Friction Welding Characteristics of Al-Mg Aluminum Alloy (A5056) and Carbon Steel (S45C) *

Akiyoshi KOBAYASHI**, Michihide MACHIDA***, Shigeo HUKAYA**** and Masatoshi SUZUKI**

The possibility of joining composite materials, conventional steel and lighter aluminum alloy, is tested using friction welding that preserves the natural environment greatly. The friction welding of aluminum alloy, Al-Mg (A5056), and carbon steel (S45C) are done under various experimental conditions and the friction welding characteristics are examined. The mechanical property (tensile strength) of the welded specimen has enough strength under the friction welding conditions of 1000 rpm, the friction pressure of above 20 MPa, the friction time of less than 1 second and a quite high upset pressure near the plastic flow pressure of A5056. The macroscopic and microscopic interface structures are also examined in relation to the friction welding conditions in order to clarify the joining mechanism of the interface between different materials by the friction welding. Moreover, the heat quantity during friction welding that relates closely to the generation of the inter-metallic compound and the joining mechanism is also examined. The amount of upset that relates closely to the mechanical properties of the welded specimen is also examined.

**Key Words**: Friction Welding, Al-Mg Aluminum Alloy, Carbon Steel (S45C), Tensile Strength and Intermetallic Compound

1. Introduction

Friction welding is an excellent joining method that has many features such as the low joining energy, non-poisonous waste gas and the possibility and easiness of the joining of different metals. On the other hand, the preservation of natural environment is the most important thesis of this century. Therefore, the friction welding has become of major interest lately as the most promising joining technique to cope with the preservation of natural environment.

Recently, in order to realize an adaptable production method that can make the lighter automobile parts or any other machine one, the possibility of the joining to make a composite material by the conventional steels and the lighter aluminum alloy is examined. Therefore, in this paper, the friction welding of Al-Mg aluminum alloy (A5056) and carbon steel (S45C) is tried and the friction characteristics are examined. Firstly, many experiments were done to find the friction welding conditions to obtain a good joining strength. Next, the mechanical property (tensile strength) of friction welded specimen was examined in relation to the friction conditions. Moreover, in order to clarify the joining mechanism of A5056 and S45C by the friction welding, the macroscopic and microscopic structures of the interface are examined in relation to the joining strength.

In general, the amount of upset in the friction welding relates closely to the mechanical property. Therefore, the relationship between the amount of upset and the mechanical property of the friction welded specimen is also examined.

2. Experiments

The experiments were done by two kinds of brake method type friction welding machines. The one is driven by conventional hydraulic pressure con-
control and another machine is controlled by servomotor system. Table 1 shows the friction welding conditions. The upset pressure of 240 MPa is obtained only by the servomotor type. At first, the experiments were tried under the friction welding conditions that were good for the friction welding between carbon steel and carbon steel. However, all these specimens were broken at the interface. After trial and error, it was clarified that the friction welding conditions shown in Table 1 are mostly good for the friction welding of A5056 and S45C. In these experiments, the friction pressures and the upset one are set quite high. Especially, the upset pressure of 240 MPa is the near value of the proof strength of A5056. In the friction welding of A5056 and S45C, a high plastic flow pressure is also needed to obtain the good joining strength in addition to the short heat quantity input. The experiments of the rotational speed of 4 000 rpm in the table were done specially in order to examine more clearly the effect of the rotational speed.

Table 2 shows the chemical composition of specimens used. The friction welding is done as S45C is the fixed side and A5056 is the rotational side. The shape of specimen is shaped as follows : the interface diameter is 15 mm and the length is 20 mm, the diameter of the clamp part is 25 mm and the total length of specimen is 70 mm.

It is considered that the oxide film formed on the interface of the aluminum alloy after machining influences strongly the friction welding characteristics. Therefore, the friction welding tests were tried in advance with various specimens at which the interface was cut immediately before (about 10 seconds) friction welding without cutting fluid, or the interface was washed and cleaned by acetone before friction welding. However, these treatments of the interface did not influence the mechanical property (tensile strength) of the welded specimen. Consequently, the friction welding were done by the specimens formed by dry cutting one day before.

