Joining phenomena and joint strength of friction welded joint between aluminium-magnesium alloy (AA5052) and low carbon steel

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The joining phenomena and the joint strength of an aluminium-magnesium alloy (AA5052) and low carbon steel (LCS) friction welded joints were investigated. The weld interface of the LCS side at a friction time of 1.2 s had a slightly transferred AA5052, and then the entire weld interface had it at a friction time of 3.0 s or longer. The joint efficiency increased with increasing friction time, but it decreased at a friction time of 12.0 s or longer. The joint at a friction time of 3.0 s with forge pressure of 190 MPa had 100% joint efficiency and the AA5052 base metal fracture with no crack at the weld interface. The weld interface of these joints also had no intermetallic compound (IMC). On the other hand, the joint at a friction time of 8.0 s, which had approximately 97% joint efficiency, fractured between the AA5052 side and the weld interface because it had the IMC at the weld interface.

Keywords: Friction welding, Aluminium alloy, Low carbon steel, Joint efficiency, Friction time, Intermetallic compound, Forge pressure, Crack

Introduction

Generally speaking, fusion welds between aluminium (Al) and such other metals as steel,[1,2] copper,[3] and titanium[4] have poor mechanical properties due to the brittle intermetallic compound (IMC) layer produced at the joint interface. In particular, fusion welded joints between Al or its alloys and various steels have some problems, e.g. the generation of blowholes and cracks at the joint interface.[1] Therefore, a welding process is urgently required, which will reduce the degradation of the mechanical and metallurgical properties of the joints between Al and dissimilar metals.

The solid state joining methods such as diffusion welding, friction welding, and so on, can be applied to join Al and other metals.[5] Many researchers have reported that the mechanical and metallurgical properties of the friction welded joints between Al and steel show desirable characteristics.[6-14] The friction welded joint between Al and steel is also affected by the IMC which is generated at the weld interface and causes a brittle fracture to the joint.[12-14] However, almost all the friction welded joints between the Al alloy and steel did not have excellent joint properties such as 100% joint efficiency. In addition, since the joining phenomena of friction welding between dissimilar materials such as Al and steel have not been fully clarified, the detailed friction welding conditions have not been clarified either. Furthermore, the joining phenomena between dissimilar materials differ from that of similar materials because the tensile strength, thermal conductivity, and so on is different in their combinations. Hence, the joining mechanism also differs and must be clarified to theoretically determine the friction welding conditions.

In previous works,[15-26] the authors clarified the joining mechanism during the friction welding process for similar material joints. The authors also presented the tensile strength of friction welded joints between pure Al and low carbon steel.[27] If combinations of dissimilar materials such as Al alloy and steel can be joined using the same method as that shown in previous reports,[15-29] the joining mechanism will be clarified. In particular, clarifications of the joining mechanism are required concerning the weldability of Al alloys with other metals because an expansion in the use of Al alloys is expected.

Based on the background described above, the authors have been clarifying the joining mechanism between dissimilar materials in the friction process. The present paper focuses on the clarification of the joining phenomena during the friction process of friction welds between an aluminium-magnesium alloy, i.e. alloy 5052, and low carbon steel. The authors 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 joints. Furthermore, the authors also show the friction welding conditions for the joint that obtained 100% joint efficiency and fractured in the alloy 5052 base metal with no crack at the weld interface.

