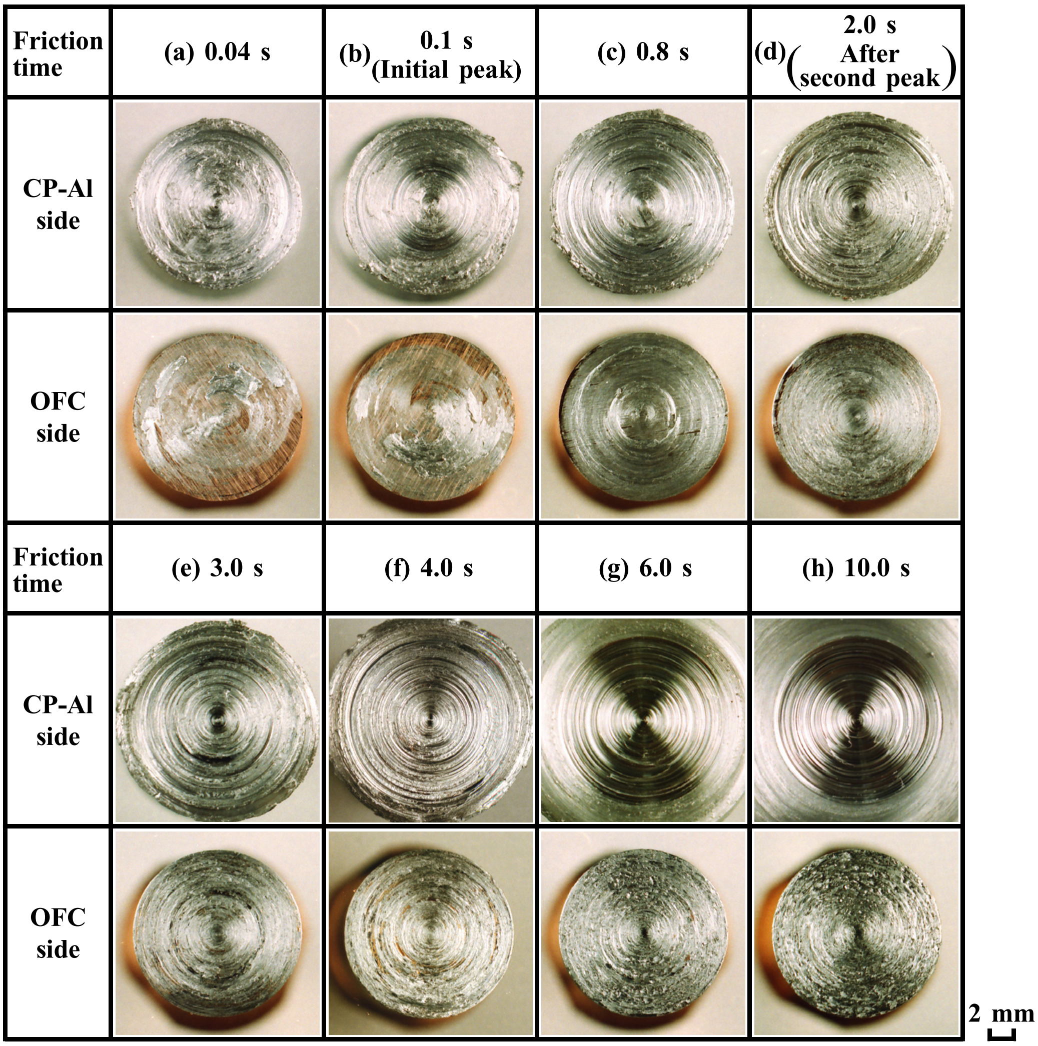

Fig. 2 Appearances of weld interfaces after welding at various friction times.

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transferred CP-Al. Then, the entire weld interface on the OFC side had transferred CP-Al when a friction time was 4.0 s (Fig. 2f). The CP-Al side became smooth like a mirror at whole weld interface, and the transferred CP-Al on the OFC side turned very rough at a friction time of 6.0 s (Figs. 2g and 2h). Thereafter, the weld interfaces of both sides at long friction time resembled those with a friction time of 6.0 s as shown in Fig. 2h, although the quantities of the flash at the CP-Al side varied.

According to this result, it was clarified that the entire weld interface on the OFC side at the friction time did not have the transferred CP-Al when the friction torque reached to the initial peak. This result differed from the friction welded joint between CP-Al and LCS under the same friction pressure (Kimura, et al., 2009a). In addition, it was clarified that the entire weld interface on the OFC side at the friction time did not also have the transferred CP-Al when the friction torque reached to the second peak. That is, the time of the CP-Al at the entire weld interface on the OFC side was about 4.0 s, of which was longer than that of the second peak torque.

