Effect of friction welding condition on joining phenomena and joint strength of friction welded joint between brass and low carbon steel

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This paper describes the effect of friction welding condition on joining phenomena and joint strength of friction welded joints between copper-zinc alloy (brass) and low carbon steel (LCS). When the joint was made at a friction pressure of 30 MPa with a friction speed of 27.5 s^{-1}, brass transferred to the half radius region of the weld interface on the LCS side. Then, transferred brass extended toward the almost whole weld interface with increasing friction time. The joint efficiency increased with increasing friction time, and then it obtained 100% and the brass base metal fracture when the joint was made with a friction time of 4.2 s or longer. However, the fact that all joints had some cracks at the periphery portion of the weld interface was due to a deficiency of transferred brass at the periphery portion on the weld interface of the LCS side. On the other hand, brass transferred to the peripheral region of the weld interface on the LCS side, and then transferred toward the entire weld interface when the joint was made at a friction pressure of 90 MPa with a friction speed of 27.5 s^{-1}. The joint efficiency increased with increasing friction time, and it obtained 100% at a friction time of 1.5 s or longer. In addition, all joints fractured from the brass base metal with no cracking at the weld interface. To obtain 100% joint efficiency and the brass base metal fracture with no cracking at the weld interface, the joint should be made with opportune high friction pressure and friction time at which the entire weld interface had the transferred brass.

Keywords: Friction welding, Brass, Low carbon steel, Transference, Joint efficiency, Friction time, Forge pressure, Fracture, Crack

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 ductility. They also have wear resistance between metals, and distinctive aesthetic appearance. However, fusion weld joints between Cu and other metals such as steel, aluminium and titanium have poor mechanical properties due to the brittle intermetallic compound layer produced at the joint interface.[1-2] In particular, 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 joints between Cu and dissimilar metals 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.[4-11] However, almost all friction welded joints between Cu alloy and steel did not have excellent joint properties such as 100% joint efficiency. In addition, 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. Furthermore, 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 friction welding conditions theoretically, it is necessary to clarify the joining phenomena. In particular, clarification of the joining phenomena is required concerning the weldability of a Cu alloy with other metals because an expansion in the use of Cu alloys is expected.

In previous works,[12-23] we clarified the joining mechanism during the friction welding process for similar

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material joints. Then, we presented the joining phenomena between dissimilar materials such as aluminium and titanium in the friction process, and the tensile strength of the joint.[24] We also presented the joining phenomena and tensile strength of the joint between pure Cu and steel.[25] If combinations of dissimilar materials such as Cu alloy and steel are joined by using the same method as in the previous reports,[12-23] the joining mechanism between them in friction welding will be clarified.

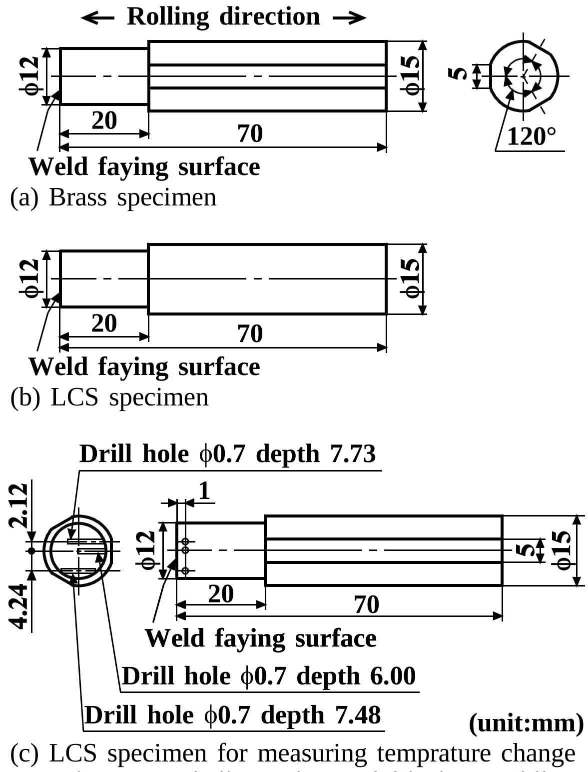
According to the background described above, the authors have been carrying out research to clarify the joining mechanism between dissimilar materials in the friction process. In the present work, we investigate the joining phenomena during the friction process of friction welds between a typical Cu alloy, i.e. alpha-beta brass (Muntz metal), and low carbon steel. We also show the joint tensile strength under various friction welding conditions, especially the effects of friction time and forge pressure on the tensile strength of the joint. Furthermore, we also show the friction welding condition for the joint, which obtained 100% joint efficiency and fractured from the brass base metal with no cracking at the weld interface.