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Experimental procedure

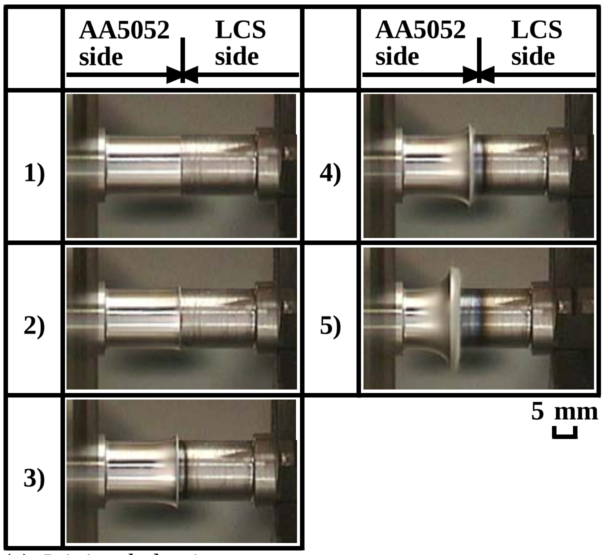
The materials used were an aluminium-magnesium alloy (alloy 5052-H112, referred to as AA5052) and low carbon steel (referred to as LCS) in rods with a diameter of 16 mm. The chemical composition of AA5052 was 0.12Si-0.19Fe-0.05Cu-0.03Mn-2.5Mg-0.18Cr-0.02Zn in mass%, its ultimate tensile strength was 188 MPa, its 0.2% yield strength was 73 MPa, and its elongation was 35%. The chemical composition of LCS was 0.13C-0.39Mn-0.21Si-0.19P-0.10S in mass%, its ultimate tensile strength was 448 MPa, its yield strength was 291 MPa, and its elongation was 35%. Those materials were machined to 12 mm in diameter of the weld faying (contacting) surface. The temperature changes during the friction process at the centreline, the half radius, and the periphery portions of the 1.0 mm longitudinal direction from the weld faying surface were measured using the LCS specimen. The details of the specimen shape for measuring temperature changes have been described in previous reports.[27-29] All weld faying surfaces of the specimens were polished with a surface grinding machine before joining to eliminate the effect of surface roughness on the joint mechanical properties.

A continuous (direct) drive friction welding machine was used for the joining. During the friction welding operations, the friction pressure and the friction speed were set to the following combinations: 30 MPa and 27.5 s^{-1} (1650 rpm). These values were the same as those of a previous report.[27] To observe the joining phenomena, the authors carried out three experimental methods. The friction torque was measured with a load-cell, and the temperatures were measured with a mineral insulated thermocouple with a chromel-alumel. The friction torque and temperature were recorded with a personal computer through an A/D converter with a sampling time of 0.05 s. The details of these methods have been also previously described.[15-30] The effect of friction time on the joint tensile strength was also investigated. All joint tensile test specimens were machined to 12 mm in diameter and 84 mm in parallel length. Moreover, analysis via EDS was carried out to analyze the chemical composition in the weld interface region. The fractured surface of the joint after joint tensile testing was analyzed using X-ray diffraction analysis.

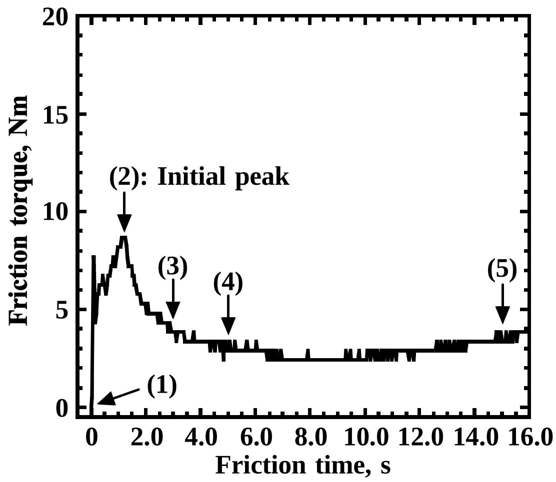
Results and Discussion

Relationship between joining behaviour and friction torque

Figure 1a shows the joining behavior during the friction process. Figure 1b shows the relationship between the friction time and the friction torque. Photos 1) to 5) correspond to the friction torques of (1) to (5) in Fig. 1, respectively. Photo 1) shows the state at the weld faying surfaces where they made contact with each other, and then the friction torque was increased. When the friction torque reached its initial peak of (2), the AA5052 side was slightly upset (deformed), as shown in photo 2). Thereafter, the friction torque decreased with increasing friction time, and then it was maintained nearly constant from (3) to (5). The upsetting and the flash (burr or collar) of AA5052 increased with increasing friction time although the LCS side was not upset, as shown in photos from 3) to 5). The elapsed time for the initial peak of this



