Effects of friction welding conditions on tensile strength of friction welded joint between 5052 Al alloy and pure copper

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Received: 7 August 2017; Revised: 26 October 2017; Accepted: 13 March 2018

Abstract

This paper described the tensile strength of friction welded joint between Al-Mg alloy (JIS A5052) and pure copper (OFC). In particular, the joining phenomena during the friction process and the effects of friction welding condition such as friction pressure, friction time and forge pressure on the joint strength have been investigated, and the metallurgical characteristics of joints have been also observed and analyzed. The adjacent region of the weld interface at the A5052 side was upset during the friction process, although that of the OFC side was hardly upset. When the joint was made with a friction pressure of 30 MPa, all joints fractured at the weld interface because those joints had the not-joined region at this portion. To reduce the not-joined region, the joint was made with increasing forge pressure. All joints did not have a joint efficiency of 100% (same tensile strength as the A5052 base metal) and the fracture on the A5052 base metal without crack at the weld interface, although the joint efficiency increased with increasing forge pressure. It was showed that the joint had the mechanically mixed layer as the lamellar structures of A5052 and OFC on the adjacent region of the weld interface at the A5052 side, and that layer influenced to the fractured point of the joint. The mechanically mixed layer decreased with decreasing friction time and with decreasing friction pressure after the initial peak. Then, the joint, which had the same tensile strength as the A5052 base metal, the fracture on the A5052 base metal with no crack at the weld interface, and less mechanically mixed layer with no the intermetallic compound (IMC) interlayer on the weld interface, could be successfully achieved. In conclusion, it was suggested that the joint should be made with a low friction pressures such as 20 MPa to prevent generating of the mechanically mixed layer, an opportune friction time such as 6.0 s without generating the IMC interlayer, and a high forge pressure such as 240 MPa in order to achieve completely joining of the weld interface and the fracture on the A5052 base metal.

Keywords : Friction welding, Aluminum alloy, Pure copper, Friction welding condition, Tensile strength, Mechanically mixed layer, Fractured point

1. Introduction

The dissimilar metal joints (referred to as dissimilar joints) has some characteristics, of which will be able to set a material to the right man in the right place. The dissimilar joints will be able to make by some welding techniques such as laser welding (for example, Seretsky and Ryba, 1976) and friction stir welding (for example, Sato, et al., 2015). However, 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 an intermediate layer (interlayer) consisting of the brittle intermetallic compound (IMC) at the interface of both base metals to be joined. Actually, fusion welded joints between aluminum or its alloys (referred to as the Al-system material) and such other materials as copper or its alloys (referred to as the Cu-system material) (Technical Committee on Structural Transition

Joint, 1978; Dawson, 1983), titanium (Ti) (The Japan Titanium Society, 2007), and various steels (Technical Committee on Structural Transition Joint, 1978; Ueda and Niinomi, 1978; Sasabe, et al., 2010) have poor mechanical properties because of the IMC interlayer produced at the joint interface (American Welding Society, 1982). Those interlayers usually give detrimental damages on mechanical and metallurgical properties of dissimilar joints (American Welding Society, 1982). For example, fusion welded joints between Al-system material and Cu-system material have also some problems, e.g. the generation of blowholes and cracks at the joint interface (Mizuno, et al., 1999). Nevertheless, easy welding method for dissimilar joints is required because an expansion in the use of dissimilar joints is expected and widely used in various component parts. In particular, the dissimilar joint between Al-system material and Cu-system material will be required in the industrial field, since those materials has superior characteristics such as high thermal conductivity. Also, this dissimilar joint will be useful with reducing the weight for the system, because the weight of Cu-system material is heavier than that of Al-system material. 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.