3.3. Cross-section of weld interface

Figure 3 shows the cross-sectional appearances of the weld interface of the joints at various friction times. In this case, the forge pressure was applied at an identical friction pressure. When the joint was made at a friction time of 0.2 s, i.e. the friction torque reached after the initial peak, the CP-Al and OFC sides were not almost joined, although some joints of both sides were combined (unified) as shown in Fig. 3a. Then, some joints at a friction time of 1.0 s had the not-joined regions at the weld interface which were indicated by arrows in Fig. 3b. However, some joints were not also joined at this friction time. When the joint was made at a friction time of 2.0 s, i.e. the friction torque reached after the second peak, it also had the not-joined regions at the weld interface which were indicated by arrows in Fig. 3c. Then, all joints of the CP-Al and OFC sides were combined when it was made at this friction time or longer. The not-joined region was slightly observed in the joint at a friction time of 3.0 s which was indicated by arrows in Fig. 3d, although that decreased. However, the not-joined region of the joint at a friction time of 6.0 s or longer was not able to observe, which was based on the optical overview observation level (Figs. 3e and 3f). Hence, the friction time will be desirable to set in the time of some extent such without not-joined region at the weld interface of the joint.

By the way, the initial peak torque was obtained at a friction time of 0.1 s in case of this combination, which was shown in Fig. 1a. However, the OFC side had a little of the transferred CP-Al as shown in Fig. 2d, and the joint was not obtained as shown in Fig. 3a. That is, the OFC and CP-Al sides were hardly welded at the initial peak. On the other hand, when the friction torque reached to the second peak, the OFC side had much the transferred CP-Al, which was shown in Fig. 2b. In addition, the OFC and CP-Al sides were welded as shown in Fig. 3c although it had the not-joined region

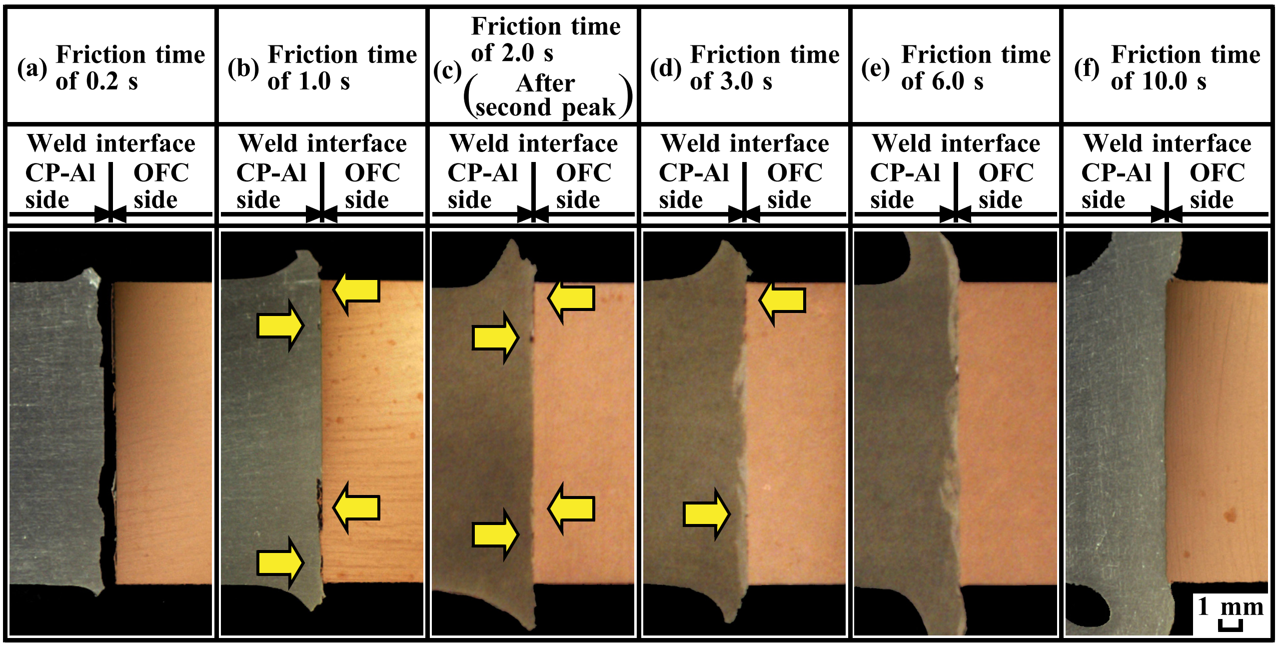

Fig. 3 Cross-sectional appearances of weld interface of joints at various friction times.

at the weld interface. Furthermore, the initial peak was decreased to tend to be observed with decreasing the overhang length (a part of 12 mm diameters) of the OFC side specimen in the preliminary experiment, although the data was not shown here. Therefore, it was considered that the scattering of the initial peak was larger than that of the second peak. However, the initial peak torque is defined as the first peak in the friction welding (Japan Friction Joining Association, 2006). Hence, the practical initial peak such as the friction welding of other dissimilar joints (For example, Kimura, et al., 2009a) was able to be considered as the second peak. That is, the friction torque curve had two peaks as the initial and second peak torques in this study.