(a) Joining behaviour



(b) Friction torque curve

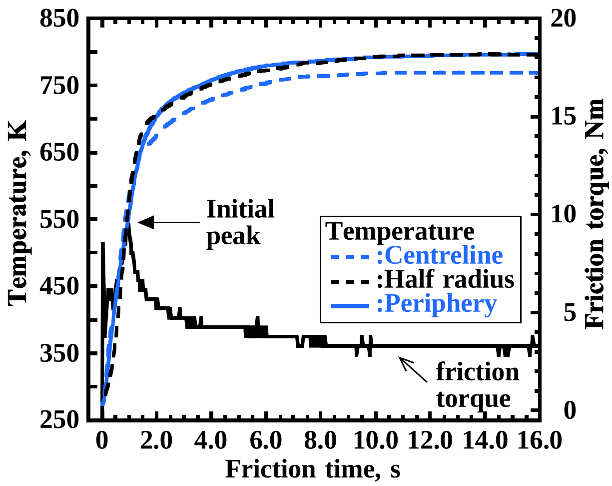
1 Joining behaviour and friction torque curve during friction process

joint was slightly shorter than that of pure Al and LCS friction welded joints under the same friction welding condition, and the initial peak was low (about 0.9 s and approximately 20 Nm, respectively).[27]

Temperature change during friction process

Figure 2 shows the relationship between the friction time and the temperature changes in relation to the friction torque during the friction process. The temperatures at the centreline, the half radius, and the periphery portions on the weld interface of the LCS side were almost the same before the friction torque reached the initial peak. The temperatures at the half radius and periphery portions were almost the same although the centreline portion was slightly low after the initial peak. However, the difference in each temperature was approximately 50 K or less at a friction time of about 2.0 s or longer. Then those three temperatures reached approximately 750 K at a friction time of about 8.0 s or longer. That is, the temperature at the weld interface reached approximately 750 K or more after the initial peak under this friction welding condition.

The measured temperatures resembled those with pure Al and LCS friction welded joints under the same friction