Experimental procedure

The materials used were alpha-beta brass (referred to as brass) plate with a thickness of 16 mm, and low carbon steel (referred to as LCS) rod with a diameter of 16 mm. The chemical composition of brass was 60.0Cu-40.0Zn in mass%, the ultimate tensile strength was 391 MPa, the 0.2% yield strength was 247 MPa, and the elongation was 46%. 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%. The brass plate was cut in a rectangular shape along the rolling direction, and then machined to a 12 mm diameter for the weld faying (contacting) surface, as shown in Fig. 1a. The LCS rod was machined to a 12 mm diameter for the weld faying surface, as shown in Fig. 1b. 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. 1c. 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.

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. These values of the friction welding conditions were determined in consideration of the previous results,[12-15,25] because the seizure portion at the weld interface of the steel friction welded joints[12-15] and the fracture portion of the joint between pure Cu and LCS[25] were different. To observe the joining phenomena, we carried out three experimental methods as follows. The details of these methods have been described in previous reports.[12-23]

(1) The joining behaviour was recorded by a digital video camera. The friction torque was measured with a load-cell. The mineral insulated thermocouple with



1 Shapes and dimensions of friction welding specimens

chromel-alumel was inserted into a drill hole of the LCS specimen, as shown in Fig. 1c. In ordinary cases, the LCS specimen was set to the rotating side, but the LCS specimen to measure temperature change, which was shown in Fig. 1c, was set to the fixed side. 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.

(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.

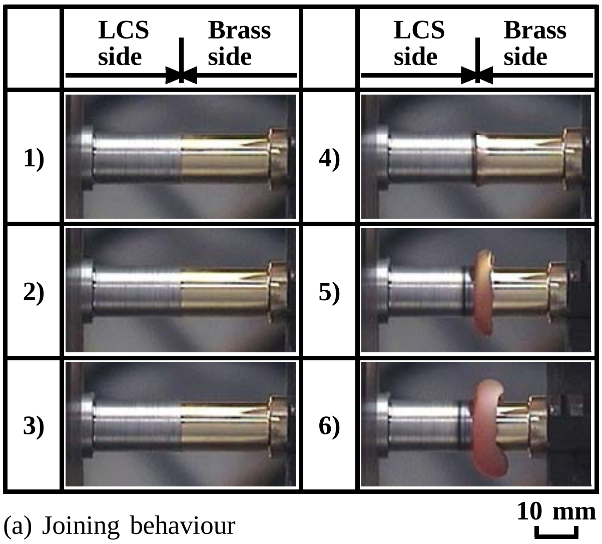
(3) The fixed side specimen was fixed with an electromagnetic clutch. When the clutch was released, the relative speed between both specimens instantly decreased to zero. In this case, friction pressure could be maintained (loaded), so that the effect of deformation on the joint during the braking time would be negligible.

In addition, the effect of friction time on joint tensile strength was also investigated by using experimental method (3). All joint tensile test specimens were machined to 12 mm in diameter and 66 mm in parallel length. Moreover, analysis via EDS was carried out to analyze the chemical composition in the weld interface region.

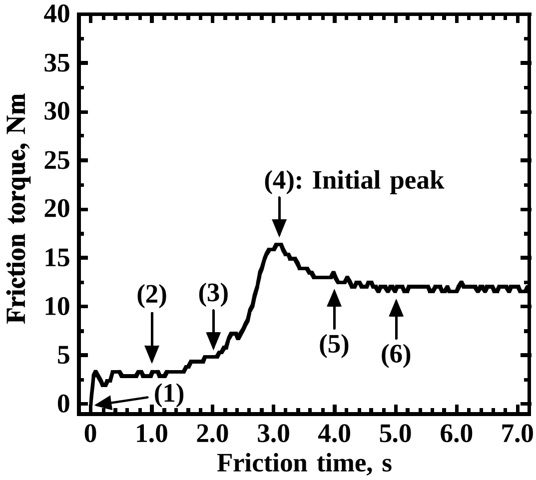
Results and Discussion

Relationship between joining behaviour and friction torque

Figure 2 shows the relationship between the joining behaviour and the friction torque with a friction pressure