3.4. Joint efficiency

Figure 4 shows the relationship between the friction time and the joint efficiency of the joints, plotted alongside the friction torque curve. In this case, the forge pressure was also applied at an identical friction pressure, i.e. 30 MPa. In addition, the joint efficiency was defined as the ratio of joint tensile strength to the ultimate tensile strength of the CP-Al base metal. Figure 5 shows an example of the appearance of the tensile tested joint (joint tensile specimen after tensile testing). When the joint was made at a friction time of 0.1 s as shown in Fig. 4, i.e. the friction torque just reached the initial peak, it had almost 0% joint efficiency, although some joints of the CP-Al and OFC sides were combined. The joint had also almost 0% joint efficiency, which was made with before a friction time of 1.2 s, i.e. the friction torque close to the second peak. Then, when the joint was made with a friction time of 1.4 s, it had approximately 20% joint efficiency. When the joint was made with a friction time of 2.0 s, i.e. the friction torque reached the after second peak, it had approximately 26% joint efficiency. However, the joint efficiency of this friction time had scattering. Thereafter, the joint efficiency increased with increasing friction time and achieved approximately 63% joint efficiency at a friction time of 12.0 s. All joints fractured at the weld interface, which had a CP-Al adhering to the weld interface on the OFC side, as shown in Fig. 5.

Figure 6 shows the examples of fractured surfaces of the tensile tested joints at various friction times. The quantity of the CP-Al adhering to the weld interface on the OFC side of fractured surfaces at a friction time such as 1.4 s or short was a little, as shown in Fig. 6a. That quantity increased with increasing friction time, and it was expanded to the whole weld interface (Fig. 6b). The whole weld interface at the OFC side had the CP-Al when a friction time was 4.0 s as shown

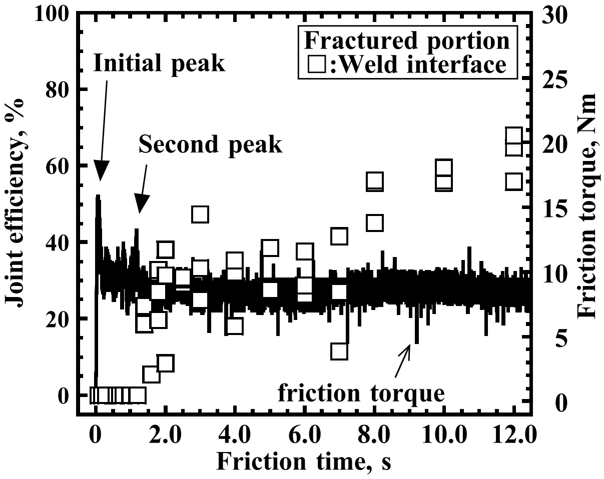

Fig. 4 Relationship between friction time and joint efficiency of joints, in relation to friction torque curve: forge pressure of 30 MPa.

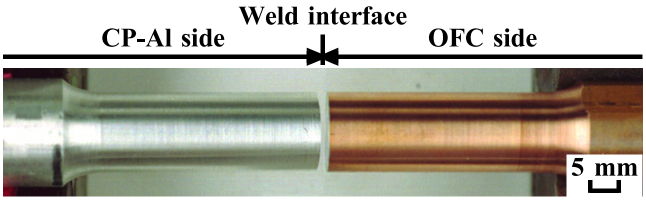

Fig. 5 Appearance of tensile tested joint: forge pressure of 30 MPa.

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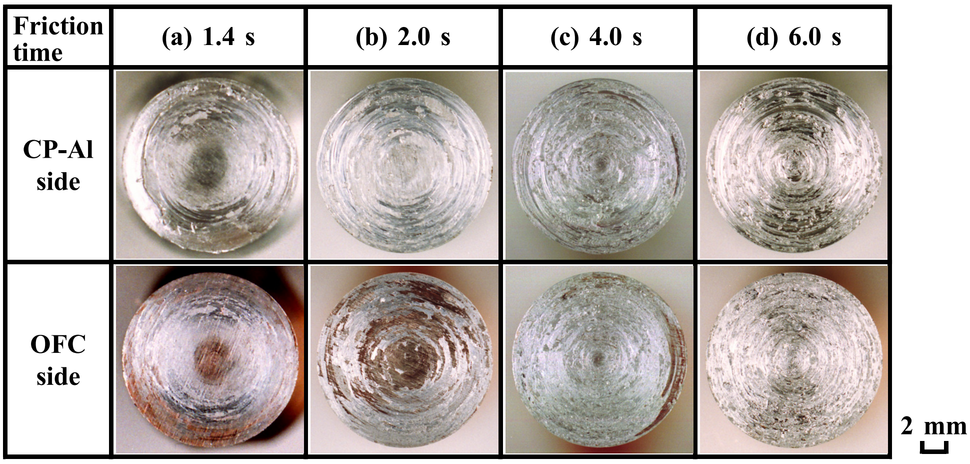
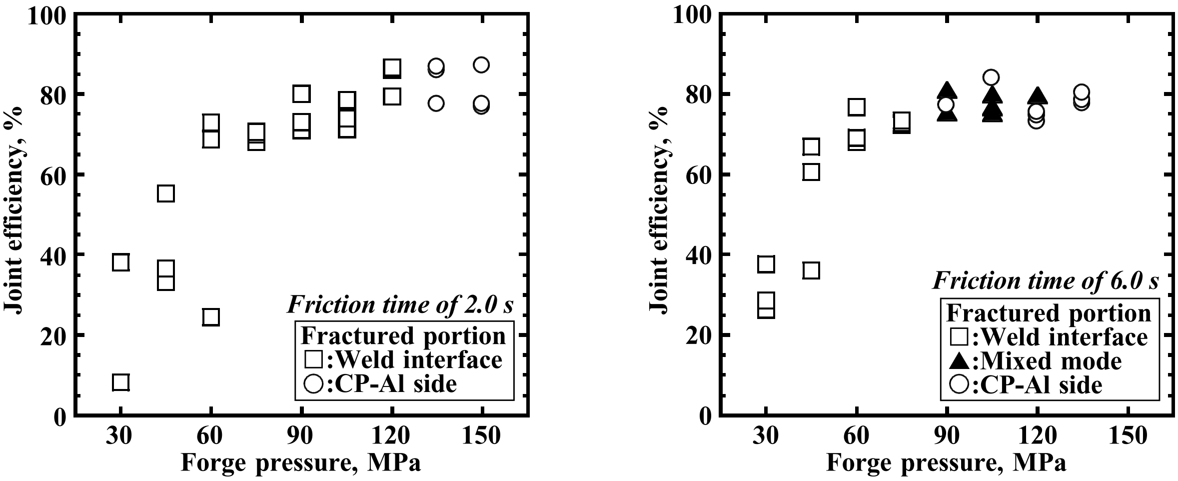