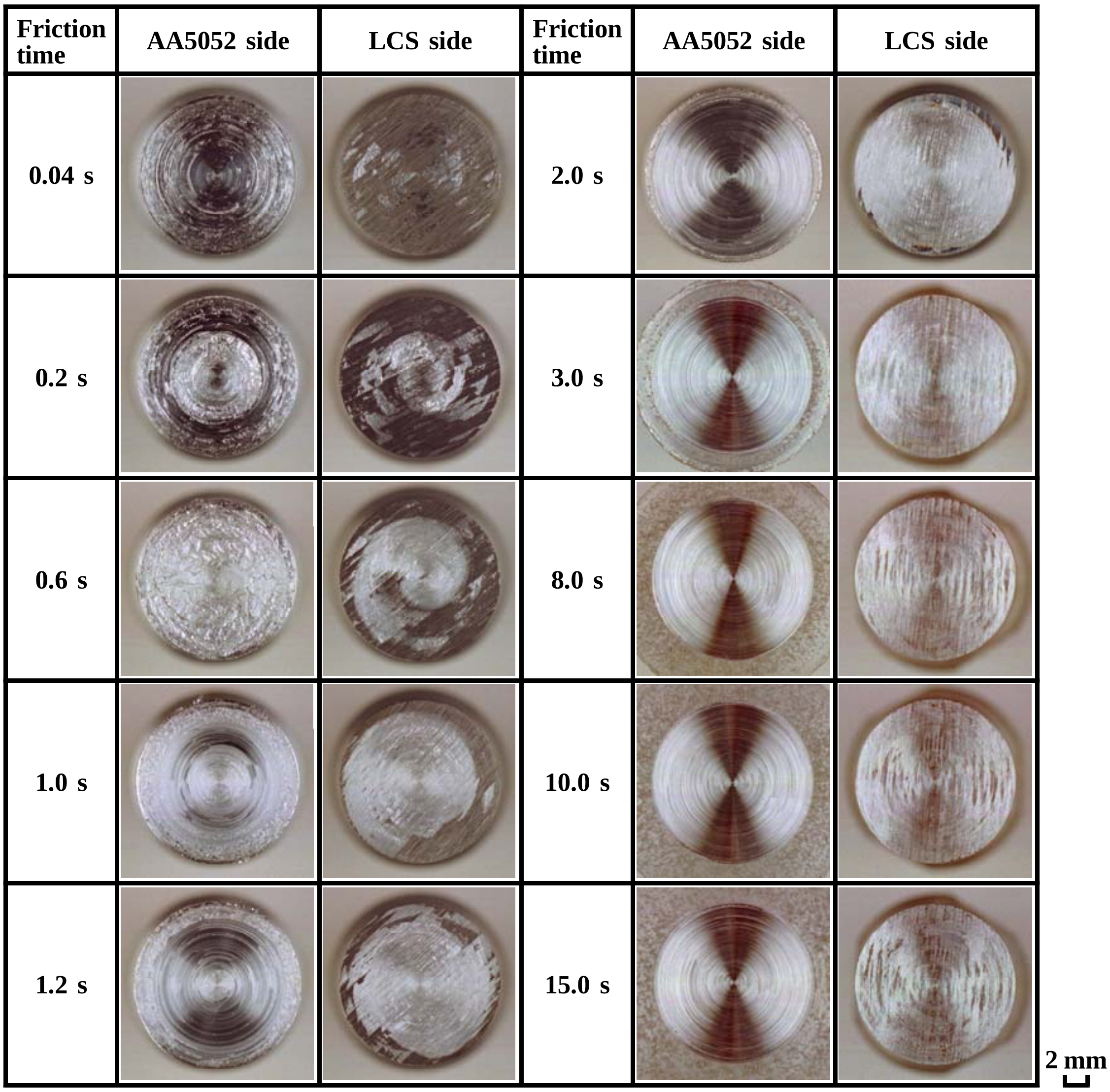


2 Relationship between friction time and temperature changes, in relation to friction torque during friction process

pressures, although the friction torque varied.[27]

Transitional changes of weld interface

Figure 3 shows examples of the appearances of the weld interfaces after welding. When the friction time was 0.04 s, i.e. both specimens had been rotated once, almost the whole weld interface of the AA5052 side was slightly worn, and AA5052 slightly transferred the weld interface on the LCS side. The concentric rubbing marks were observed at the central region of the weld interface on the AA5052 side, and the transferred AA5052 on the LCS side increased when the friction time was 0.2 s. At a friction time of 0.6 s, the concentric rubbing marks of the weld interface on the AA5052 side were extended toward the whole weld interface and also slightly roughened. Then the weld interface on the AA5052 side became smooth like a mirror at the half radius region at a friction time of 1.0 s. When the friction time was 1.2 s, i.e. the friction torque was close to the initial peak, the smooth surface of the weld interface on the AA5052 side extended, and the flash on the AA5052 side increased. However, the peripheral region of the weld interface on the LCS side had slight transferred AA5052, i.e. the entire weld interface of the LCS side had not transferred

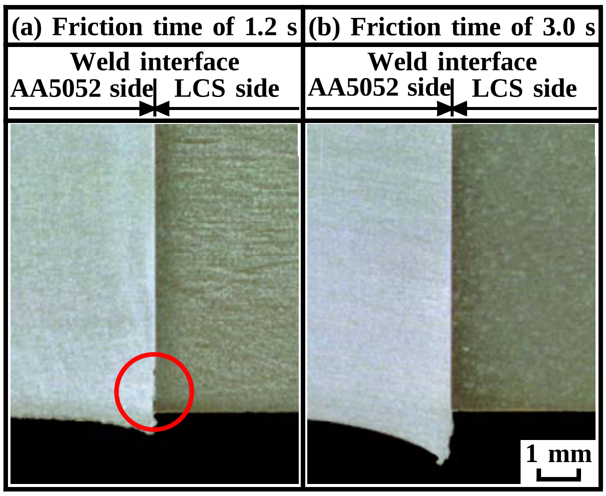


3 Appearances of weld interfaces after welding

AA5052. Then the flash on the AA5052 side and the transferred AA5052 on the LCS side increased with increasing friction time. When the friction time was 3.0 s, the entire weld interface of the LCS side had the transferred AA5052. Thereafter, the flash of AA5052 increased with increasing friction time, whereas the LCS side was not deformed. In addition, the smooth surface of the weld interface on the AA5052 side had a similar surface when the friction time was 2.0 s or longer. The appearances of the weld interfaces on the LCS side also had similar surfaces as when the friction time was 3.0 s or longer. Based on these results, the entire weld interface of the LCS side did not have transferred AA5052 when the friction torque reached the initial peak. This result resembled the transitional changes of the weld interface of the brass and LCS friction welded joint at the same friction pressure although the joining phenomena varied.[29]