3. Experimental Results

3.1 Mechanical properties of friction welded specimen

Figures 1 and 2 show the relationships between the tensile strength of welded specimen and the friction time under each rotational speed (1 000, 2 000 rpm). In both figures, dotted line shows the tensile strength of A5056 itself. The tensile strength of the specimen friction welded under the conditions of the rotational speed 2 000 rpm are almost below that of A5056 itself. And the equal or stronger tensile strength than that of A5056 itself are mainly obtained under the friction welding conditions of rotational speed 1 000 rpm and the friction time 0.5 to 1 second.

Figure 3 shows the joint efficiency of the specimens of rotational speed 1 000 rpm to examine the influence of the friction welding conditions. It is seen that the upset pressure of 240 MPa improves the joint efficiencies wholly. From another experiments of A5056 and S45C under different friction welding conditions in which the rotational speed is 3 200 rpm (suitable rotational speed to the friction welding of carbon steels), it is seen that the upset is not almost produced at the beginning stage of 1 (friction pressure : 30 MPa) to 2 (friction pressure : 20 MPa) second during friction process because of the hard and high heat resisting oxide film generated on the interface sur-

<table>
<thead>
<tr>
<th>Rotational speed</th>
<th>N(r.p.m.)</th>
<th>1000, 2000, (4000)</th>
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<tbody>
<tr>
<td>Friction pressure</td>
<td>Pf(MPa)</td>
<td>10, 20, 60</td>
</tr>
<tr>
<td>Upset pressure</td>
<td>Pu(MPa)</td>
<td>0, 160, 240</td>
</tr>
<tr>
<td>Friction time</td>
<td>t1(s)</td>
<td>0.5, 1.0, 3.0</td>
</tr>
<tr>
<td>Upset time</td>
<td>t2(s)</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 2 Chemical composition of metals (mass%) | C  Si  Mn  P  S  Cu  Ni  Cr |
<table>
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<tr>
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<tbody>
<tr>
<td>S45C</td>
<td>0.48</td>
<td>0.24</td>
<td>0.72</td>
<td>0.22</td>
<td>0.16</td>
<td>0.01</td>
<td>0.02</td>
<td>0.13</td>
</tr>
<tr>
<td>A5056</td>
<td>0.14</td>
<td>0.08</td>
<td>0.08</td>
<td>4.6</td>
<td>0.01</td>
<td>0.05</td>
<td>0.06</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 1 Relationship between tensile strength and friction pressure

Friction time, s

N = 1000 rpm

second is of low grade for all friction pressure conditions and becomes lower as the friction pressure increases. It is considered that this reason depends on the generation rate of the intermetallic compound at the interface as mentioned in next section. That is to say, as the friction pressure is higher, the generation rate of the intermetallic compound increases. And the reason why the good tensile strength was not obtained wholly by the rotational speed of 2000 rpm, depends on the too fast heat input rate.

3.2 Observation of interface by SEM

In the case of the friction welding between different metals, it is said that the intermetallic compound at the interface is generated by the influence of the friction heat etc. and the mechanical properties deteriorate\(^a\). Therefore, the relationship between friction welding conditions and intermetallic compound is examined.

Figures 4 (a), (b), (c) and (d) show the photographs of the interface on the rotational speed 1000 rpm by SEM. In the photographs of Figs. 4 (a) and (b), the intermetallic compound is not observed, and the tensile strengths in Fig. 1 corresponding to Figs. 4 (a) and (b) show the value over that of the A5056 itself. On the other hand, the intermetallic compound which has about 1.5 \(\mu\)m thickness is observed clearly in the photographs of Figs. 4 (c) and (d), and the tensile strength deteriorates to a half value of A5056 itself. The friction time of Figs. 4 (a), (b) and (c) is same, however, the friction pressure of Fig. 4 (c) is six times that of Figs. 4 (a) and (b). As the heat quantity generated by the rotational friction varies in proportion linearly to the torque and the rotational speed\(^b\), it is considered that the friction pressure of 60 MPa has a too large heat input rate by the increase of torque based on the increase of friction pressure.