Fig. 6 Fractured surfaces of tensile tested joints at various friction times: forge pressure of 30 MPa.

in Fig. 6c, although the adhesion of the CP-Al at the peripheral portion of that was a little. Then, the entire weld interface at the OFC side had the CP-Al at a friction time such as 6.0 s or longer as shown in Fig. 6d. The joint efficiency increased with increasing the quantity of the CP-Al adhering to the weld interface on the OFC side (see Fig. 4). Hence, the joint should be made with opportune friction time because the fractured surface on the OFC side has large CP-Al as shown in Fig. 6d. However, all joints fractured at the weld interface as shown in Fig. 5. Therefore, the joint also should be made with applying forge pressure that was higher than applied friction pressure, because the bonding strength between CP-Al and OFC was able to be estimate poor.

3.5. Improving joint efficiency

Generally speaking, forge pressure will be able to reduce a not-joined region from the joint, to increase adhesion between both specimens and to improve the joint efficiency. In an attempt to improve the joint efficiency, the joints were made with adding high forge pressure. Figure 7 shows the relationship between the forge pressure and the joint efficiency of the joints. In this case, a friction time was set to 2.0 and 6.0 s. Figure 8 shows the examples of the appearances of the tensile tested joints. When the joint was made at a friction time of 2.0 s as shown in Fig. 7a, i.e. the friction torque reached after the second peak, it had approximately 20% joint efficiency. Then, the joint efficiency increased with increasing forge pressure, and then it achieved approximately 80% at a forge pressure of 90 MPa or higher, although it had a scattering. Furthermore, all joints at a forge pressure of 135 MPa or higher were fractured from the CP-Al side as shown in Fig. 8b, although all joints at a forge pressure of 120 MPa or lower were fractured from the weld interface as shown in Fig.



(a) Friction time of 2.0 s

(b) Friction time of 6.0 s

Fig. 7 Relationship between forge pressure and joint efficiency of joints at various friction times: (a) friction time of 2.0 s and (b) friction time of 6.0 s.

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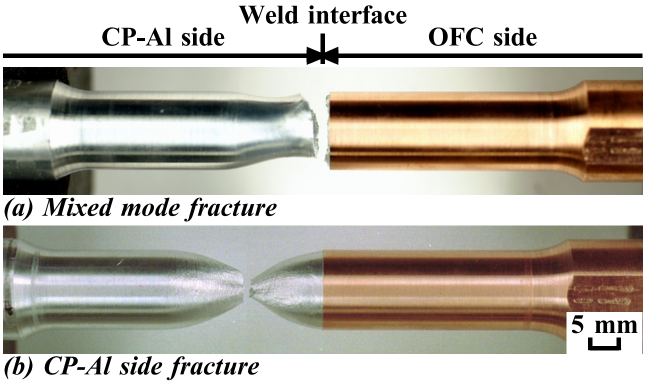

Fig. 8 Appearances of tensile tested joints at various forge pressures.

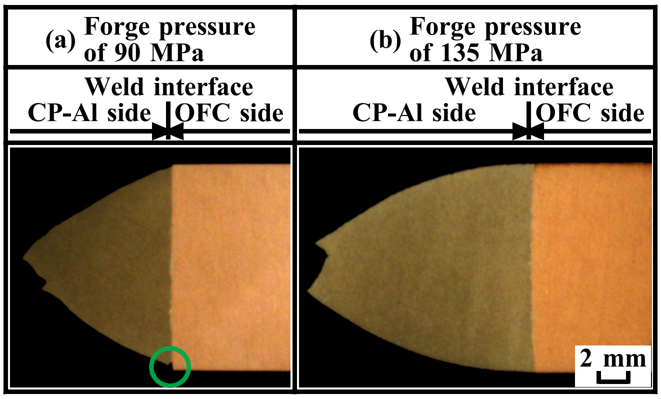

Fig. 9 Cross-sectional appearances of tensile tested joint with the CP-Al side fracture: friction time of 6.0 s and forge pressure of (a) 90 MPa and (b) 135 MPa.