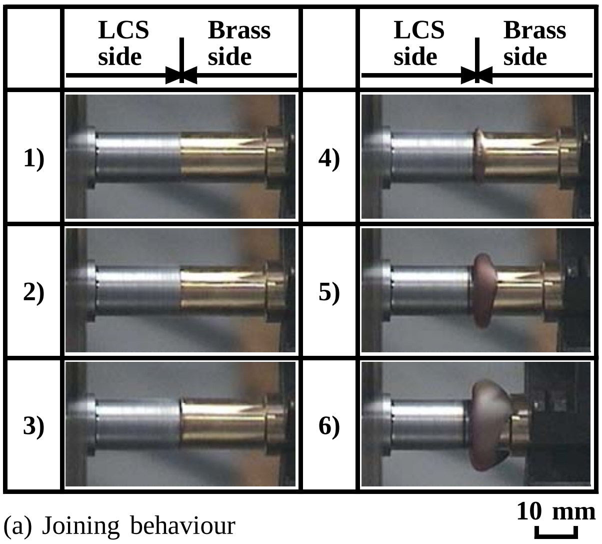


(a) Joining behaviour

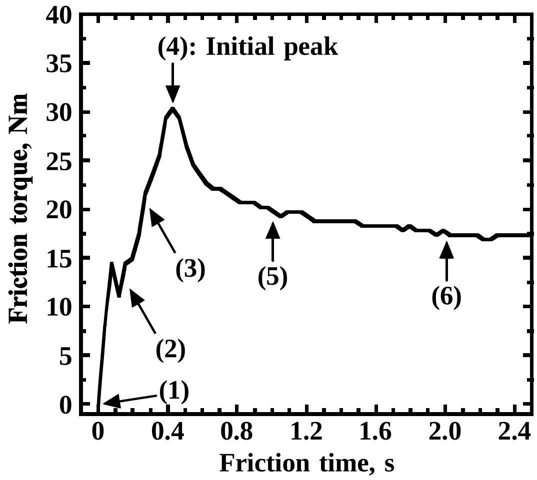


(b) Friction torque curve

2 Joining behaviour and friction torque curve during friction process; friction pressure of 30 MPa



(a) Joining behaviour



(b) Friction torque curve

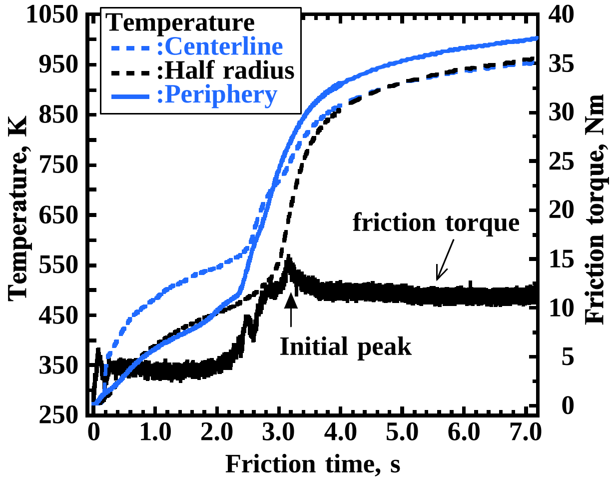
3 Joining behaviour and friction torque curve during friction process; friction pressure of 90 MPa

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, then the friction torque was increased and kept nearly constant. Photos 2) and 3) were similar to 1), that is the friction torque maintained nearly constant between (2) and (3). The friction torque increased with increasing friction time, and then it reached the initial peak at (4). The brass side was slightly upset (deformed) as shown in photo 4). Thereafter, the friction torque decreased with increasing friction time, and then it was maintained nearly constant between (5) and (6). In addition, the upsetting and the flash (burr or collar) of brass increased with increasing friction time although the LCS side was not upset, as shown in photos 5) and 6).

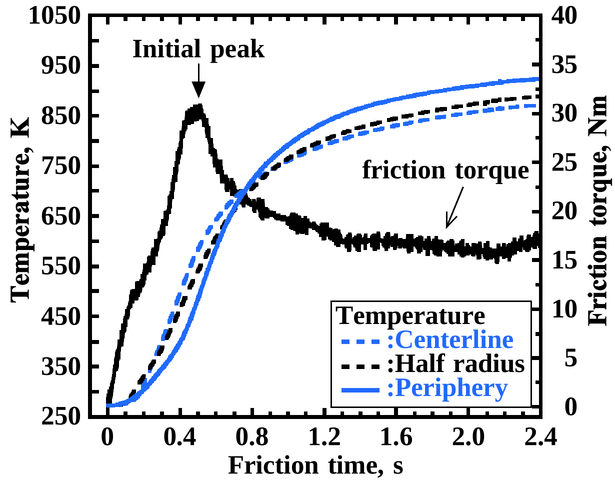
Figure 3 shows the relationship between the joining behaviour and the friction torque with a friction pressure of 90 MPa. Photos 1) to 6) in Fig. 3a correspond to friction torques (1) to (6) in Fig. 3b. Photo 1) shows when the weld faying surfaces initially contacted each other. Photo 2) was similar to 1), although the friction torque was increased. The brass side was slightly upset as shown in photo 3), and then the friction torque reached the initial peak at (4). Thereafter, the friction torque decreased with increasing friction time, and then it was maintained nearly constant between (5) and (6). The joining phenomena of those joints were similar although the friction torque varied during the friction process. The elapsed times for the initial peak were close to that of pure Cu and LCS friction welded joints under the same friction welding conditions.[25]