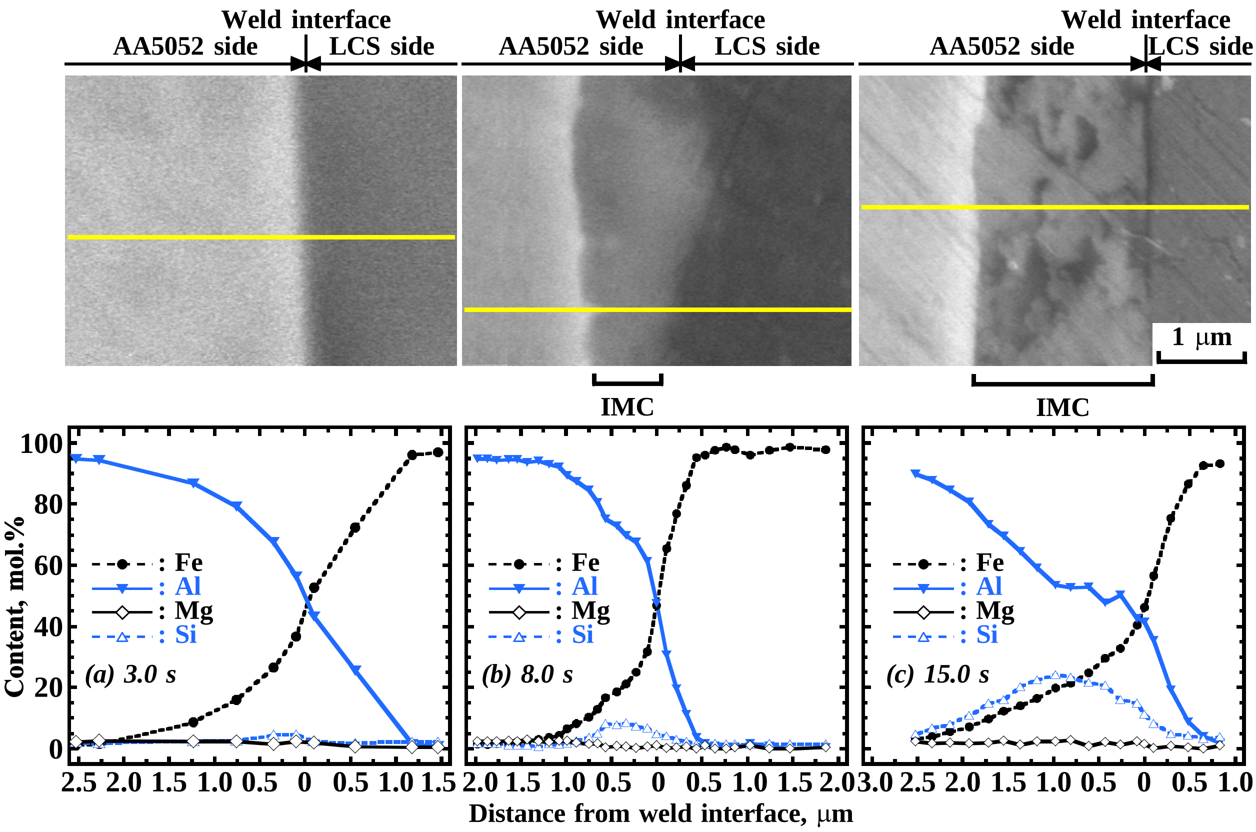
Observation of weld interface region

Figure 4 shows the cross-sectional appearances of the weld interface region of the joints with friction times of 1.2 and 3.0 s. In this case, forge pressure was applied at an identical friction pressure, i.e. 30 MPa. The joint at a friction time of 1.2 s, i.e. the friction torque close to the initial peak, had such defects as a not-joined region at the peripheral region of the weld interface indicated by the circle in Fig. 4a. However, when the joint was made at a friction time of 3.0 s, i.e. the entire weld interface of the LCS side was obtained the transferred AA5052, there was no defect at the weld interface, as shown in Fig. 4b. The fact that the joint at a friction time of 1.2 s had the not-joined region at the weld interface was due to a deficiency of the transferred AA5052 at the periphery portion on the weld interface of the LCS side.

