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Effect of Friction Welding Condition on Joining Phenomena and Tensile Strength of Friction Welded joint between Pure Copper and Low Carbon Steel*

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Abstract

This paper describes the effect of the friction welding condition on the joining phenomena and tensile strength of friction welded joint between pure copper (OFC) and low carbon steel (LCS). When the joint was made at friction pressure of 30 MPa with friction speed of 27.5 s^{-1}, OFC transferred to the half radius region of the weld interface on the LCS side, and then transferred toward the entire weld interface. The temperatures at the centerline, half radius and periphery portions on the weld interface of the LCS side were almost the same after the initial peak. When the joint was made at a friction time of 2.4 s, i.e. the friction torque was close to the initial peak, that had obtained approximately 40% joint efficiency and fractured from the weld interface with a little OFC adhering to the weld interface on the LCS side. The joint efficiency increased with increasing forge pressure, and it reached approximately 80% at a forge pressure of 180 MPa. This joint fractured at the softened OFC region adjacent to the weld interface. On the other hand, OFC transferred to the peripheral region of the weld interface on the LCS side when the joint was made at friction pressure of 90 MPa with friction speed of 27.5 s^{-1}. However, OFC transfer was not obtained at the central region because the temperature at the periphery portion was higher than that of the other portions. The joint efficiency increased with increasing friction time, and it obtained approximately 74% at a friction time of 1.2 s. Moreover, all joints fractured between the OFC side and the weld interface, although the joints were made with higher forge pressure. To obtain higher joint efficiency and fracture in the OFC side, the joint should be made with low friction pressure and high forge pressure, and with the friction time at which the friction torque reaches the initial peak.

Key words : Friction Welding, Oxygen Free Copper, Low Carbon Steel, Weld Interface, Joint Efficiency, Friction Pressure, Forge Pressure, Friction Time

1. Introduction

Copper (Cu) and many of its alloys are well-known materials that have highly attractive characteristics in terms of metallurgical property and workability, e.g. high electrical and thermal conductivity, good corrosion resistance, and good high elasticity. They are widely used for important components in a wide variety of electrical and mechanical parts, air conditioner heat exchangers, condensers for ships or plants, and so on. On the other hand, fusion welds between Cu and other metals such as steel, aluminum and titanium have poor mechanical properties due to the brittle intermetallic compound layer produced at the joint interface(1),(2).

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Moreover, fusion welds between Cu or its alloys and various steels have some problems, e.g. cracking of the joint interface[(1),(3)]. A welding process for dissimilar joints with Cu that will result in less degradation of the mechanical and metallurgical properties of the joint is therefore urgently required.

The solid state joining methods such as diffusion welding, friction welding, and so on, can be applied to join Cu and other metals. Many researchers have reported that the mechanical and metallurgical properties of friction welded joints between Cu or its alloys and steel show desirable characteristics[(4)−(9)]. However, the joining mechanism of friction welding between dissimilar materials such as Cu and steel has not been fully clarified, so that the friction welding conditions for material combinations are determined by trial and error. In addition, the joining mechanism between dissimilar materials differs from that of similar materials because mechanical properties such as tensile strength and thermal properties such as 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 previous works[(10),(11)], we clarified the joining mechanism during the friction welding process for similar material joints. We showed that the friction welded joints of several steels had 100% joint efficiency using only the first stage (up to the initial peak) of the friction process without adding forge pressure[(10),(12),(13)]. Furthermore, we presented the friction welding condition for making several Al alloy joints with high joint efficiency[(14),(15)]. If combinations of dissimilar materials such as Cu and steel are joined by using the same method as in previous reports, the joining mechanism between them in friction welding will be clarified.

The authors have been carrying out research to clarify the joining mechanism between dissimilar materials in the friction process. In the present work, we investigate the joining phenomena during the friction process of friction welds between pure Cu and low carbon steel. We also show that the joint tensile strength under various friction welding conditions are reported, especially the effects of friction pressure, friction time, and forge pressure on the tensile strength of the joint.