5 which had the CP-Al adhering to the weld interface on the OFC side as shown in Fig. 6b. The joint efficiency also increased with increasing forge pressure at a friction time of 6.0 s as shown in Fig. 7b. Some joints at forge pressures of 90 to 120 MPa fractured between the weld interface and the CP-Al side (mixed mode fracture) as shown in Fig. 8a, and others fractured from the CP-Al side as shown in Fig. 8b. Then, all joints at a forge pressure of 135 MPa fractured from the CP-Al side as shown in Fig. 8b. That is, the joint at a forge pressure of 135 MPa or higher fractured from the CP-Al side.

Figure 9 shows the examples of the cross-sectional appearances of the tensile tested joint with the CP-Al side fracture. In this case, those joints were made with a friction time of 6.0 s. The tensile tested joint at a forge pressure of 90 MPa or lower had cracks at the periphery portion of the weld interface, which was indicated by a circle as shown in Fig. 9a. That is, the entire weld interface was not joined completely. On the other hand, the weld interface of the tensile tested joint at a forge pressure of 135 MPa or higher had neither a not-joined region nor a defect, as shown in Fig. 9b. That is, the CP-Al and OFC sides had tightly joined at the entire weld interface. Hence, the joint also should be made with high forge pressure such as 135 MPa or higher. However, those joints did not achieve 100% joint efficiency.

Figure 10 shows examples of the Vickers hardness distribution across the weld interface at the peripheral portion of the joints with a forge pressure of 135 MPa, which was made with friction times of 2.0 s and 6.0 s. The joint with a friction time of 2.0 s as shown in Fig. 10a had a softened region at all measured line of the CP-Al side in longitudinal direction from the weld interface, which was approximately 75 to 93% hardness of the CP-Al base metal. In addition, the joint with a friction time of 6.0 s as shown in Fig. 10b had also a softened region at all measured line of the CP-Al side, which was approximately 76 to 90% hardness of the CP-Al base metal. Furthermore, the OFC side of this joint had a softened region that extended about 2 mm in the longitudinal direction from the weld interface. Other measured portions of these joints as well as the other joints also had a softened region at the CP-Al side, although the area of those regions differed (data not shown due to space limitations). Moreover, the area of a softened region at the periphery portion of the CP-Al side was larger than that of the central portion. In particular, the joint had a softened region at the CP-Al side, in spite of that made with high forge pressure such as 120 MPa or higher. Because both used materials had work hardening

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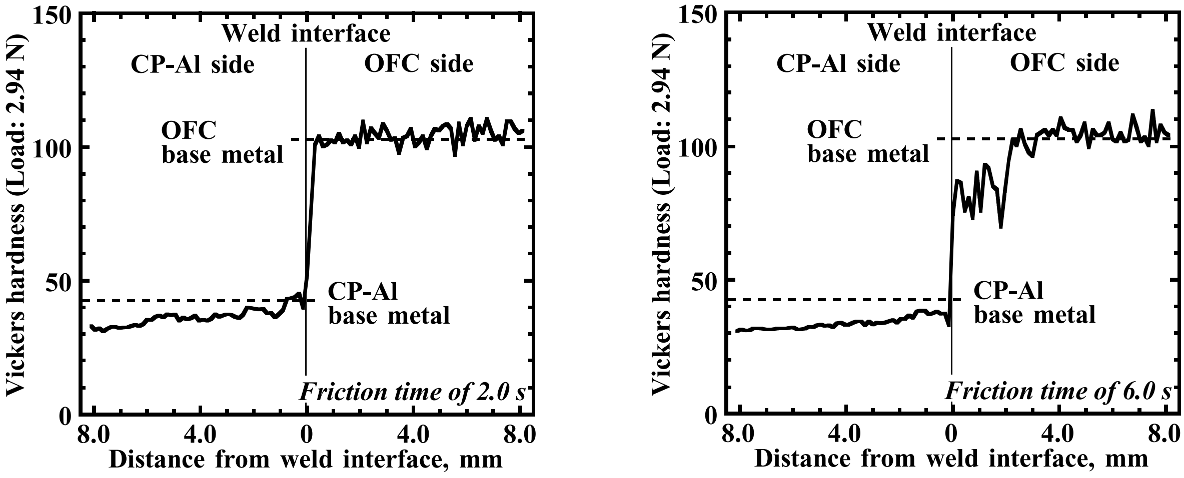

(a) Friction time of 2.0 s

(b) Friction time of 6.0 s

Fig. 10 Vickers hardness distribution across weld interface at peripheral portion of joint with forge pressure of 135 MPa: (a) friction time of 2.0 s and (b) friction time of 6.0 s.

treatments, a softened region at the adjacent region of the weld interface of the joint was generated, which described in the experimental procedures section. That is, the joint was annealed during the cooling stage after welding by friction heat which was kept into the exhausted flash from the weld interface. Therefore, it was clarified that the joint at a forge pressure of 135 MPa or higher was fractured from the CP-Al side, although that did not achieve 100% joint efficiency. Hence, the joint should be made with high forge pressure for obtaining the CP-Al side fracture.