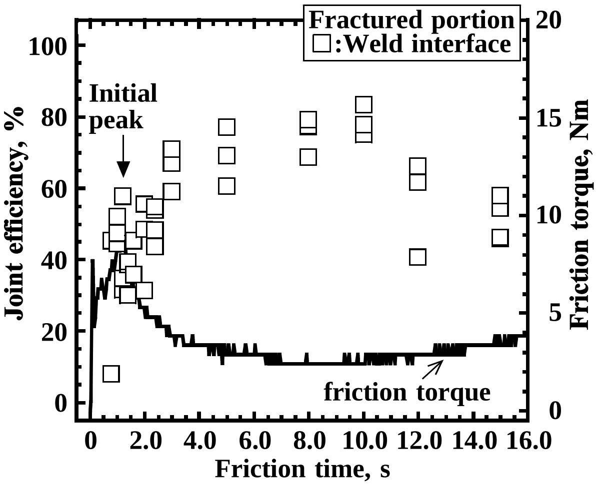


4 Cross-sectional appearances of weld interface region of joints; friction time of (a) 1.2 s and (b) 3.0 s

Figure 5 shows the SEM images and the EDS analysis results of the weld interface region at friction times of 3.0, 8.0, and 15.0 s. The weld interface of a friction time of 3.0 s was clear and had no IMC layer, as shown in Fig. 5a. In addition, the distribution corresponding to Al, Mg, Fe, and Si by EDS analysis had no plateau part at the weld interface. The joint at a friction time of 5.0 s also did not have the IMC layer, based on the SEM observation level although that data was not shown due to space limitations. However, the joint at a friction time of



5 SEM images and EDS analysis results of weld interface region; friction time of (a) 3.0, (b) 8.0, and (c) 15.0 s



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

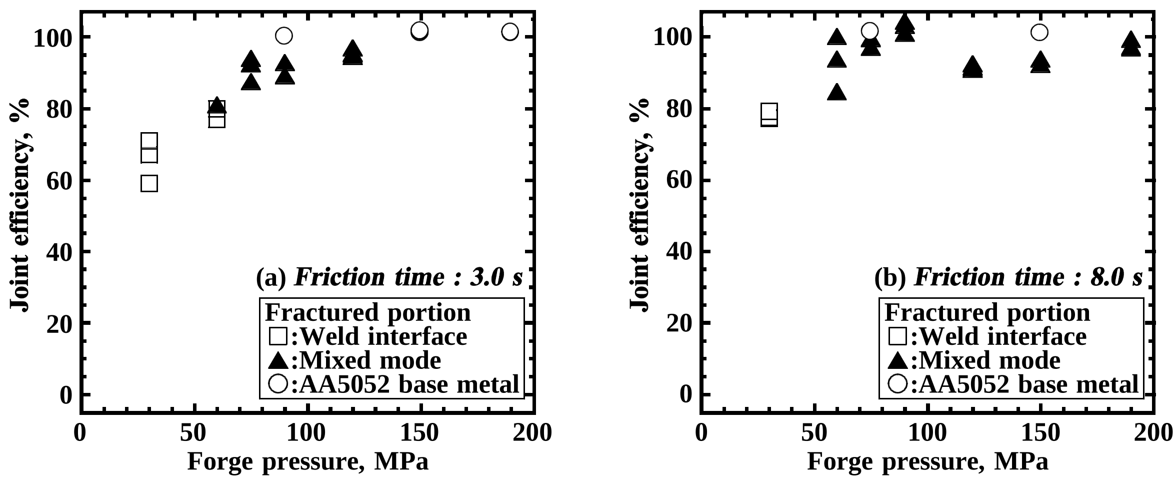
8.0 s had an IMC layer and its width was about 0.7 μm, as shown in Fig. 5b. The composition of the IMC layer was approximately 63Al-33Fe in mol.%, so it is considered Fe_2Al_5 or $FeAl_3$. Moreover, the distribution corresponding to Si had a plateau part at the weld interface of this joint whose width was about 1.0 μm. On the other hand, the IMC layer was not observed at any other region of this joint. That is, at a friction time of 8.0 s, the IMC did not exist at the entire weld interface. The joint at a friction time of 15.0 s had an IMC layer whose width was about 1.5 μm, as shown in Fig. 5c. This joint also had a plateau part at the weld interface of Si whose width was about 2 μm. Hence, when the joint was made with a friction time of 8.0 s or longer, IMC was generated at the peripheral regions of the weld interface and that increased with increasing friction time.