In the preceding work (Kimura, et al., 2015), the authors clarified the joining mechanism during the friction welding process between commercially pure Al (CP-Al) and oxygen free copper (OFC). Furthermore, the friction welding condition for the joint, which had the fracture on the CP-Al side with no crack at the weld interface by tensile test, was established. If combinations of dissimilar materials such as Al alloy and OFC can be joined by using the same welding technique as that shown in the preceding report (Kimura, et al., 2015), the joining mechanism will be clarified. In particular, the clarifications of the joining mechanism and the joint mechanical properties are strongly required concerning the weldability of Al alloy and pure Cu, since the tensile strength of Al alloy is higher than that of CP-Al and an expansion in the use of Al alloy is expected. In this connection, some researchers have reported of friction welding between Al alloy and pure Cu. For example, Ochi et al. (2003) tried for making the joint of Al-Cu-Mg alloy (JIS A2024) and pure Cu or Al-Zn-Mg alloy (JIS A7075) and pure Cu. Hazlett (1962) demonstrated the characteristics of the weld interface of the joint between Al-Cu-Mg alloy (JIS A2024) and pure Cu. Kannan et al. (2016) experimented for making the joint between Al-Cu-Mg alloy (JIS A2025) tube plate and pure Cu tube. Moreover, Itoh et al. (1998) tried for making the joint of Al-Mg-Si alloy (JIS A6061) and pure Cu with insert metal of CP-Al. Nevertheless, the joining mechanism of friction welding between Al alloy and pure Cu has not been fully clarified, so that the friction welding conditions for material combinations are determined by trial and error. That is, the good joint, which has the tensile strength of the Al alloy base metal with no crack at the weld interface, was not obtained. In addition, the friction welding condition of the good joint between CP-Al and OFC without the fracture from the weld interface (Kimura, et al., 2015) will be considered different from that of the good joint between Al alloy and OFC. Actually, the opportune friction welding condition for obtaining good joint differed in the combination of pure Al and stainless steel (Kimura, et al., 2017a) and/or Al-Mg-Si alloy (JIS A6063) and stainless steel (Kimura, et al., 2017b). It is indicated as one of the reason that the IMC interlayer can be easily generated at the interface between Al-system materials and other materials (Ikeuchi, 1996). However, because the characteristics of the generated IMC of the joint with each combination differed, the simulation of an opportune friction welding condition for obtaining good joint between dissimilar joint was difficult. Hence, to directly weld Al alloy and OFC by the experiment is necessary for clarification of the joining mechanism and making good joint without the IMC interlayer.

Based on the above background, the authors have been carrying out research to clarify the joining mechanism during the friction process of dissimilar joints, because the easy welding technique for the dissimilar joints with high reliability will be conducted to the expansion of the freedom for design of welding engineering. The authors investigate the joining phenomena during the friction process of friction welds between a typical Al-Mg alloy (AA5052, which was standardized as JIS A5052 in 5000 series of Al alloy) and OFC in the present work, since this material has good weldability. The authors also show the tensile strength of the friction welded joints under various friction welding conditions; especially the effects of friction time and forge pressure on those. Furthermore, the authors show the friction welding condition for joints that had the same tensile strength as the Al alloy base metal and the fracture on the Al alloy base metal with no crack at the weld interface, by tensile test.

2. Experimental procedures

The materials used were a typical Al-Mg alloy (type JIS A5052BE-H112, referred to as A5052) in rods with a diameter of 95 mm and OFC (JIS C1020 BD-H) in rods with a diameter of 16 mm. Two kinds of A5052 with slightly different

Fig. 1 Shape and dimensions of friction welding specimen of OFC side for measuring temperature change at weld interface. This specimen with this information was used for measuring temperature during the friction process. Three thermocouples were inserted to every hole, and then those temperatures were measured.

tensile properties were used for this experiment because they were purchased at different times. The chemical composition of one of the A5052 was 0.06Si-0.16Fe-0.01Cu-0.01Mn-2.60Mg-0.25Cr-Al in balance (mass%), the ultimate tensile strength was 200 MPa, the 0.2% yield strength was 81 MPa, and the elongation was 36%. The chemical composition of another was 0.06Si-0.12Fe-0.01Cu-0.03Mn-2.50Mg-0.25Cr-Al in balance (mass%), the ultimate tensile strength was 201 MPa, the 0.2% yield strength was 86 MPa, and the elongation was 35%. Also, two kinds of OFC with slightly different tensile properties were used for this experiment. The chemical composition of both OFCs was 99.99Cu in mass%. Their ultimate tensile strengths were 326 and 321 MPa, their 0.2% yield strengths were 311 and 318 MPa, and their elongations were 15 and 18%, respectively. All materials were used for this experiment as-received condition. In this connection, the joining phenomena and the joint mechanical properties had similar results of which will be demonstrated later, although those used materials in this study had slightly different chemical compositions and mechanical properties.

The materials were machined to 12 mm diameters for the weld faying (contacting) surface. Furthermore, the temperature changes at the centerline, half radius, and periphery locations of 1.0 mm longitudinal direction from the weld faying surface were measured using the OFC specimen for clarification of the temperature during the friction process, which was shown in Fig. 1. In this instance, the sufficient data could be obtained in order to understand the temperature distribution of the radius direction in the weld interface and the temperature change at those locations, although the temperature on the weld interface during the friction process was able to estimate as those or higher. All weld 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 (Hasui and Matsui, 1983; Futamata, et al., 1989; Fuji et al., 1994, 1995; Kimura, et al., 2005, 2011).

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

- (1) A conventional friction welding method that has a brake system when the friction time expired, for measuring the friction torque and temperature change on the weld interface.
- (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 on the adjacent region of the weld interface and measuring of the joint tensile strength.

To clarify the joining phenomena during the friction process, the authors carried out three above welding methods. In addition, the experimental methods of (2) and (3) were used to obtain the joint without braking deformation. The details of these methods were described in the previous report (Kimura, et al., 2015).

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), friction pressures of 20, 30, and 60 MPa, the range of a friction time from 0.04 to 30.0 s, the range of a forge pressure from 20 to 300 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. Also, the temperatures were measured with mineral insulated thermocouples composed with a chromel-alumel which were inserted to holes of the OFC specimen.