2. Experimental procedures

The materials used were oxygen free copper (referred to as OFC) and low carbon steel (referred to as LCS) in rods with a diameter of 16 mm. Two kinds of OFC having slightly different tensile properties were used for this experiment because the purchase time was different. The chemical composition of OFC base metals was 99.99Cu in mass%. The ultimate tensile strengths of OFC were 321 and 326 MPa, the 0.2% yield strengths were 309 and 311 MPa, and the elongations were 13.5 and 14.6%, respectively. The chemical composition of LCS was 0.16C-0.45Mn-0.20Si-0.12P-0.18S in mass%, the ultimate tensile strength was 451 MPa, the yield strength was 284 MPa, and the elongation was 36%. Those materials were machined to 12 mm in diameter of the weld faying (contacting) surface as shown in Figs. 1(a) and 1(b). In addition, the temperature change during the friction process at the centerline, half radius and periphery portions of the 1.0 mm longitudinal direction from the weld faying surface were measured by using the LCS specimen as shown in Fig. 1(c). 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 a dissimilar material joint.

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 s^{-1} (1650 rpm) and 30 MPa, and 27.5 s^{-1} and 90 MPa. To observe the joining phenomena, we carried out three experimental methods as follows. The detailed characteristics of these methods have been described in previous reports[(10)−(15)].

(1) The friction torque and temperature change during the friction process were measured by the conventional method. The friction torque was measured with a load-cell. The

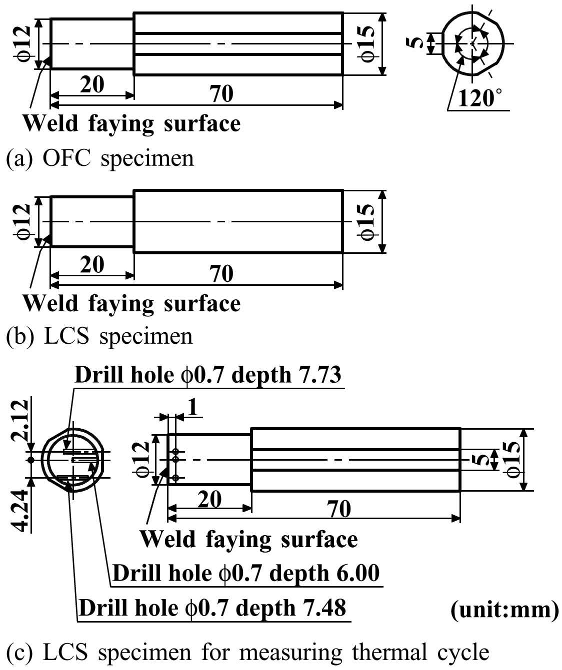

Fig. 1 Shapes and dimensions of friction welding specimens.

mineral insulated thermocouple with chromel-alumel was inserted into a drill hole of the LCS specimen, as shown in Fig. 1(c). The friction torque and temperature were recorded with a personal computer through an A/D converter with a sampling time of 0.05 or 0.001 s. Incidentally, the friction torque measured with the load-cell lacked continuity in the stepwise part as shown in Fig. 2 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 process.

(2) The fixed (steady) side chuck was directly connected to a hydraulic cylinder. The fixed side specimen was simultaneously and forcibly separated from the rotating side specimen when the friction time expired. The weld interface was separated at each friction time and observed. In this experimental method, the transitional joining phenomena were clarified when the weld faying surfaces contacted each other at each applied friction time.

(3) The fixed 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, friction pressure could be maintained (loaded), so that the effect of deformation on the joint during the braking time could be considered to be negligible. That is, forge pressure was applied at an identical friction pressure. As the braking time was smaller than 0.04 s, i.e. one rotation of the specimen, its effect was negligible. In this experimental method, the cross-sectional appearances of weld interface regions were observed at each applied friction time.

In addition, the effect of friction time on joint tensile strength was also investigated by using experimental method (3). All tensile test specimens were machined to 12 mm in diameter and 84 mm in parallel length. Vickers hardness distributions at the half radius location of the weld interface regions were measured with a load of 9.81 N (1 kgf). The measuring range was 8 mm from the weld interface, and the measuring interval was 150 μm. The fractured surface of the joint after joint tensile testing was analyzed using X-ray diffraction analysis.

3. Results and Discussion

3.1. Friction torque curve

Figure 2 shows the friction torque curves under friction pressures of 30 and 90 MPa.

When friction pressure was 30 MPa, both weld faying surfaces contacted each other and then the friction torque was increased. The friction torque reached the initial peak that was approximately 18 Nm when friction time was about 2.3 s. However, the initial peak torque was not as clear under this friction pressure. On the other hand, the initial peak torque was observed clearly when friction pressure was 90 MPa. In this case, the initial peak was approximately 40 Nm when friction time was about 0.2 s.