Joint efficiency

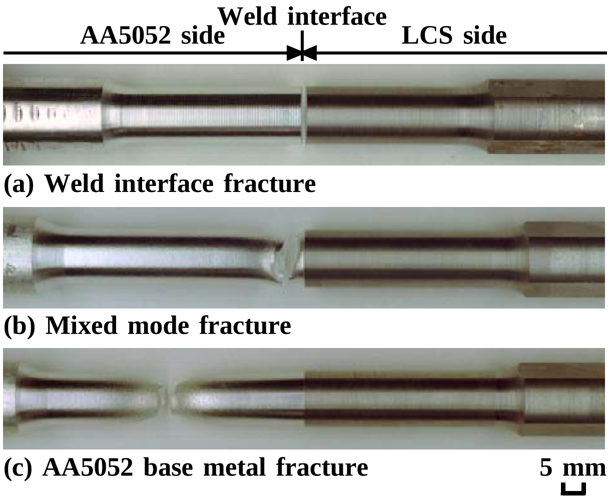
Figure 6 shows the relationship between the friction time and the joint efficiency of the joint, plotted alongside the friction torque curve. The joint efficiency was defined as the ratio of the joint tensile strength to the ultimate tensile strength of the AA5052 base metal. In this case, forge pressure was applied at an identical friction pressure, i.e. 30 MPa. The joint efficiency at a friction time of 0.8 s was approximately 18% because a sufficient quantity of heat for welding could not be produced during this friction time. Then the joint efficiency increased with increasing friction time. The joints had approximately 41% joint efficiency at a friction time of 1.2 s, i.e. the friction torque close to the initial peak. Thereafter, the joint efficiency increased with increasing friction time and obtained approximately 78% at friction times of 8.0 and 10.0 s. Then the joint efficiency slightly decreased with increasing friction time. In addition, all joints fractured at the weld interface, which had slight AA5052 adhering to the LCS side of the fractured surface. The fractured surface of those joints had a surface similar to the weld interface at all friction times, as shown in Fig. 3. In this connection, the patterns of the Al and Fe_2Al_5 peaks by the X-ray diffraction analysis were observed on the fractured surfaces at a friction time of 8.0 s or longer. However, those peaks were not observed on the fractured surfaces at a friction time of 3.0 s or shorter. Hence, it was clarified that the rupture of the joint at a long friction time was occurring in the IMC layer.

Improving joint efficiency

In previous work,[27] the authors showed that the friction welded joint between pure Al and LCS did not achieve 100% joint efficiency due to a decrease in the tensile strength of the pure Al base metal by the Bauschinger effect. On the other hand, forge pressure will be able to improve the weld interface adherence and joint efficiency.[9,10,30] To improve the weld interface adherence and the joint efficiency, the effect of forge pressure on joint efficiency was investigated. Figure 7 shows the relationship between the forge pressure and joint efficiency of the joints which were made at friction times of 3.0 and 8.0 s. Figure 8 shows the appearances of the joint tensile test specimens at various forge pressures after tensile testing. The joint efficiency of the joint at a friction time of 3.0 s increased with increasing forge pressure, as shown in Fig. 7a. The joint changed from a weld interface fracture (Fig. 8a) to a mixed mode fracture (Fig. 8b). When the joint was made with a forge pressure of 150 MPa or over, it obtained 100% joint efficiency and fractured on the AA5052 base metal, as shown in Fig. 8c. On the other hand, the joint efficiency of the joint at a friction time of 8.0 s also increased with increasing forge



7 Relationship between forge pressure and joint efficiency of joint; friction time of (a) 3.0 s and (b) 8.0 s



8 Appearances of joint tensile test specimens of joint at various forge pressures after tensile testing

pressure, as shown in Fig. 7b. However, almost all joints did not achieve 100% joint efficiency and had a mixed mode fracture when the joint was made with a forge pressure of 150 MPa or over. Based on these results, the fact that the joint did not achieve 100% joint efficiency was due to the generation of IMC at the weld interface.