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. Furthermore, analysis via SEM-EDS was carried out to analyze the chemical composition on the adjacent region of the weld interface.

3. Results

3.1. Relationship between joining behavior and friction torque

Figure 2 shows the relationship between the joining behavior and the friction torque during the friction process. In this case, the joint was made with a friction pressure of 30 MPa. Photos 1) to 6) in Fig. 2a correspond to the friction torque of (1) to (6) in Fig. 2b, respectively. Photo 1) shows the state at the weld faying surfaces as they contacted each other, and then the friction torque increased. A5052 side was slightly upset (deformed) as shown in photo 2), and then the friction torque reached the initial peak of (3) in Fig. 2b. Thereafter, the upsetting and the flash of A5052 increased with friction time although the OFC side was not upset, as shown in photos 4) to 6) in Fig. 2a. Also, the friction torque maintained nearly constant from (4). The initial peak torque was approximately 13 Nm, and the elapsed time for the initial peak was about 1.4 s. The numerical values of the elapsed time for the initial peak were almost similar to those of CP-Al/OFC joint (Kimura, et al., 2015) at the same friction pressure, although the initial peak torque differed. Additionally, the joining behavior also resembled those with such another friction pressure as 20 or 60 MPa, although the change of the friction torque varied (data not shown due to space limitations).

Fig. 2 Joining behavior and friction torque curve during friction process; friction pressure of 30 MPa. Photos 1) to 6) in the left side correspond to the friction torque of (1) to (6) in the right side graph. A5052 side had the one-sided deformation during the friction process.

3.2. Transitional changes of weld interface

Figure 3 shows the appearances of the weld interfaces at various friction times. In this instance, the joint was also made with a friction pressure of 30 MPa. 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 A5052 side, and the A5052 sparsely transferred the weld interface on the OFC side (Fig. 3a). The quantity of the transferred A5052 on the OFC side was repeatedly increased and/or decreased, and was extended toward the whole weld interface on the OFC side with friction time (Fig. 3b). When a friction time was 1.5 s as shown in Fig. 3c, i.e. the friction torque just reached the initial peak, the entire weld interface on the OFC side did not have the transferred A5052 completely, although the flash of A5052 increased. Also, the A5052 side became slightly smooth and the flash was exhausted to the radial direction. Then, the flash of A5052 increased with friction time (Fig. 3d). When a friction time was 3.0 s, entire weld interface on the OFC side had the transferred A5052 (Fig. 3e). That is, the A5052 was completely transferred on the OFC side at this friction time (3.0 s). Thereafter, the flash of A5052 increased with friction time as shown in Fig. 3d. However, the flash of the OFC side was hardly observed at all friction times. This result was the same as the result of Fig. 2a. 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 A5052 when the

Fig. 3 Appearances of weld interfaces after welding at various friction times; friction pressure of 30 MPa. This result was obtained by the welding method which the fixed side (OFC) specimen is simultaneously and forcibly separated from the rotating side (A5052) specimen when the friction time expired. A5052 transferred the weld interface on the OFC side, and it increased with friction time.

friction torque reached to the initial peak. This result resembled the transitional changes of the weld interface of the joint between Al-Zn-Mg alloy (JIS A7075) and OFC (Kimura, et al., 2003) as well as CP-Al/OFC joint (Kimura, et al., 2015) at the same friction pressure although the friction time differed. Additionally, the transitional changes of the weld interface also resembled those with such another friction pressure as 20 or 60 MPa, although the friction time was different. Hence, Al-system materials seem to produce the one-sided deformation for the friction welded joint between Al-system materials and pure Cu during the friction process regardless of friction pressure.

3.3. Joint efficiency

Figure 4 shows the relationship between the friction time and the joint efficiency of joints, and those were plotted

Fig. 4 Relationship between friction time and joint efficiency of joints, in relation to friction torque; friction pressure of 30 MPa and forge pressure of 30 MPa. This result was obtained by the welding method which 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. The joint efficiency was defined as the ratio of the joint tensile strength to the ultimate tensile strength of the A5052 base metal. The joint efficiencies were plotted alongside the friction torque curve that was shown with Fig. 2b. The open square symbols were the results of the fracture at the weld interface as shown in Fig. 5. All joint fractured at the weld interface.

Fig. 5 Example of appearance of joint tensile tested specimen for weld interface fracture; friction pressure of 30 MPa. This photo is typical appearance of the joint tensile tested specimen with the weld interface fracture in a friction pressure of 30 MPa.