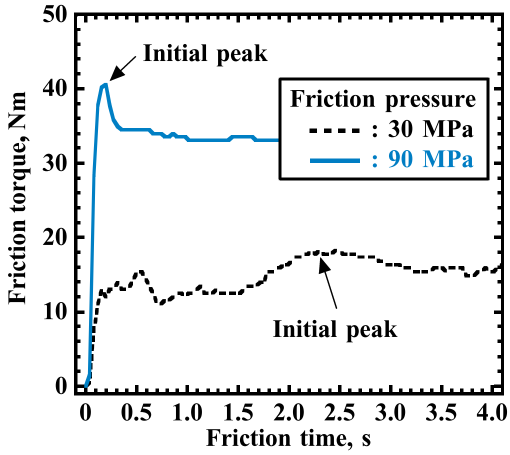

Fig. 2 Friction torque curves during friction process.

3.2. Transitional changes of weld interface

Figure 3 shows the examples of the appearance of the weld interfaces after welding under friction pressure of 30 MPa. When friction time was 0.04 s, i.e. both specimens had been rotated once, OFC transferred to around the half radius region of the weld interface on the LCS side. In addition, the concentric rubbing marks were observed at a similar region of the weld interface on the OFC side. Transferred OFC on the LCS side increased with increasing friction time and the concentric rubbing marks on the OFC side were extended. Also, the color of the transferred OFC on the LCS side and the weld interface of the OFC side turned colors such as blue, red and green. The flash (burr or collar) of the OFC increased with increasing friction time, whereas the LCS side was not deformed. When friction time was 2.4 s, i.e. the friction torque close to the initial peak, OFC transferred to the entire weld interface on the LCS side, and the flash on the OFC side was increased. The surface of the transferred OFC at the peripheral region of the weld interface on the LCS side turned slightly rough. The roughness increased with increasing friction time. Then, almost the entire weld interface turned very rough at a friction time of 4.0 s.

Figure 4 shows the examples of the appearance of the weld interfaces after welding under friction pressure of 90 MPa. When a friction time was 0.04 s, OFC transferred at the peripheral region of the weld interface on the LCS side. Also, the concentric rubbing marks were observed at a similar region of the OFC side. Transferred OFC of the weld interface on the LCS side increased, and its central region had almost no OFC when friction time was 0.2 s. Then, the central region of the LCS side had almost no OFC transfer although the flash from the OFC side was increased with increasing friction time. The transferred OFC on the LCS side and the weld interface of the OFC side also became colorful. That is, OFC was hardly transferred at the central region of the weld interface on the LCS side under friction pressure of 90 MPa. The flash of OFC side increased with increasing friction time, whereas the LCS side was not deformed and the weld interface on the LCS side was not turned rough.

3.3. Temperature change during friction process

Figures 5 and 6 show the temperature changes with the friction torques during the friction