Temperature change during friction process

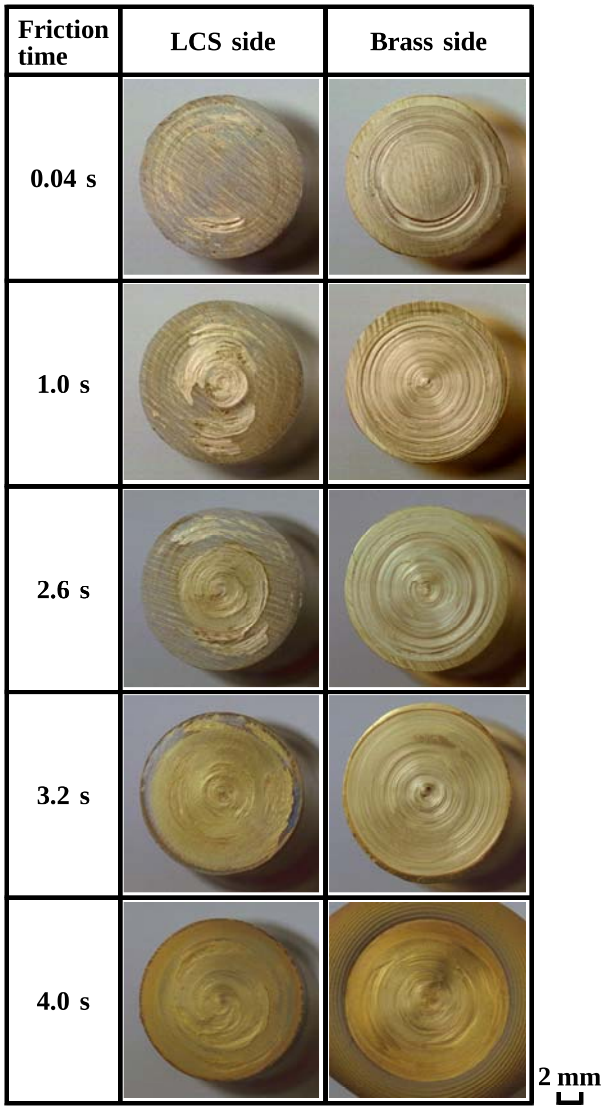
Figures 4 and 5 show the temperature changes with the friction torques during the friction process. When friction pressure was 30 MPa as shown in Fig. 4, the temperature at the centerline portion on the weld interface of the LCS side was higher than the periphery temperature before the friction torque reached the initial peak. However, the periphery temperature was higher than the centerline temperature after the initial peak. In addition, the temperatures at the centerline and half radius portions were almost the same after the initial peak. On the other hand, when friction pressure was 90 MPa as shown in Fig. 5, the temperatures at the centerline, half radius and



4 Temperature change and friction torque during friction process; friction pressure of 30 MPa



5 Temperature change and friction torque during friction process; friction pressure of 90 MPa



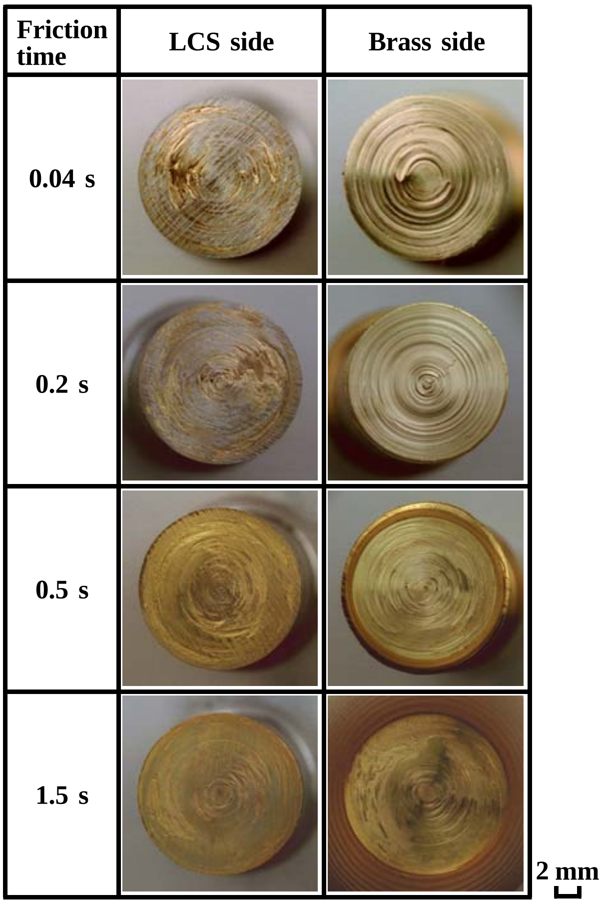
6 Appearances of weld interfaces after welding; friction pressure of 30 MPa

periphery portions were almost the same before the friction torque reached the initial peak. The periphery temperature was higher than the centerline temperature after the initial peak. Moreover, the temperatures at the centerline and half radius portions were almost the same after the initial peak. The maximum temperatures with a friction pressure of 90 MPa were lower than those of 30 MPa, although the friction torque varied. This result was due to the temperature of the yield strength of the brass base metal. That is, the temperature of the high strength was lower than that of the low strength, when the base metal is upsetting under the loaded friction pressure.[16] This difference in the measured temperatures under both friction pressures was similar to that of pure Cu and LCS friction welded joints at the same friction pressures.[25]