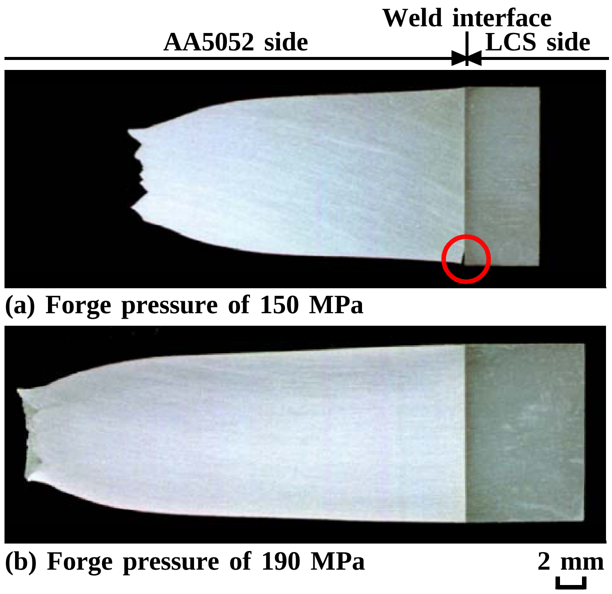
Figure 9 shows the cross-sectional appearances of the joint tensile test specimens with the AA5052 base metal fracture after tensile testing. The joint at a forge pressure of 150 MPa had cracks at the periphery portion of the weld interface after tensile testing, which was indicated by a circle as shown in Fig. 9a. On the other hand, the weld interface of the joint at a forge pressure of 190 MPa had neither a not-joined region nor a defect after tensile testing, as shown in Fig. 9b. In addition, these joints have no IMC, as shown in Fig. 5a. That is, the joint had 100% joint efficiency and the AA5052 base metal fracture with no crack when it was made with high forge pressure. Thus, to obtain 100% joint efficiency and the AA5052 base metal fracture with no crack at the weld interface, the joint should be made with high forge pressure, and with opportune friction time at which the entire weld interface of the LCS side had the transferred AA5052.

Conclusions

This report described the joining phenomena and the joint strength of a friction welded joint between an aluminium-magnesium alloy (AA5052) and low carbon steel (LCS) from the viewpoint of the friction time and forge pressure. The following conclusions are provided.

1. When the joint was made at a friction pressure of 30 MPa with a friction speed of 27.5 s^{-1}, the upsetting (deformation) occurred at the AA5052 base metal. Then, the weld interface of the LCS side had a slightly transferred AA5052 when the joint was made at a friction time of 1.2 s, i.e. the friction torque was close to the initial peak. Thereafter, AA5052 transferred toward the entire weld interface of the LCS side at a friction time of 3.0 s or longer.

2. The joint efficiency of the joint at a friction time of 3.0 s increased with increasing forge pressure. Then, the joint had 100% joint efficiency with the AA5052 base metal fracture when it was made with a forge pressure of 150 MPa or over. The weld interface of these joints had no intermetallic compound (IMC) based on the SEM observation level. Moreover, the joint with a forge pressure of 190 MPa had no crack at the weld interface after tensile testing.



9 Cross-sectional appearances of joint tensile test specimens with AA5052 base metal fracture after tensile testing; forge pressure of (a) 150 MPa and (b) 190 MPa

3. The joint efficiency of the joint at a friction time of 8.0 s also increased with increasing forge pressure. However, the joint had approximately 97% joint efficiency, which was made with a forge pressure of 150 MPa or over. Almost all joints fractured between the AA5052 side and the weld interface. The weld interface of these joints had IMC, and it corresponded to Fe_2Al_5 or $FeAl_3$.

In conclusion, to obtain 100% joint efficiency and the AA5052 base metal fracture with no crack at the weld interface, the joint should be made with high forge pressure, and with opportune friction time at which the entire weld interface of the LCS side had the transferred AA5052.

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