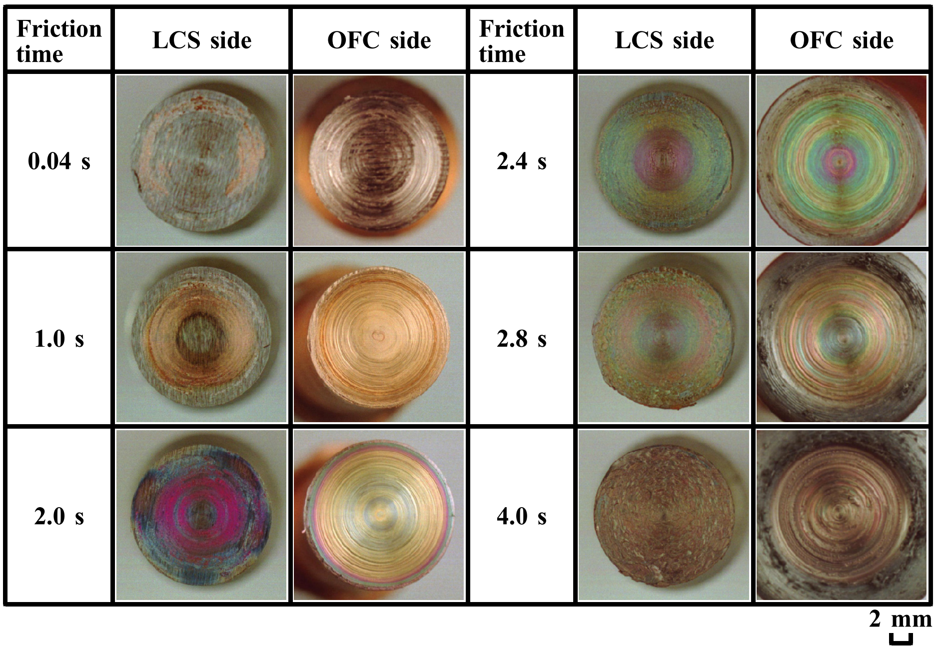

Fig. 3 Appearances of weld interfaces after welding; friction pressure of 30 MPa.

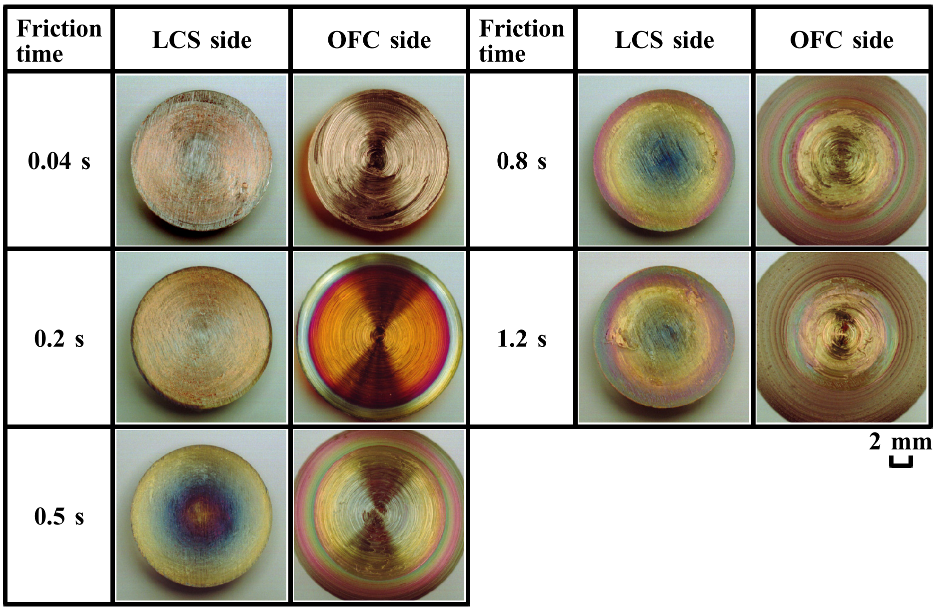

Fig. 4 Appearances of weld interfaces after welding; friction pressure of 90 MPa.

process. When friction pressure was 30 MPa as shown in Fig. 5, the periphery temperature was lower than that of the others before the friction torque reached the initial peak. However, the temperatures at the centerline, half radius and periphery portions on the weld interface of the LCS side were almost the same after the initial peak. That is, the difference in each temperature was small after the initial peak. On the other hand, the maximum temperatures with a friction pressure of 90 MPa were lower than those of 30 MPa, although the friction torque varied, as shown in Fig. 6. In addition, the centerline and half radius temperatures were lower than that of the periphery portion. Hence, because the temperature of the centerline portion at a friction pressure of 90 MPa was not high enough, that region of the weld interface on the LCS side did not have the OFC transfer (see Fig. 4).

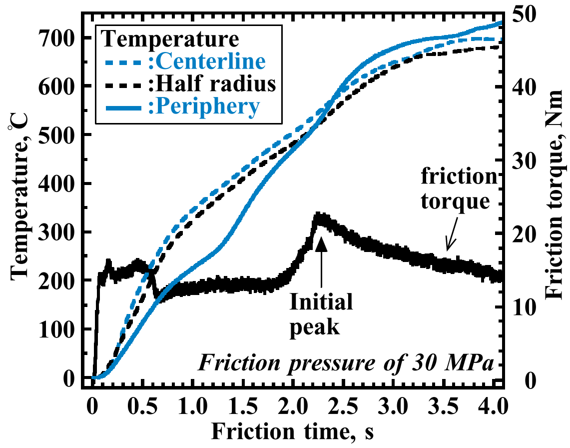

Fig. 5 Temperature change and friction torque during friction process; friction pressure of 30 MPa.