Transitional changes of weld interface

Figure 6 shows the examples of the appearances of the weld interfaces after welding under friction pressure of 30 MPa. When a friction time was 0.04 s, i.e. both specimens had been rotated once, brass transferred around the half radius region of the weld interface on the LCS side. In addition, the concentric rubbing marks were observed at the similar region of the weld interface on the brass side, and its whole weld interface was slightly worn. Transferred brass on the LCS side increased with increasing friction time and the concentric rubbing marks on the brass side were extended. When a friction time was 3.2 s, i.e. the friction torque reached the initial peak, brass transferred to the whole weld interface without the peripheral region on the LCS side, and the flash on the brass was increased. Then, the LCS side was not deformed, although the flash from the brass side was increased with increasing friction time. However, the transferred brass at the peripheral region on the LCS side was not increased. The fact that the peripheral region of the weld interface on the LCS side did not have the transferred brass was due to the low temperature in this region before the initial peak.

Figure 7 shows the examples of the appearances of the weld interfaces after welding under friction pressure of 90 MPa. When a friction time was 0.04 s, brass transferred at the peripheral region of the weld interface on the LCS side. Also, the concentric rubbing marks were observed at the whole weld interface of the brass side. Transferred brass of the weld interface on the LCS side increased with



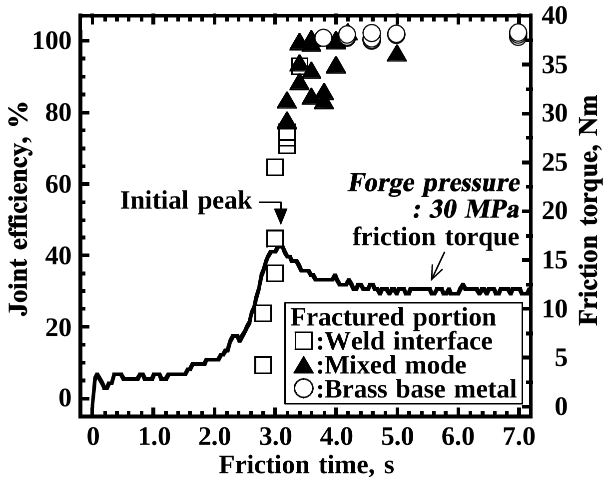
7 Appearances of weld interfaces after welding; friction pressure of 90 MPa

increasing friction time. When a friction time was 0.5 s, i.e. the friction torque reached the initial peak, brass transferred to almost whole weld interface without the slight peripheral region on the LCS side, and the flash on the brass was increased. Then, almost the entire weld interface of the LCS side had transferred brass when a friction time was 1.5 s.

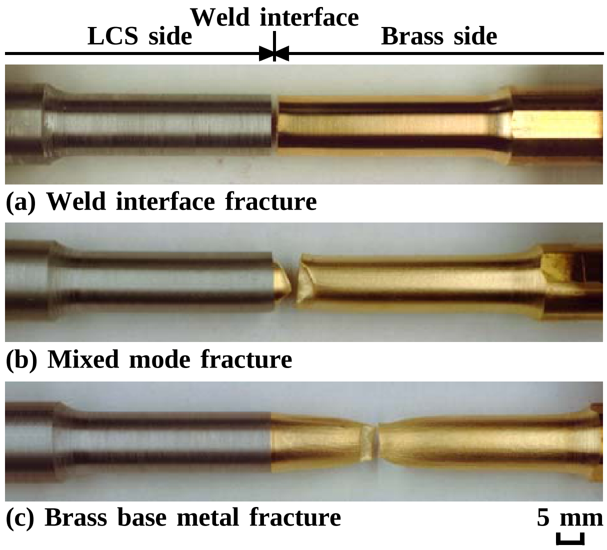
According to these results, the entire weld interface had transferred no brass when the friction torque reached the initial peak under these friction pressures. In addition, the brass side flash increased with increasing friction time, whereas the LCS side was not deformed.

Joint efficiency

Figure 8 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 brass base metal. Figure 9 shows the appearances of the joint tensile test specimens after tensile testing. In this case, forge pressure was applied at an identical friction pressure, i.e. 30 MPa. The joint efficiency at a friction time of 2.8 s was approximately 16%. The joint fractured at the weld interface, which had a little brass adhering on the LCS side interface, as shown in Fig. 9a. In this connection, the brass and LCS were not welded before a friction time of 2.8 s because a sufficient quantity of heat for welding could not be produced (see Fig. 4). The joint efficiency increased with increasing friction time. The joint had