4. Discussion

To clarify the joint characteristics, SEM observation with EDS analysis was carried out. Figure 11 shows the examples of the SEM images and EDS analysis results at the peripheral portion for the adjacent region of the weld interface of the joints. When the joint was made with a friction time of 2.0 s and a forge pressure of 30 MPa as shown in Fig. 11a, the adjacent region at the CP-Al side of it had lamellar structures between CP-Al and OFC. In addition, the distribution lines at lamellar structures corresponding to Al and Cu were scattered. Hence, this joint had the mechanically mixed (mechanical mixing) layers. Similar mechanically mixed layers were also observed in several dissimilar friction welded joints (Ruge, et al., 1986; American Welding Society, 1991; Yilmaz, et al., 1996; Fuwano, et al., 2000; Kim, et al., 2003; Straffelini, et al., 2004; Meshram, et al., 2007; Jayabharath, et al., 2007; Arivazhagan, et al., 2008; Ambroziak, 2010; Kimura, et al., 2011b) as well as that in the same combination of this study (Ando, et al., 1963; Aritoshi, et al., 1991; Ochi, et al., 2007). Furthermore, this joint had also the not-joined region at the adjacent region on the CP-Al side of the weld interface, which was indicated by arrows. However, the distribution lines corresponding to Al and Cu had no plateau part of the weld interface of this joint, which was based on the SEM observation level. That is, this had no IMC layer at the weld interface. On the other hand, when the joint was made with a friction time of 6.0 s and a forge pressure of 135 MPa as shown in Fig. 11b, it had the difference contrast images at the adjacent region of the weld interface with its width of about 0.8 μm. The distribution lines corresponding to Al and Cu had small plateau part, and the approximate composition of this region was mainly (53-79)%Al-(47-21)%Cu (in at.%). Similar compositions of IMC were also observed in linear friction welded joint of the same combination of this study (Dalgaard, et al., 2011; Bhamji, et al., 2012) as well as friction welded joints (Aritoshi, et al., 1991; Itoh, et al., 1998; Lee, et al., 2005) of that combination. Hence, it was clarified that this joint with a long friction time such as 6.0 s had the IMC layer at the weld interface, although the identification of that will be necessary by using X-ray diffraction technique and so on. However, this joint did not have a not-joined region at the adjacent region of the weld interface. From those results, the producing situation of the mechanically mixed layer, not-joined region, and IMC layer of the joint were differed.

Table 1 shows the summary of the mechanically mixed layer, not-joined region and IMC of the joint at various friction welding conditions of which were corresponding to the joint fractured portion. The mechanically mixed layers were observed at the CP-Al side of all joints, although that width (length of the longitudinal direction) differed. In a previous report (Kimura, et al., 2011b), the joint properties of the friction welded joint between OFC and pure Ti was affected to the mechanically mixed layer. However, the mechanically mixed layer of this combination was not considered