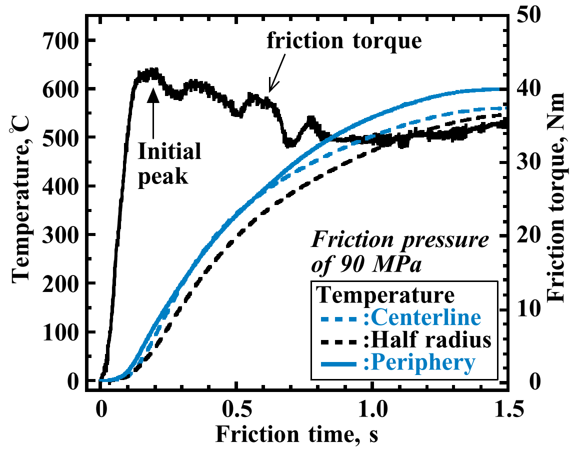

Fig. 6 Temperature change and friction torque during friction process; friction pressure of 90 MPa.

3.4. Joint efficiency

Figure 7 shows the relationship between the friction time and the joint efficiency of the joint, plotted alongside the friction torque curve at a friction pressure of 30 MPa. The joint efficiency was defined as the ratio of joint tensile strength to the ultimate tensile strength of the OFC base metals. Figure 8 shows an example of the appearance of the joint tensile test specimen after tensile testing at a friction pressure of 30 MPa. In this case, forge pressure was applied at an identical friction pressure, i.e. 30 MPa. The joint efficiency at a friction time of 1.8 s was approximately 2% because a sufficient quantity of heat could hardly be produced for welding during this friction time. Then, the joint efficiency increased with increasing friction time. The joints had approximately 42% joint efficiency at a friction time of 2.4 s, i.e. the friction torque close to the initial peak. Thereafter, the joint efficiency slightly decreased with increasing friction time after the friction torque reached the initial peak. All joints fractured at the weld interface, which had a little OFC adhering to the weld interface on the LCS side, as shown in Fig. 8. The fractured surface of those joints had a surface similar to the weld interface at each friction time, as shown in Fig. 3. In addition, the peaks corresponding to Cu and Fe were observed on those fractured surfaces on the LCS side. That is, the peak of the intermetallic compound between Cu and Fe was not detected on those surfaces by X-ray diffraction analysis. Hence, it was considered that the intermetallic compound at the weld interface was not involved with the fracture position of the joint.

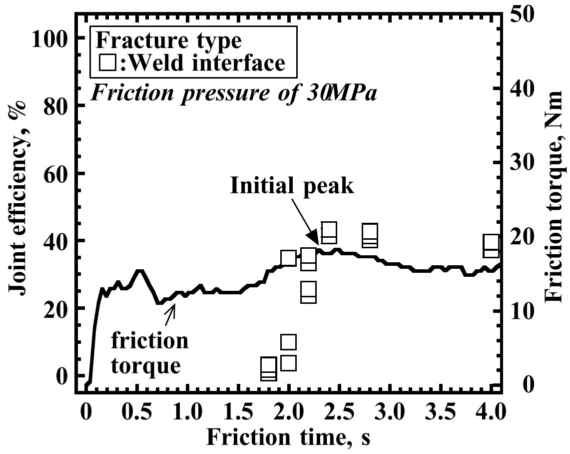

Fig. 7 Relationship between friction time and joint efficiency of joint, in relation to friction torque; friction pressure of 30 MPa and forge pressure of 30 MPa.

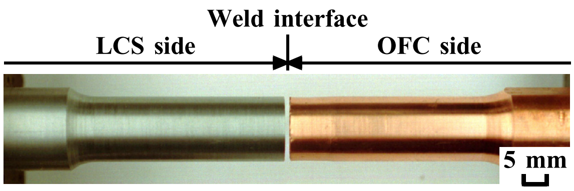

Fig. 8 Example of joint tensile test specimen appearance after tensile testing; friction pressure of 30 MPa.