8 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

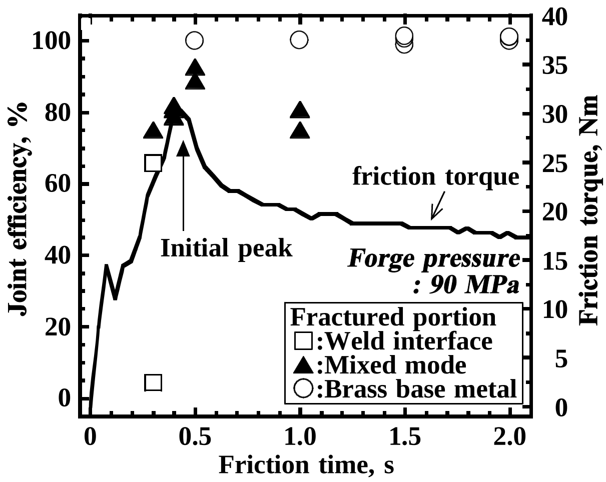


a weld interface fracture; *b* mixed mode fracture; *c* Brass base metal fracture

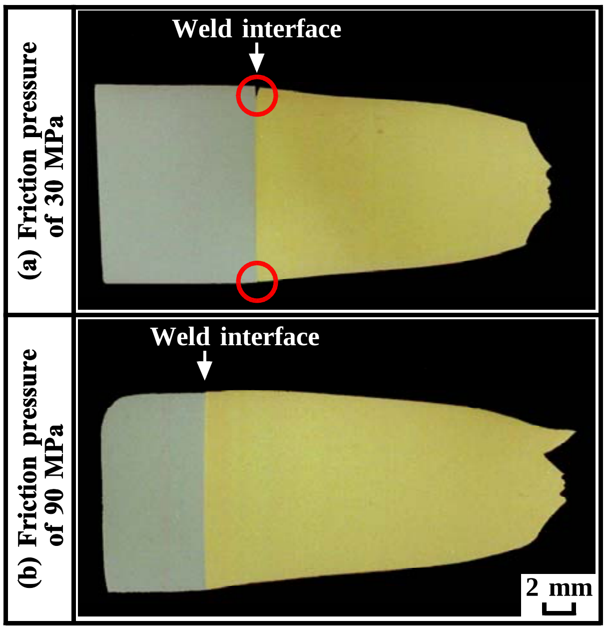
9 Appearances of joint tensile test specimens after tensile testing

approximately 76% joint efficiency at a friction time of 3.2 s, i.e. the friction torque close to the initial peak. Almost all joints fractured between the brass side and the weld interface (mixed mode fracture), as shown in Fig. 9b, although some of the joints fractured at the weld interface as shown in Fig. 9a. The joint efficiency increased with increasing friction time. Then, the joint was changed to the brass base metal fracture (Fig. 9c) from the mixed mode fracture (Fig. 9b). Some of the joints had 100% joint efficiency and those fractured at the brass base metal when a friction time was 4.2 s or longer. However, the joint efficiency was scattered.

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. In this case, forge pressure was applied at an identical friction pressure, i.e. 90 MPa. The joint efficiency at a friction time of 0.3 s was approximately 48%, and the



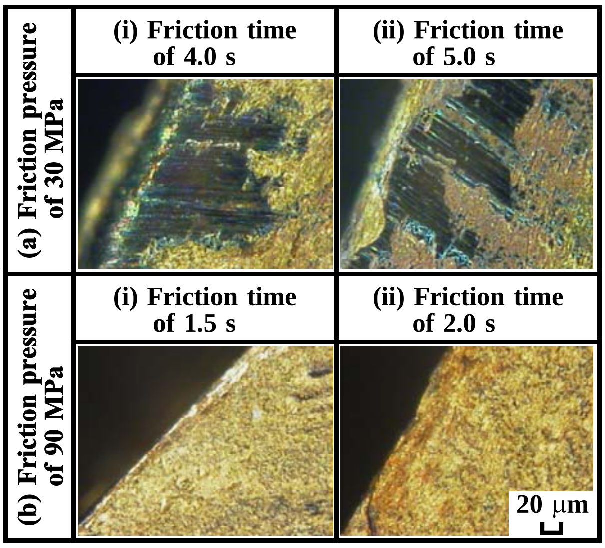
10 Relationship between friction time and joint efficiency of joint, in relation to friction torque; friction pressure of 90 MPa and forge pressure of 90 MPa



11 Cross-sectional appearances of fractured specimens with brass base metal fracture of joints after tensile testing; friction pressure of (a) 30 and (b) 90 MPa

joint had the weld interface or mixed mode fracture. The joint efficiency increased with increasing friction time, and it was approximately 94% at a friction time of 0.5 s, i.e. the friction torque close to the initial peak. In addition, one of the joints had 100% joint efficiency and it fractured at the brass base metal. Then, all joints had 100% joint efficiency and the brass base metal fracture when a friction time was 1.5 s or longer.