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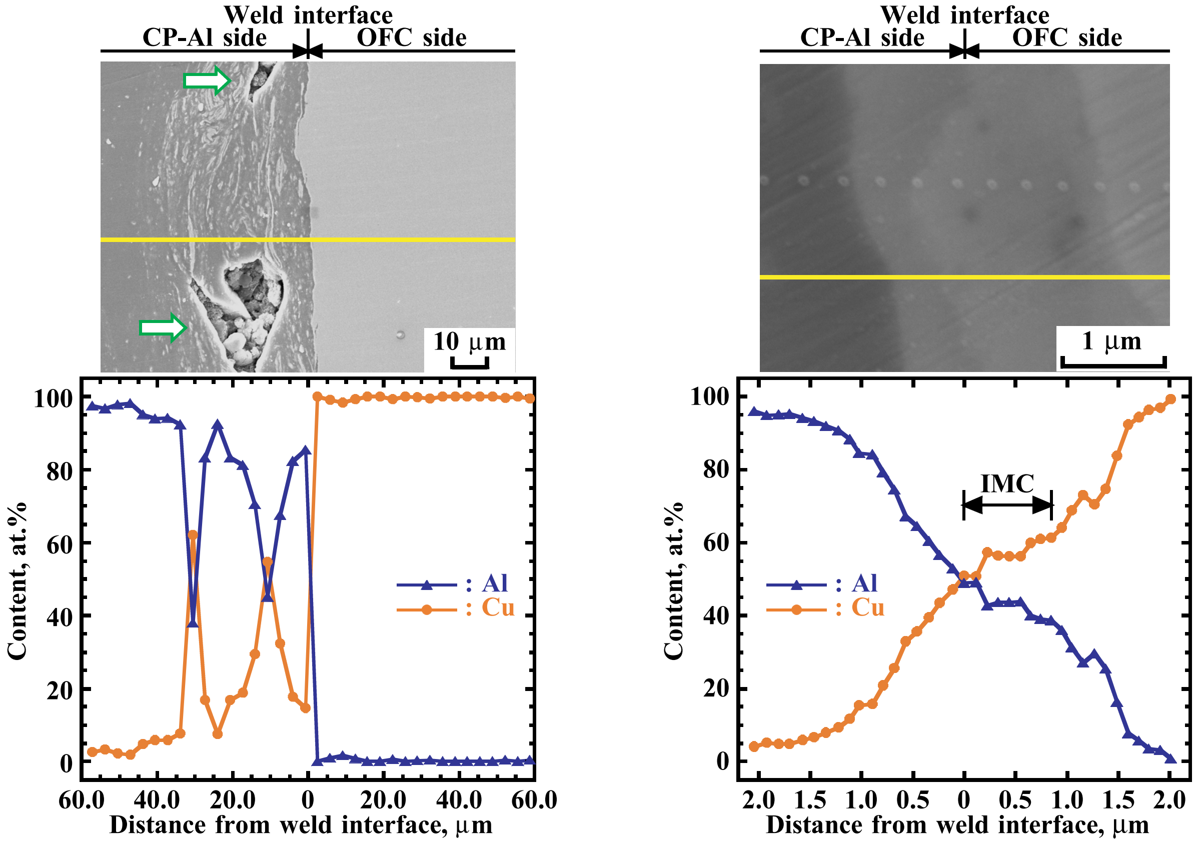

(a) Friction time of 2.0 s and forge pressure of 30 MPa

(b) Friction time of 6.0 s and forge pressure of 135 MPa

Fig. 11 SEM images and EDS analysis results at peripheral portion for the adjacent region of weld interface of joints at various friction welding conditions.

Table 1 Summary of mechanically mixed layer, not-joined region and IMC of joints at various friction welding condition, corresponding to joint fractured portion.

Friction time, s		**2.0**		**6.0**	
Forge pressure, MPa		**30**	**135**	**30**	**135**
Central portion	Mechanically mixed layer	○	○	○	○
	Not-joined region	○	○	―	―
	IMC	―	―	―	―
Half-radius portion	Mechanically mixed layer	○	○	○	○
	Not-joined region	○	○	―	―
	IMC	―	―	―	―
Peripheral portion	Mechanically mixed layer	○	○	○	○
	Not-joined region	○	―	―	―
	IMC	―	―	―	○
Joint fractured portion		Weld interface	CP-Al side	Weld interface	CP-Al side

※○ : Observed, ― : Not observed

to affect of the joint tensile strength because all joints with a forge pressure of 135 MPa at both friction times were fractured at the CP-Al side, as shown in Fig. 8b. On the other hand, the not-joined region was observed in the joints at a friction time of 2.0 s, and that was not observed in those at a friction time of 6.0 s. Moreover, the not-joined region was slightly observed in the joint with a forge pressure of 135 MPa, although that decreased with increasing forge pressure.

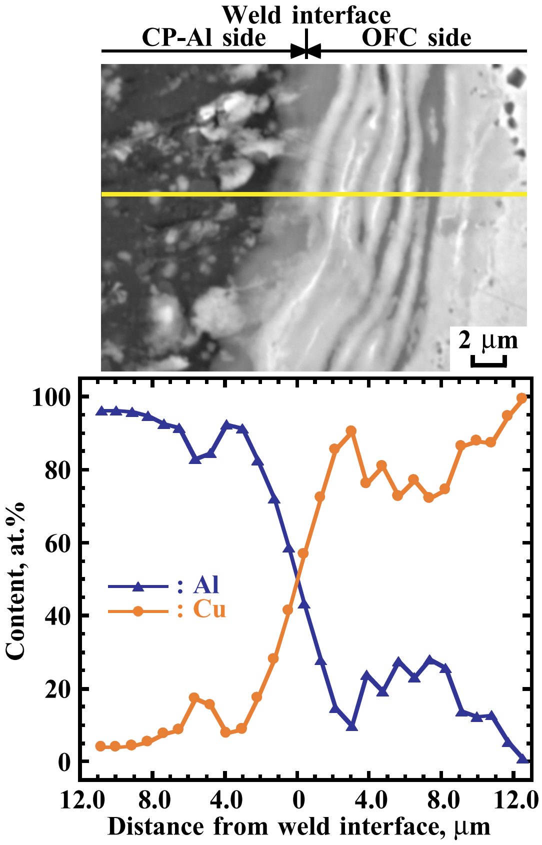

Fig. 12 SEM image and EDS analysis result at peripheral portion for the adjacent region of weld interface of joint: friction time of 4.0 s and forge pressure of 135 MPa.