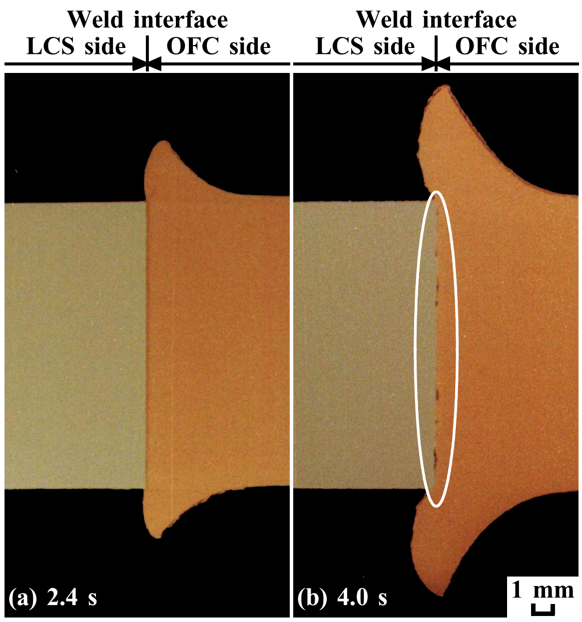

Fig. 9 Cross-sectional appearance of weld interface region of joints; friction pressure of 30 MPa, friction time of 2.4 and 4.0 s.

Figure 9 shows the cross-sectional appearances of the weld interface region at friction time of 2.4 and 4.0 s. The joint at a friction time of 2.4 s had no defects such as a not-joined region at the weld interface. However, the joint at a friction time of 4.0 s had the not-joined regions at the weld interface, which is indicated by a circle. Although further investigation is necessary to elucidate the detailed production mechanism of the not-joined region at the weld interface, it is considered that the friction time should be set to an optimum time, i.e. the time at which the friction torque reaches the initial peak.

Figure 10 shows the relationship between the friction time and the joint efficiency of the joint, plotted alongside the friction torque curve at a friction pressure of 90 MPa. Figure 11 shows an example of the appearance of the joint tensile test specimens after tensile testing at a friction pressure of 90 MPa. In this case, forge pressure was applied at an identical friction pressure, i.e. 90 MPa. The joint efficiency of the joint at a friction time of 0.2 s was approximately 35%, which fractured from the weld interface with a little OFC adhering to the weld interface on the LCS side, as shown in Fig. 11(a). The joint efficiency increased with increasing friction time, and it reached approximately 74% at a friction time of 1.2 s. This joint fractured between the OFC side and the weld interface (mixed mode fracture), as shown

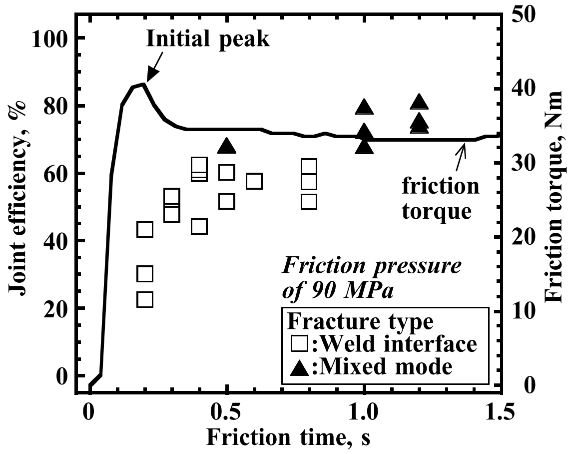

Fig. 10 Relationship between friction time and joint efficiency of joint, in relation to friction torque; friction pressure of 90 MPa and forge pressure of 90 MPa.

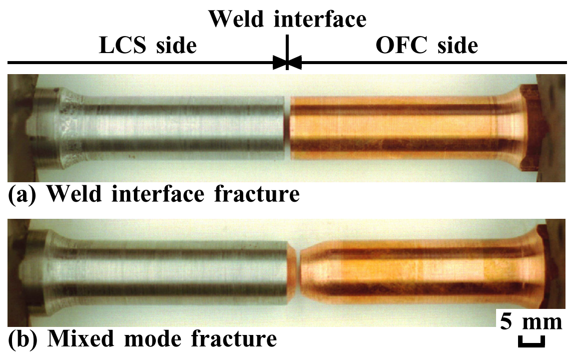

Fig. 11 Example of joint tensile test specimens appearance after tensile testing; friction pressure of 90 MPa.