Figure 5 shows the examples of the results of rotational speed 2000 rpm. In the experimental results of 2000 rpm, although the welding conditions of the friction pressure 10 MPa, friction time 0.5 and 1 second did not generate the intermetallic compound, the intermetallic compound is observed under other almost welding conditions. Figure 6 shows an example of the experimental results of rotational speed 4000 rpm. The intermetallic compound was observed in all specimens friction welded by rotational speed 4000 rpm.

From these results, it is clarified as follows. When SUS3C and A5056 is friction welded, the intermetallic compound at the interface of SUS3C and A5056 is generated depending on the friction welding conditions. The increase of rotation speed namely the increase of friction velocity facilitates the formation of the intermetallic compound. The intermetallic

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\(^a\)Mechanical properties of the intermetallic compound depend on the friction welding conditions.

\(^b\)The heat generated by the friction varies linearly with the friction torque and rotational speed.
compound influences remarkably the mechanical property (tensile strength) of welded specimen, and the generation of the intermetallic compound deteriorates strongly the joint strength. However, the mechanical strength of welded specimen depends on closely not only the intermetallic compound but also the microscopic structure near the interface as shown in the results of the upset pressure 240 MPa. Therefore, the structure near the interface is examined in relation to the mechanical property of welded specimen at the next section.
3.3 Observation of structure near interface

In this friction welding of different metals such as each melting temperature differs remarkably, the burr associated with the softening by the friction heat is generated from only the softer and lower melting temperature metal. Therefore, in order to clarify how both metals influence the joining mechanism, the observations of the structure of both metals were done.

Firstly, the structure of S45C after friction welding was observed. As a result, the structure near the interface of S45C did not differ from that of the base metal and was not affected entirely by the friction heat needed for a good junction of S45C and A5056. The structure of S45C at the interface did not change under the microscopic view of the optical microscope because of the relatively high melting temperature. However, it is considered that the interface structure in nano scale differs from that of the base metal because a good joining strength is obtained⁷⁷.

Next, Fig. 7 shows an example of the structures of A5056 near the interface after friction welding. In the figures, the upset pressure $P_s=0$ MPa is the result friction welded by only the friction pressure $P_f$ in order to examine the effect of the upset pressure to the joining strength. In the experiments without upset pressure, although the fine structure by the friction pressure and the heat associated by the friction is generated, the structure is not pressed to the axial direction by the upset pressure. Therefore, the fine structure does not have a good joining strength. Consequently, the specimen welded without the upset pressure was broken at the interface. Figures 7 (b) and (c) show the structures in which the good joining strength was obtained. As shown in the figures, the structure that is generated during the friction process presents a minute structure fined to the axial direction by the upset pressure. The thickness of the minute structure is found about 50 μm. As the upset pressure increases, it is found that the softened structure contiguous to the minute structure is also fined to the axial direction and increases the thickness. From these results, the attachment effect by the quite high upset pressure near the plastic flow pressure of A5056 is also very important to obtain the good joining strength to the friction welding of A5056 and S45C in addition to the presence of the intermetallic compound.

From the observations of the generation process of the minute structure, it was found that the joining strength relates closely to the shape of the macroscopic minute structure formed during friction process. Figure 8 illustrates the modeled minute structure shapes. The good joining strength was obtained

![interface](image)

(a) $P_f=10$ MPa, $P_s=0$ MPa, $t_s=1.0$ s

![interface](image)

(b) $P_f=20$ MPa, $P_s=610$ MPa, $t_s=1.0$ s

![interface](image)

(c) $P_f=20$ MPa, $P_s=240$ MPa, $t_s=1.0$ s

Fig. 7 Appearance of minute structure near interface (1000 rpm)


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when the minute structure is formed as the two peaks shape as shown in the figure. Figure 9 illustrates the mechanism of the two peaks shape formation in connection with the burr formation. At the beginning of the friction welding, the outside diameter part of specimen is heated and softened fastest, and this part is forced out as burr by the friction pressure (thrust force) along the edge of the S45C.