Generally speaking, the joint properties of the friction welded joint were affected to the not-joined region. Hence, it is desirable to be able to reduce the not-joined region from the joint. However, those not-joined region were not also considered to affect of the joint tensile strength of this combination because all joints at a friction time of 2.0 s with a forge pressure of 135 MPa was fractured at the CP-Al side (see Fig. 7a). Therefore, to obtain good joint without defects, the friction time should be set to over 2.0 s (the time of the friction torque reached after the second peak torque), because the not-joined region decreased with increasing friction time (see Fig. 3). On the other hand, the IMC layer was observed at the peripheral portion in the joint, which was made with a friction time of 6.0 s and a forge pressure of 135 MPa, as shown in Fig. 11b. However, the joint at a friction time of 2.0 s did not have the IMC layer, as shown in Fig. 11a. Hence, it was able to estimate that the IMC layer was produced with a long friction time such as 6.0 s, although the joint with a forge pressure of 30 MPa at this friction time was not able to observe in this study. In addition, the IMC layer was not able to completely exhaust as the flash even if the joint will be made with adding high forge pressure, because the joint with a forge pressure of 135 MPa had the IMC layer at the peripheral portion (see Fig. 11b). However, that IMC was not also considered to the joint tensile strength because the thickness of IMC layer of the joint was thin and all joints at a friction time of 6.0 s with a forge pressure of 135 MPa was fractured at the CP-Al side (see Fig. 7b). The joint fractured portion was affected by IMC layer, that thickness was a few micrometer or thick (Nakanishi, et al., 1976; Lee, et al., 2005). Hence, IMC layer should be reduced from the weld interface because that layer is the possibility as a weak point of the joint for using it. Therefore, the friction time also should be set to below 6.0 s obtaining good joint without IMC layer, because that was not generated at the weld interface by friction heat.

Based on the result that showed it in Table 1, the characteristics of the joint which was made with a friction time of 4.0 s and a forge pressure of 135 MPa, was investigated. Figure 12 shows the SEM image and EDS analysis result at the peripheral portion for the adjacent region of the weld interface of the joint. The distribution lines corresponding to Al and Cu by EDS analysis had no plateau part at the weld interface although the mechanically mixed layers were observed at the CP-Al side. In this connection, IMC layer was not also observed in other portions of this joint. That is, an IMC layer was not observed at the weld interface of this joint, which was based on the SEM observation level. In addition, the joint, which was made with this friction welding condition, had also approximately 82% joint efficiency with the CP-Al side

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fracture as shown in Fig. 8b although it had also a softened region on the CP-Al side. Furthermore, this joint did not have the not-joined region at the weld interface, and that tensile tested joint did not have cracks at the periphery portion of the weld interface as shown in Fig. 9b. That is, the CP-Al and OFC sides had tightly joined at the entire weld interface.

It is considered that the further investigation must elucidate the detailed for the improvement of the joint efficiency by other friction welding condition, because the joint was not obtained 100% joint efficiency. However, as a conclusion, the joint should be made with higher forge pressure and with the suitable friction time at which the entire weld interface of the OFC side had the transferred CP-Al. Therefore, the joint will be able to obtain higher joint efficiency with fracture on the CP-Al side by setting to that friction welding condition, because it will not have a not-joined region and IMC at the weld interface.

5. Conclusions

This paper described the joining phenomena and the tensile strength of friction welded joint between type 1070 commercially pure aluminum (CP-Al) and oxygen free copper (OFC). The following conclusions are provided.

(1) When the joint was made at a friction pressure of 30 MPa with a friction speed of 27.5 s^{-1}, the upsetting (deformation) occurred at the CP-Al side. In addition, the friction torque curve had two peaks as the initial and second peak torques.

(2) When the joint was made at a friction time of 3.0 s or longer, almost whole weld interface of the OFC side had the transferred CP-Al, and it was obtained approximately 30% joint efficiency. When the joint was made at a friction time of 3.0 s or longer, the entire weld interface of the OFC side had the transferred CP-Al, and the joint efficiency of it increased. However, all joints fractured from the weld interface, which had the CP-Al adhering to the weld interface on the OFC side.

(3) When the joint was made with a friction time of 2.0 s, the joint efficiency increased with increasing forge pressure, and then the joint had the CP-Al side fracture at a forge pressure of 135 MPa or higher. However, the joint did not achieve 100% joint efficiency because the adjacent region of the CP-Al side had softened region. In addition, this joint had no intermetallic compound (IMC) at the weld interface although the not-joined region was slightly observed.

(4) When the joint was made with a friction time of 6.0 s, the joint efficiency also increased with increasing forge pressure and then the joint was obtained the CP-Al side fracture at a forge pressure of 135 MPa. However, this joint did not have the not-joined region at the weld interface although the IMC layer was slightly observed.

(5) When the joint was made with a friction time of 4.0 s and a forge pressure of 135 MPa, it had the CP-Al side fracture. This joint did not have the not-joined region and IMC layer at the weld interface, which was based on the SEM observation level.

In conclusion, to obtain higher joint efficiency with fracture on the CP-Al side, the joint should be made with higher forge pressure and with the suitable friction time at which the entire weld interface of the OFC side had the transferred CP-Al.

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