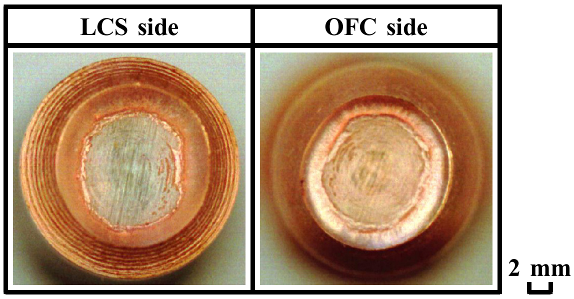

Fig. 12 Example of fractured surfaces of joint tensile test specimens after tensile testing; friction pressure of 90 MPa.

in Fig. 11(b). That is, the central region of the weld interface was hardly joined, as shown in Fig. 12. This result was caused by low temperature of the central region during the friction process. In this connection, the peak of the intermetallic compound was not observed on these fractured surfaces.

3.5. Improving joint efficiency

In an attempt to improve the joint efficiency, the joints were made by adding forge pressure. Figure 13 shows the relationship between the forge pressure and the joint efficiency of the joint under friction pressure of 30 MPa at a friction time of 2.4 s. Figure 14 shows an example of the appearance of the joint tensile test specimens after tensile testing at various forge pressures under friction pressure of 30 MPa. The joint efficiency increased with increasing forge pressure. Following higher joint efficiency, the joint was changing through the mixed mode fracture (Fig. 14(b)) to the OFC side fracture (Fig. 14(c)) from the weld interface fracture (Fig. 14(a)). When forge pressure was 180 MPa, the joint efficiency was approximately 80%, and all joints fractured from the OFC side, as shown in Fig. 14(c). Then, the joint efficiency hardly increased at a forge pressure of 210 MPa. Figure 15 shows the Vickers hardness distribution across the weld interface at the half radius of the joint at a forge pressure of 180 MPa. The joint had a softened region that extended about 7.5 mm in the longitudinal direction

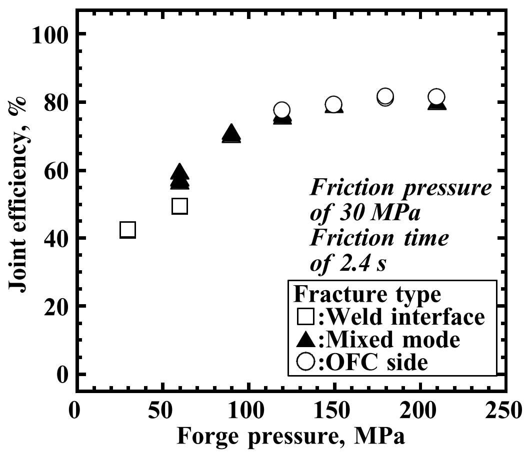

Fig. 13 Relationship between forge pressure and joint efficiency of joint; friction pressure of 30 MPa.

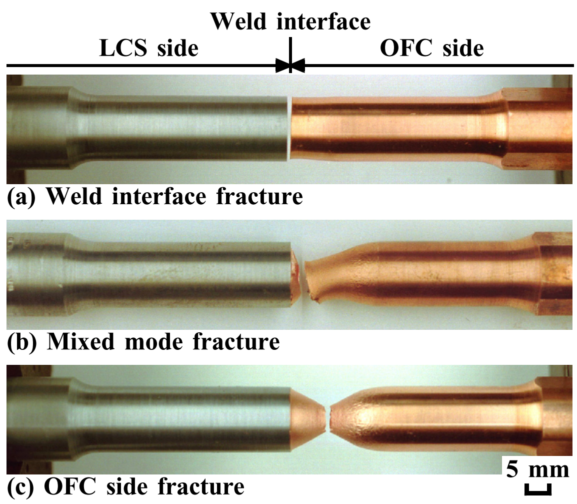

Fig. 14 Example of joint tensile test specimens appearance of joint at various forge pressures after tensile testing; friction pressure of 30 MPa.

of the OFC side. This joint also had a hardened region that extended about 2.5 mm in the longitudinal direction on the LCS side. Hence, the joint did not achieve 100% joint efficiency by the softening of the adjacent region of the weld interface on the OFC side. However, the joint fractured from the OFC side with a forge pressure of 180 MPa.