Figure 11 shows the cross-sectional appearances of the fractured specimens with the brass base metal fracture of the joint after tensile testing. The joint at a friction pressure of 30 MPa had cracks at the periphery portion of the weld interface after tensile testing, which is indicated by circles as shown in Fig. 11a. On the other hand, the weld interface of the joint at a friction pressure of 90 MPa had neither the not-joined region nor defects such as

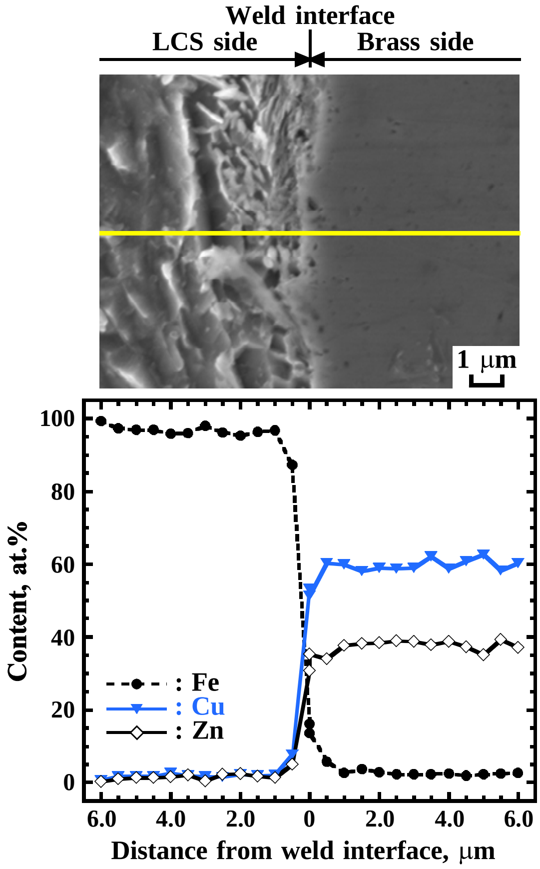


12 Optical overviews at peripheral region of weld interface on LCS side after welding; friction pressure of (a) 30 and (b) 90 MPa

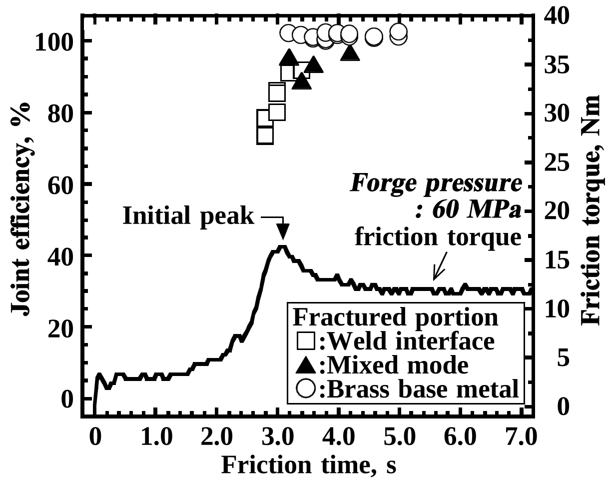
cracking after tensile testing, as shown in Fig. 11b. That is, brass and the LCS were tightly joined at a friction pressure of 90 MPa. Figure 12 shows optical overviews at the peripheral region of the weld interface on the LCS side after welding. When friction pressure was 30 MPa, the peripheral region of the weld interface had slight transferred brass (a in Fig. 12i). In addition, the quantity of transferred brass was not increased with increasing friction time (a in Fig. 12ii). However, the transferred brass at the peripheral region of the weld interface of the joint at a friction pressure of 90 MPa had more than that of 30 MPa (b in Figs. 12i and ii). Consequently, the fact that the joint at a friction pressure of 30 MPa had some cracks at the weld interface was due to a deficiency of transferred brass at the peripheral region on the weld interface of the LCS side. Incidentally, it is considered that the joint will not obtain the brass base metal fracture when the joint is made with more high friction pressure, because the central portion of the weld interface is not welded.[25-27] Hence, the friction pressure should be set to opportune high friction pressure.

Observation of weld interface region

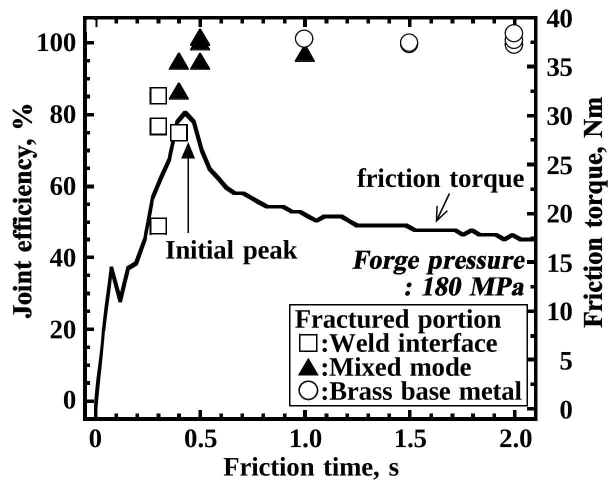
To clarify the joint properties in detail, we carried out the SEM observation of the weld interface of the joint that had the brass base metal fracture. Figure 13 shows the SEM image and EDS analysis result at the half radius portion of the weld interface region of the joint with the brass base metal fracture. In this case, the joint was made with a friction pressure of 90 MPa, a friction time of 2.0 s, and a forge pressure of 90 MPa. The weld interface was clear, and the distribution lines corresponding to Cu, Fe, and Zn by EDS analysis had no plateau part at the weld interface. That is, an intermetallic compound layer was not observed. Although further investigation is necessary to elucidate the detailed metallurgical characteristics of the joint, to obtain 100% joint efficiency and the brass base metal fracture with no cracking at the weld interface, the joint should be made with friction pressure and friction time as follows: opportune high friction pressure and friction time at which the entire weld interface had the transferred brass.