Fig. 6 Examples of fractured surfaces of joint tensile tested specimens at various friction times; friction pressure of 30 MPa and forge pressure of 30 MPa. Those photos are typical appearances of fractured surfaces of joint tensile tested specimens with the weld interface fracture in a friction pressure of 30 MPa. Fractured surfaces resembled the appearances of the weld interfaces at the same friction time.

alongside the friction torque curve. The joint efficiency was defined as the ratio of the joint tensile strength to the ultimate tensile strength of the A5052 base metal. Figure 5 shows an example of the appearance of the joint tensile tested specimen. In this case, those joints were made with a friction pressure of 30 MPa and a forge pressure of 30 MPa. The joint efficiency was low (approximately 2%) at a friction time of 1.0 s or short, as shown in Fig. 4. That is, the joint strength at a friction time before the initial peak was extremely low. When joints were made with a friction time of 1.5 s, i.e. the friction torque just reached to the initial peak, the joint efficiency was approximately 10%. Then, the joint efficiency increased with friction time, and was approximately 23% at a friction time of 15.0 s. All joints fractured from the weld interface as shown in Fig. 5.

Figure 6 shows examples of the fractured surfaces of the joint tensile tested specimens with a friction pressure of 30 MPa at various friction times. The quantity of the A5052 adhering to the weld interface on the OFC side of fractured surfaces at a friction time such as 1.5 s or short (before the initial peak) was a little (Fig. 6a through Fig. 6c). The quantity of the A5052 on the OFC side increased with friction time, and it was expanded to the whole fractured surface, and then the entire fractured surface had the A5052 when a friction time was 3.0 s or longer (Fig. 6d through Fig. 6f). Those fractured surfaces resembled the appearances of the weld interfaces at the same friction time as shown in Fig. 3. Thus, the friction time of the entire fractured surface on the OFC side having the A5052 was in good agreement with that with the entire weld interface on the OFC side having the transferred A5052.

Figure 7 shows the SEM images and EDS analysis results at the peripheral portion on the adjacent region of the weld interfaces for joints. When the joint was made with a friction time of 3.0 s and a forge pressure of 30 MPa as shown in Fig. 7a, the adjacent region of the weld interface at the A5052 side of the joint had the lamellar structures between A5052 and OFC. A part of the lamellar structure was showed as the OFC that scattered throughout the A5052 side, and then the distribution lines were scattered. Also, this joint had the not-joined region, which was indicated by arrows as shown

Fig. 7 SEM images and EDS analysis results at peripheral portion on adjacent region of weld interfaces for joints; friction pressure of 30 MPa and forge pressure of 30 MPa. Fig. 7a is the result of a friction time of 3.0 s, and Fig. 7b is the result of a friction time of 10.0 s, respectively. Those results were obtained by using samples of the cross-sectional appearances of weld interfaces of joints as shown in Fig. 8. Those were observed and analyzed at the peripheral portion on adjacent region of weld interfaces of joints. The adjacent region of the weld interface at the A5052 side of the joint had the lamellar structures between A5052 and OFC, and the width of it increased with friction time.

in this figure. The joint with a friction time of 10.0 s and a forge pressure of 30 MPa as shown in Fig. 7b had also the lamellar structures at the A5052 side, and the distribution lines corresponding to A5052 and OFC was scattered. That is, it was clarified that the joint had the mechanically mixed (mechanical mixing) layers on the adjacent region of the weld interface at the A5052 side. However, the IMC interlayer was not observed of those joints, which was based on the SEM observation level. Other measuring portions of these joints had the mechanically mixed layer and did also not have the IMC interlayer. Furthermore, the width (distance from the weld interface at the longitudinal direction) of the mechanically mixed layers increased with friction time (compare between Fig. 7a and Fig. 7b). Hence, it is desirable to be set of an opportune friction time which generate less mechanically mixed layers of the joint because that layer will be affected to the joint strength (Aritoshi, et al., 1991; Kimura, et al., 2011, 2015) in addition to the IMC interlayer as reported by some researchers (Nakanishi, et al., 1976; Lee, et al., 2005; Chen, et al., 2006; Saeid, et al., 2010; Wei, et al., 2016). However, all joints fractured from the weld interface as shown in Fig. 5. A similar mechanically mixed layer was also observed even in several friction welded joints for dissimilar materials combination as reported by many researchers (Ruge, et al., 1986; Yilmaz, et al., 1996; Fuwano, et al., 2000; Straffelini, et al., 2004; Meshram, et al., 2007; Arivazhagan, et al., 2008; Kimura, et al., 2011) in addition to CP-Al/OFC joint (Aritoshi, et al., 1991; Kimura, et al., 2015).

Figure 8 shows the cross-sectional appearances of the weld interfaces of joints at various friction times. All joints had the not-joined regions at the weld interface, although those decreased with increasing friction time. Thus, it was clarified that the A5052 and OFC was not completely joined. In this connection, the fractured surfaces (see Fig. 6) as well as the weld interfaces on the OFC side had large A5052 (Fig. 3e and Fig. 3f). Hence, the joint should be made with the friction time such as 3.0 s after the time which obtained the transferred A5052 on the entire OFC side. Nevertheless, all joints

Fig. 8 Cross-sectional appearances of weld interfaces of joints at various friction times; friction pressure of 30 MPa and forge pressure of 30 MPa. This result was also obtained by the welding method which 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. All joints had the not-joined regions at the weld interface, although those decreased with increasing friction time.

fractured from the weld interface. Therefore, the joint also should be made with applying forge pressure that was higher than applied friction pressure, because the bonding strength between A5052 and OFC was poor.