Figure 16 shows the relationship between the forge pressure and the joint efficiency of the joint under friction pressure of 90 MPa at a friction time of 1.2 s. The joint efficiency was approximately 77% at any forge pressure, and those were lower than the maximum joint efficiency with a friction pressure of 30 MPa. In addition, all joints had the mixed mode fracture as shown in Fig. 11(b). That is, the central region of the weld interface was hardly joined as shown in Fig. 12. These joints also had softened at the peripheral region of the OFC side. Hence, it was difficult that the joint did not have the softened region at the adjacent of the weld interface under these friction pressures. Meanwhile, the joint was made through friction pressure of 30 MPa at a friction time of 2.4 s with a forge pressure of 180 MPa, which fractured from the OFC side although it had approximately 80% joint efficiency (see Fig. 13). That is, the entire weld interface could be joined by such a low friction pressure as 30MPa. Therefore, to obtain higher joint efficiency and fracture in the OFC side, the joint should be made with low friction pressure and high forge pressure, and with the friction time at which the friction torque reaches the initial peak.

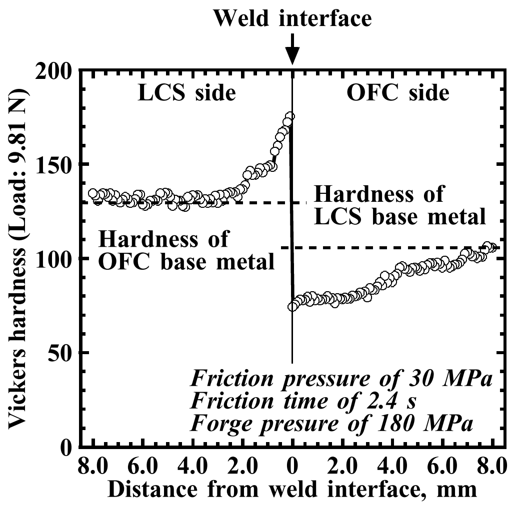

Fig. 15 Vickers hardness distribution across weld interface of joint; friction pressure of 30 MPa, friction time of 2.4 s, and forge pressure of 180 MPa.

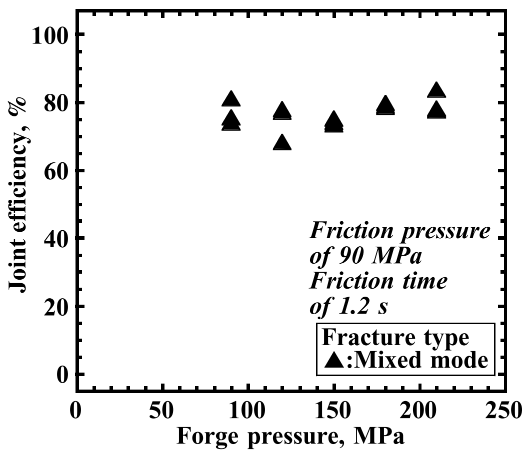

Fig. 16 Relationship between forge pressure and joint efficiency of joint; friction pressure of 90 MPa.

4. Conclusions

This report described the effect of friction welding condition on joining phenomena and tensile strength of friction welded joint between pure copper (OFC) and low carbon steel (LCS). In particular, we investigated the joining phenomena during friction process, and the joint tensile strength of the joint under various friction welding conditions such as friction pressure, friction time, and forge pressure. The following conclusions are provided.

(1) For a joint made under friction pressure of 30 MPa:

i. OFC transferred to the half radius region of the weld interface on the LCS side, and then it transferred toward the entire weld interface.

ii. The temperatures at the centerline, half radius and periphery portions on the weld interface of the LCS side were almost the same after the initial peak.

iii. When the joint was made at a friction time of 2.4 s, i.e. the friction torque was close to the initial peak, that had obtained approximately 40% joint efficiency and fractured from the weld interface with a little OFC adhering to the weld interface on the LCS side. Then, the joint efficiency slightly decreased with increasing friction time.

iv. The joint efficiency at a friction time of 2.4 s increased with increasing forge pressure, and it reached approximately 80% at a forge pressure of 180 MPa. This joint fractured at the softened OFC region adjacent to the weld interface.

(2) For a joint made under friction pressure of 90 MPa:

i. OFC transferred to the peripheral region of the weld interface on the LCS side. However, the central region did not obtain OFC transfer.

ii. The temperature at the periphery portion was higher than that of the other portions.

iii. The joint efficiency increased with increasing friction time, and it reached approximately 74% at a friction time of 1.2 s.

iv. The joint efficiency at a friction time of 1.2 s hardly increased and all joints fractured between the OFC side and the weld interface, although the joints were made with higher forge pressure.

In conclusion, to obtain higher joint efficiency and fracture in the OFC side, the joint should be made with low friction pressure and high forge pressure, and with the friction time at which the friction torque reaches the initial peak.

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