13 SEM image and EDS analysis result of weld interface region; friction pressure of 90 MPa, friction time of 2.0 s, and forge pressure of 90 MPa



14 Relationship between friction time and joint efficiency of joint, in relation to friction torque; friction pressure of 30 MPa and forge pressure of 60 MPa



15 Relationship between friction time and joint efficiency of joint, in relation to friction torque; friction pressure of 90 MPa and forge pressure of 180 MPa

Influence of forge pressure

To reduce the cracking from the joint and to decrease the scatter of the joint efficiency, the effect of forge pressure on joint efficiency was investigated. Figure 14 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. In this case, forge pressure was applied at 60 MPa. The joint efficiency at a friction time of 2.8 s was approximately 75%. The joint fractured at the weld interface, which had a little brass adhering on the LCS side interface, as shown in Fig. 9a. The joint efficiency increased with increasing friction time. The joints had approximately 96% joint efficiency at a friction time of 3.2 s, i.e. the friction torque close to the initial peak. One of the joints had cracks at the periphery portion of the weld interface although it had 100% joint efficiency with the brass base metal fracture. All joints had the mixed mode fracture. Then, many joints had 100% joint efficiency and the brass base metal fracture when a friction time was 3.8 s or longer. However, these joints had cracks at the periphery portion of the weld interface, as shown in Fig. 11a. In this connection, the joint had slight cracking at the weld interface after tensile testing when it was made with higher forge pressure, e.g. 180 MPa. That is, increase of forge pressure for the joint efficiency and improvements of the fractured portion of the joint were small under friction pressure of 30 MPa, although the scatter of the joint efficiency and the cracking at the weld interface were decreased with them.

Figure 15 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. In this case, forge pressure was applied at 180 MPa. The joint efficiency at a friction time of 0.3 s was approximately 70%. Also, the joint fractured at the weld interface, which had a little brass adhering on the LCS side interface. The joint efficiency increased with increasing friction time and it had approximately 99% at a friction time of 0.5 s (the friction torque was close to the initial peak). Then, the joint had 100% joint efficiency and the brass base metal fracture when a friction time was 1.5 s or longer. In addition, all joints had no cracking at the weld interface, as shown in Fig. 11b. Increase of forge pressure for the joint efficiency and improvements of the fractured portion of the joint were also small although the scatter of the joint efficiency was decreased with them when friction pressure was 90 MPa. That is, it was clarified that the effect of increasing forge pressure on the joint properties of the joint between brass and LCS was small, although the scatter of the joint efficiency and the cracking at the weld interface were decreased with them.

Conclusions

This report described the effect of the friction welding condition on joining phenomena and joint strength of a friction welded joint between copper-zinc alloy (brass) and low carbon steel (LCS). In particular, we investigated the joining phenomena during the 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) Brass transferred to the half radius region of the weld interface on the LCS side. Then, transferred brass extended toward the almost whole weld interface with increasing friction time.
   (ii) The centerline temperature on the weld interface of the LCS side was higher than the half radius and periphery temperatures before the initial peak. Then, the periphery temperature was higher than the centerline and half radius temperatures after the initial peak.
   (iii) The joint efficiency increased with increasing friction time, and then it obtained 100% and the brass base metal fracture when the joint was made with a friction time of 4.2 s or longer. However, the fact that all joints had some cracks at the periphery portion of the weld interface was due to a deficiency of transferred brass at the periphery portion on the weld interface of the LCS side.
   (iv) The joint also had cracks at the periphery portion of the weld interface after tensile testing when it was made with higher forge pressure.
2. For a joint made under friction pressure of 90 MPa:
   (i) Brass transferred to the peripheral region of the weld interface on the LCS side, and then transferred toward the entire weld interface.
   (ii) The temperatures at the centerline, half radius and periphery portions were almost the same before the friction torque reached the initial peak. Then, the periphery temperature was higher than the centerline and half radius the temperatures after the initial peak. Moreover, the maximum temperatures were lower than those with a friction pressure of 30 MPa.
   (iii) The joint efficiency increased with increasing friction time, and it obtained 100% at a friction time of 1.5 s or longer. In addition, all joints fractured from the brass base metal with no cracking at the weld interface.

In conclusion, to obtain 100% joint efficiency and the brass base metal fracture with no cracking at the weld interface, the joint should be made with opportune high friction pressure and friction time at which the entire weld interface had the transferred brass.

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