3.4. Effect of forge pressure on joint strength

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 tensile strength of joints with increasing forge pressure was investigated. Figure 9 shows the relationship between the forge pressure and the joint efficiency of joints at a friction pressure of 30 MPa. In this case, a friction time was set to 3.0 s, because entire weld interface on the OFC side had the transferred A5052 as shown in Fig. 3e. When joints were made at a forge pressure of 30 MPa, those had a joint efficiency of approximately 4.4%. Then, the joint efficiency increased

Fig. 9 Relationship between forge pressure and joint efficiency of joints; friction pressure of 30 MPa and friction time of 3.0 s. The open square symbols were the results of the fracture at the weld interface as shown in Fig. 5, and the solid circular symbols were the results of the fracture in the A5052 base metal as shown in Fig. 10, respectively. The joint efficiency increased with increasing forge pressure, and some joints at a forge pressure of 210 MPa or over had a joint efficiency of 100% and the fracture on the A5052 base metal as shown in Fig. 10.

Fig. 10 Example of appearance of joint tensile tested specimen for A5052 base metal fracture; friction pressure of 30 MPa. This photo is typical appearance of the joint tensile tested specimen with the A5052 base metal fracture in a friction pressure of 30 MPa and a forge pressure of 210 MPa or over.

with increasing forge pressure. When joints were made with a forge pressure of 210 MPa or over, some joints had a joint efficiency of 100% and the fracture on the A5052 base metal as shown in Fig. 10. However, those had the scattering, and some joints had the fracture at the weld interface as shown in Fig. 5. That is, all joints did not have the fracture on the A5052 base metal at the same forge pressure.

Figure 11 shows the SEM images and EDS analysis results at the adjacent regions of the weld interface of joint with a forge pressure of 240 MPa. The joint had the lamellar structures at the A5052 side, and the distribution lines corresponding to A5052 and OFC was scattered. That is, this joint had also the mechanically mixed layers on the adjacent region of the weld interface at the A5052 side. The mechanically mixed layer at the peripheral portion differed with that of the central portion (Fig. 11a and Fig. 11b). Furthermore, the mechanically mixed layer could not be decreased by adding high forge pressure, and this result was compared with the result of the joint with a forge pressure of 30 MPa (compare between Fig. 7a and Fig. 11a). Hence, it was difficult to obtaining good joint with reliability such as a joint efficiency of

Fig. 11 SEM images and EDS analysis results at adjacent region on weld interfaces for joint; friction pressure of 30 MPa, friction time of 3.0 s, and forge pressure of 240 MPa. Fig. 11a is the result of the peripheral portion of the joint, and Fig. 7b is the result of the central portion of the joint, respectively. Those were observed and analyzed at the difference portions of the same joint. The width of the mechanically mixed layers differed at the central and peripheral portions in the same joint.

100% as well as the fracture on the A5052 base metal at a friction pressure of 30 MPa, because the mechanically mixed layer will be generated during the friction process, and the width of that layer differed at the radius direction of the weld interface.

3.5. Influence of friction pressure

On the basis of the result described above, in an attempt to make the joint which has a joint efficiency of 100% and the fracture on the A5052 base metal, the joint strength with another friction pressure that is not 30 MPa was investigated. Figure 12 shows the relationship between the friction time and the joint efficiency of joints in relation to the friction torque curve, which were made with a friction pressure of 20 MPa. In this instance, the forge pressure was set to 270 MPa, because some joints with a joint efficiency of 100% and the fracture on the A5052 base metal were obtained with a forge pressure of 210 MPa or over (see Fig. 9). When the joint was made with this friction pressure (20 MPa), the initial peak torque decreased and the elapsed time for the initial peak torque increased, and those results were compared with the results of the joint with a friction pressure of 30 MPa as shown in Fig. 2b. The joint efficiency increased with friction time, and some joints had a joint efficiency of 100% with the fracture on the A5052 base metal at a friction time of 6.0 s or longer, although those had scattering. However, some joints with a forge pressure of 270 MPa fractured from the weld interface.

Fig. 12 Relationship between friction time and joint efficiency of joints, in relation to friction torque; friction pressure of 20 MPa and forge pressure of 270 MPa. The open square symbols were the results of the fracture at the weld interface as shown in Fig. 5 or Fig. 14a, and the solid circular symbols were the results of the fracture in the A5052 base metal as shown in Fig. 14b, respectively. The joint efficiencies were plotted alongside the friction torque curve that was measured at the same friction pressure. The joint efficiency increased with friction time, and some joints after a friction time of 6.0 s had a joint efficiency of 100% and the fracture on the A5052 base metal as shown in Fig. 14b.