Therefore, the outside part of the softened and minute structure was thinned along the outer diameter. On the other hand, the center of the specimen is not still heated sufficiently in this friction time and forms a thin minute structure. When the friction time is long, the center of specimen is also heated sufficiently and forms the one peak type shape of the minute structure in relation to the forced flow as illustrated in Fig. 8(c).

3.4 Generated heat quantity and tensile strength

From the experimental results and considerations as mentioned in sections 3.2 and 3.3, it is suggested that the heat quantity (heat gain) generated during the friction process influences remarkably to the formation of the intermetallic compound. Therefore, the relationship between the heat quantity generated during friction process and the tensile strength of welded specimen is examined.

Here, the heat quantity $Q$ generated by the general rotational friction is expressed as follows\(^{1}\),

$$Q = \sum_{i=0}^{n}(1.047 \times 10^{-4} \times T \times N)$$

(1)

where, $t_i$ is the friction time and $T$ the friction torque and $N$ the rotational speed.

Figure 10 shows the relationship between heat

![Diagram](image-url)

(a) Welded structure model

![Images](image-url)

(b) Structure of part (1)

(c) Structure of part (2)

Fig. 9 Welded structure model by friction welding

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gain (heat quantity) and tensile strength under the rotational speed 1 600 rpm. The friction torque $T$ of Eq.(1) is obtained from the experimental value. In the figures, the intermetallic compound did not generate less than 4.65 kW heat gain, and that generated over 8.61 kW. The range of the heat gain at that the good joining strength is obtained is 0.8 to 1.7 kW in Fig. 10 (a) and is 0.8 to 3.8 kW in Fig. 10 (b). The extent of the heat gain in Fig. 10 (b) depends on the attachment effect by the high upset pressure.

3. 5 Amount of upset

In general, the amount of upset in the friction welding relates closely to the mechanical property of the friction welded specimen is examined.

Figure 11 shows an example of the relationship between the tensile strength of welded specimen and the total upset length. In the figure, dotted line shows the tensile strength of A5056 itself. As seen in the figure, the amount of upset in friction welding of different metals such as A5056 and S45C is unrelated to the tensile strength, different from the friction welding of same metals. As this reason, the intermetallic compound generated at the interface in the friction welding of different metals influences remarkably to the tensile strength as mentioned before.

4. Conclusions

In order to realize an adaptable production method that can make the lighter automobile parts or any other machine one that preserves natural environment, the possibility of the joining to make a light composite material by the conventional steel (S45C) and the lighter aluminum alloy (A5056) is tried by friction welding, and the friction welding characteristics are examined experimentally. The friction welding characteristics was estimated based on the mechanical property (tensile strength) and the joining mechanism of S45C and A5056 was examined. The obtained results are as follows.

(1) Good joining strength of A5056 and S45C by friction welding is obtained under the friction welding conditions of rotational speed 1 000 rpm, friction pressure 10 to 20 MPa, friction time 0.5 to 1 second, upset pressure 240 MPa, and is not obtained under the friction welding conditions of rotational speed over 2 000 rpm.

(2) Upset is generated only from A5056. The amount of upset in the friction welding of A5056 and S45C is unrelated to the tensile strength, different from the friction welding of same metals.

(3) In the welded specimen that the good joining strength is obtained, the intermetallic compound at the interface was not found. However, the welded specimen that the generation of intermetallic compound was observed at the interface was broken at the interface. Therefore, the intermetallic compound generated in the friction welding of A5056 and S45C deteriorates strongly the joint strength.

(4) In order to obtain a good joint strength in the friction welding of A5056 and S45C, the upset pressure of 240 MPa close to the plastic flow pressure of A5056 that has an attachment effect is needed, in addition to
the selection of the friction welding condition that does not generate the intermetallic compound at the interface.

(5) Heat quantity less than 0.8 kW is insufficiency to make the joining of A5056 and S45C possible, and heat quantity of over 8.6 kW generates the intermetallic compound at the interface.

References