To clarify the effect of the forge pressure on the joint strength of the joint at this friction pressure (20 MPa) in details, the joint strengths at friction times of 6.0 and 8.0 s were investigated. Figure 13 shows the relationship between the forge pressure and the joint efficiency of joints. All joints had a joint efficiency of 100% and the fracture on the A5052 base metal as shown in Fig. 14b when those were made with a friction time of 6.0 s and a forge pressure of 240 MPa (see Fig. 13a). However, some joints at other forge pressures had the fracture at the weld interface although those had the local constriction part (necking) at the A5052 side, and that was shown in Fig. 14a. On the other hand, some joints with a friction time of 8.0 s had the fracture at the weld interface as shown in Fig. 13b. This joint had no crack at the weld interface. That is, the good joint with the fracture on the A5052 base metal has been achieved with the condition of a friction time of 6.0 s and a forge pressure of 240 MPa, and that was not obtained at other friction welding conditions. In addition, the good joint was able to make with the above friction welding conditions, although the joint which have the tensile strength of the Al alloy base metal with no crack at the weld interface was not achieved previously.

Figure 15 shows the SEM image and EDS analysis result at the peripheral portion on the adjacent region of the weld interface for the joint. In this case, the joint was made with a friction time of 6.0 s and a forge pressure of 240 MPa. The distribution lines were not scattered, although the joint had little mechanically mixed layers on the adjacent region of the weld interface at the A5052 side. That is, the mechanically mixed layer was very thin at this friction welding

Fig. 13 Relationship between forge pressure and joint efficiency of joints at various friction times; friction pressure of 20 MPa. The left side plots were results of a friction time of 6.0 s, and the right side plots were results of a friction time of 8.0 s, respectively. All joints had a joint efficiency of 100% and the fracture on the A5052 base metal when those were made with a friction time of 6.0 s and a forge pressure of 240 MPa. However, that was not obtained at other friction welding conditions.

Fig. 14 Examples of appearances of joint tensile tested specimens; friction pressure of 20 MPa. Those photos are typical appearances of the joint tensile tested specimens in a friction pressure of 20 MPa and a forge pressure of 210 MPa or higher. The joint with the A5052 base metal fracture had no crack at the weld interface.

condition. In addition, the IMC interlayer was not also observed. Other measuring portions of this joint did not have the IMC interlayer, although that had very thin mechanically mixed layer. Hence, it could be considered that all joints fractured from the A5052 base metal at this friction welding condition.

4. Discussion

4.1. Temperature change at adjacent region of weld interface

As described above, all joints which have a joint efficiency of 100% and the fracture on the A5052 base metal could be obtained at a friction pressure of 20 MPa (Fig. 13). However, the joint efficiency of the joint with a friction pressure of 30 MPa had scattering, and some joints fractured from the weld interface (Fig. 9). That is, all joints with the fracture on the A5052 base metal could not be obtained at a forge pressure, when the joint was made with a friction pressure of 30 MPa. To clarify this result, the temperature change at the adjacent region of the weld interface during the friction process was measured. Figure 16 shows the relationship between friction time and temperature changes at various measured portions of the OFC side during the friction process, in relation to friction torque curves. When the joint was made with a friction pressure of 30 MPa as shown in Fig. 16a, the temperatures at the centerline, half radius and periphery portions of the weld interface at the OFC side were almost the same, although the difference in each temperature was approximately 100 K before the initial peak. Then, the temperature achieved approximately 650 K (377 °C) at a friction time of 3.0 s. On the other hand, the temperatures at all measured portions were also almost the same when the joint was made with a friction pressure of 20 MPa as shown in Fig. 16b. The temperature was approximately 600 K (327 °C) at a friction time of 6.0 s. That is, the temperature at the weld interface of the joint at a friction pressure of 20 MPa was lower than that of the joint at a friction pressure of 30 MPa. Actually, it was demonstrated that the CP-Al and pure Cu could be diffusion welded when the bonding temperature was 473 K (200 °C) or higher (Ohashi and Hashimoto, 1976). Also, the IMC interlayer at the interface of the diffusion welded joint grew with increasing heating temperature (Enjo et al., 1979). Moreover, when the friction welded joint between CP-Al and pure Cu was post-weld heat treated with a heating temperature of 623 K (350 °C), the IMC interlayer was not observed.

Fig. 15 SEM image and EDS analysis result at peripheral portion on adjacent region of weld interface for joint; friction pressure of 20 MPa, friction time of 6.0 s, and forge pressure of 240 MPa. This result was observed and analyzed at the peripheral portion on adjacent region of weld interface of joint. The joint with the A5052 base metal fracture that was made at a friction pressure of 20 MPa, had thin mechanically mixed layer at the weld interface. That is, the width of the mechanically mixed layers of this joint was thinner than that of the joint with a friction pressure of 30 MPa. This joint had also no IMC interlayer.

Fig. 16 Relationship between friction time and temperature changes at various measured portions of OFC side during friction process, in relation to friction torque curve at friction pressures of 30 and 20 MPa. Those results were measured by using the specimen, of which was shown in Fig. 1. The temperature change and friction torques were measured. The temperature during the friction process at a friction pressure of 30 MPa differed with that of 20 MPa.

Fig. 17 Relationship between forge pressure and joint efficiency of joints; friction pressure of 30 MPa and friction time of 4.0 s. The joint efficiency with this friction welding condition had scattering, and many joints fractured from the weld interface, although one of the joints had 100% joint efficiency with the A5052 base metal fracture. The number of the joint with the A5052 base metal fracture decreased with increasing friction pressure.

) or higher, it decreased the joint strength because that generated the IMC interlayer at the weld interface (Morozumi and Kikuchi, 1982). Hence, it can be considered that the temperature at the weld interface should be set to a range of 473 to 623 K for obtaining good joint. Furthermore, it could be considered that the mechanically mixed layer with high temperature condition will be easily generated than the low temperature, and the width of those layers were demonstrated as Fig. 11 and Fig. 15. That is, the scattering of the joint efficiency of the joint at the same friction welding condition also seems to be the caused by the difference of the temperature at the weld interface during the friction process. If there is not suitable temperature at the weld interface for friction welding between A5052 and OFC, the joint with a friction pressure of 30 MPa and a friction time of 4.0 s will be able to be made to the joint with the fracture on the A5052 base metal. That is, this time had high temperature condition because the temperature at the weld interface of this friction time was about 660 K (387 °C) as shown in Fig. 16a. However, the joint efficiency of the joint with a friction time of 4.0 s had scattering as shown in Fig. 17, and many joints fractured from the weld interface as shown in Fig. 5, although one of the joints had 100% joint efficiency with the A5052 base metal fracture. Thus, it also could be considered that there is suitable temperature at the weld interface for friction welding between A5052 and OFC, because the number of the joint with the A5052 base metal fracture decreased with increasing friction pressure (compare Fig. 17 and Fig. 13). On the other hand, if the joint will be made with a friction pressure of 30 MPa and a friction time of 2.0 s, it will be able to be made to the joint with the fracture on the A5052 base metal. Nevertheless, it will be difficult to obtain the joint at a friction pressure of 30 MPa with the fracture on the A5052 base metal, since the entire weld interface on the OFC side did not have the transferred A5052 as shown in Fig. 3. Hence, it is desirable to be set after the time which the entire weld interface had the transferred A5052. Therefore, it can be considered that the friction pressure should be set to 20 MPa, although the further investigation must elucidate the detailed temperature and the weldability for the joint between A5052 and OFC.

4.2. Investigation of fractured point for joint

Based on the above results, it was clarified that all joints fractured on the A5052 base metal when joints were made with a friction pressure of 20 MPa, a friction time of 6.0 s, and a forge pressure of 240 MPa. However, some joints, which was made with another friction time and forge pressure under a friction pressure of 20 MPa, fractured at the weld interface (see Fig. 13). To clarify this result, the cross-section of those joints was observed. Figure 18 shows the cross-sectional appearances of the weld interfaces of those joints at various friction welding conditions. Also, the weld interface of all joints did not have the not-joined regions at all friction welding conditions. Thus, it could understand that some joints fractured on the A5052 base metal in those friction welding conditions. Therefore, the forge pressure should be set to 240 MPa or higher, because the weld interface of the joint with a forge pressure of 210 MPa could not be completely joined and some of those fractured from the weld interface as shown in Fig. 13. Nevertheless, all joints with a forge pressure of 270 MPa did not have the fracture on the A5052 base metal. However, it was found that the OFC side as well as the A5052 side was deformed (see Fig. 18). In particular, the OFC side was deformed to a convex shape from the viewpoint

Fig. 18 Cross-sectional appearances of weld interfaces of joints at various forge pressures; friction pressure of 20 MPa and friction times of 6.0 and 8.0 s. The weld interface of all joints did not have the not-joined regions. The deformation of the OFC side to the radial direction of the joint with a friction time of 6.0 s and a forge pressure of 270 MPa resembled that of the joint with a friction time of 8.0 s and a forge pressure of 240 MPa.

of the A5052 side, and the deformation enlarged to the radial direction of the weld interface with increasing forge pressure and friction time. Then, the deformation of the OFC side to the radial direction of the joint with a friction time of 6.0 s and a forge pressure of 270 MPa (Fig. 18a-iii) resembled that of the joint with a friction time of 8.0 s and a forge pressure of 240 MPa (Fig. 18b-ii). Also, when the joint was made with a friction time of 8.0 and a forge pressure of 240 MPa, all joints did not have the A5052 base metal fracture. Hence, the fractured point of the joint seems to be cause of the deformation of the OFC side to the radial direction of the joint. Therefore, it could be considered that a forge pressure of 270 MPa was high because all joints with this friction time did not have the A5052 base metal fracture (see Fig. 13). If the deformation at the weld interface will be affected to the fractured point of the joint, it is considered that all joints with a friction time of 7.0 s and a forge pressure of 240 MPa will be fractured on the A5052 base metal. On the other hand, it is also considered that all joints with that friction welding condition will be not fractured on the A5052 base metal, because the deformation of that joint will be able to estimate larger than that of the joint with a friction time of 6.0 s. To clarify those, the tensile strength and the fractured portion of the joint with a friction time of 7.0 s and a forge pressure of 240 MPa were investigated. Consequently, the joint efficiencies of those joints were 100%. Almost all joints fractured from the weld interface as shown in Fig. 14a although one of the joints fractured at the A5052 base metal as shown in Fig. 14b. That is, all joints at this friction welding condition did not have the fracture on the A5052 base metal. Hence, it is desirable that the friction time was set to 6.0 s for obtaining good joint. Actually, the deformation at the weld interface to the radial direction was affected to the fractured point of some dissimilar friction welded joints (Aritoshi, et al., 1991; Fuji, et al., 1995; Kimura, et al., 2014). It was considered that one of the reason was the fiber structure at the adjacent region corresponding to the fractured position flowed from the longitudinal direction of the joint to the outer surface (Kimura et al., 2006). That is, the flow of the fiber structure at the welded interface and its adjacent region of the joint were turned perpendicular to the outer surface from the longitudinal direction. Therefore, the deformation at the weld interface seems to influence the fractured point of the joint.

According to the above consideration, the joint should be made with following conditions: a low friction pressures such as 20 MPa to prevent generating of the mechanically mixed layer, an opportune friction time such as 6.0 s without generating the IMC interlayer, and a high forge pressure such as 240 MPa in order to achieve completely joining of the weld interface. Of course, further investigation is also necessary to elucidate the detailed the fractured point and the deformation of the OFC side to the radial direction of the joint. This is a future investigation subject. However, the good joint with the above friction welding conditions had successfully achieved the 100% joint efficiency with the fracture in the A5052 base metal, as shown in Fig. 13. That is, it was indicated that the good joint between Al alloy and pure

Cu material could make by setting to friction welding condition as follows: a friction pressure for less generating of the mechanically mixed layer, a friction time for no generate of the IMC interlayer, and a forge pressure for the suitable deformation of the weld interface. In conclusion, the good joint between Al-Mg alloy and pure Cu, which did not have the fracture in the weld interface, was able to make with the opportune friction welding conditions.

5. Conclusions

This report described the joining phenomena during the friction process of friction welds between Al-Mg alloy (JIS A5052) and oxygen free copper (OFC). Then, the tensile strength of the friction welded joints at various friction welding conditions, especially the effects of friction time and forge pressure, were demonstrated. The following conclusions are provided.

- (1) The adjacent region of the weld interface at the A5052 side was upset during the friction process, although that of the OFC side was hardly upset.
- (2) The joint was not obtained a joint efficiency of 100%, although the joint efficiency increased with friction time because those joints had the not-joined region at the weld interface.
- (3) All joints at a friction pressure of 30 MPa did not have a joint efficiency of 100%, although the joint efficiency increased with increasing forge pressure. This joint did not have the intermetallic compound (IMC) interlayer on the weld interface. However, this joint had the mechanically mixed layers on the adjacent region of the weld interface at the A5052 side. Then, this layer affected to the fractured point of the joint.
- (4) All joints achieved a joint efficiency of 100%, the fracture on the A5052 base metal with no crack at the weld interface when joints were made with a friction pressure of 20 MPa, a friction time of 6.0 s, and a forge pressure of 240 MPa. The joint with this friction welding condition also did not have the IMC interlayer on the weld interface, although that had the less mechanically mixed layers on the adjacent region of the weld interface at the A5052 side.
- (5) It was suggested that the joint should be made with a low friction pressures such as 20 MPa to prevent generating of the mechanically mixed layer, an opportune friction time such as 6.0 s without generating the IMC interlayer, and a high forge pressure such as 240 MPa in order to achieve completely joining of the weld interface and the fracture on the A5052 base metal.

In conclusion, the good joint between Al-Mg alloy and pure Cu, which did not have the fracture in the weld interface, was able to make with the opportune friction welding conditions.

Acknowledgements

This research was partially supported by the Ministry of Education, Culture Sports, Science and Technology, Japan, Grant-in-Aid for Scientific Research (C) (MEXT KAKENHI), Grant Number 16K06748. The authors wish to thank the staff members of the Machine and Workshop Engineering at the Graduate School of Engineering, University of Hyogo. Also, the authors wish to thank Prof. Emeritus Dr. Akiyoshi Fuji and Mr. Harumi Hashimoto Technical Officer in Kitami Institute of Technology for their kindly and aggressive assisting to this study.

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