Abstract
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Key words
friction welding, joint, aluminum, copper, intermediate material, thermal elastic-plastic stress analysis

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Development of Al/Cu Dissimilar Joint by New Friction Welding Method *
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Abstract
Although Al alloy–pure Cu joints have been produced by the conventional welding method, some combination cannot be joined with high efficiency. The efficiency is considered to be reduced by the formation of intermetallic compounds and the involvement of metal flake in the joint specimens. The present study examined an A2017 Al alloy–Cu joint formed by a new friction welding technology, in which an intermediate material is inset for friction between joint specimens. The optimal welding were determined by thermal elastic-plastic stress analysis. The joints formed by the new technology exhibited the following features: (1) a maximum joint efficiency of 60% (versus 50% in the conventional process); (2) no intermetallic compounds or metal flake involvement (as observed under scanning electron microscopy); (3) increased oxygen content at the Al side near the interface, but marginal increase at the Cu side. We also determined the precise position of the welding interface based on the change in oxygen content near the interface. To produce robust joints using this combination of materials, both materials should be plastically deformed by maintaining the strength balance between Al and Cu near the interface.

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1 Introduction

Conventional friction welding methods\(^1\)-\(^4\) are not always applicable to dissimilar materials\(^5\) because of the direct rotational friction between the specimens. First, the interface between the two materials may be affected by intermetallic compound formation and flakes in one material from the other material\(^6\)-\(^8\). Second, if the two metals have quite different melting points or flow stresses, they are difficult to weld because the metal with lower melting point softens while the other metal remains hard; moreover, the flow stress is less reduced in the metal with higher melting point.

To solve these problems, we propose a new friction welding process for materials that cannot be joined by conventional techniques. The proposed process is schematized in Fig.1. In the new technique, the friction heat in both specimens can be varied and controlled by inserting an intermediate material (IM) that makes friction between the specimens.

During the friction process, the IM makes an orbital motion between the contact surfaces of the two specimens. After heating and softening the interface between the specimens, the IM is quickly removed from between the specimens. The specimens are then pressed together and join under an applied upset pressure.

In this study, suitable friction upset conditions were determined based on thermal elastic–plastic stress analysis.

To reduce the weight and cost of the Cu, we employed pure Al/Cu joints in the various electric parts and the heat exchanger\(^7\),\(^8\).

However, pure Al is too soft to be molded into structural members. Therefore, Al alloys with higher strengths than that of pure Al are required as joint materials against Cu\(^8\).

For the above reasons, dissimilar joints between Al alloys and pure Cu formed by friction welding have been investigated in detail\(^8\). The joint efficiencies of Al alloys such as the 1xxx, 5xxx, and 6xxx series exceed 80%, whereas those of the 2xxx and 7xxx series reach only 30% or 50%. The reduced efficiencies of these series result from the generation of intermetallic compounds and the involvement of flakes in one metal from the other metal at the material interface\(^8\). The same phenomena have been reported in pure Al/Cu joints formed by friction welding\(^7\) or diffusion welding\(^9\).

The proposed technology avoids such phenomena because the specimens are not in contact during the friction stage.

In this study, the proposed technology was experimentally applied to the joining of two dissimilar materials (2017 aluminum alloy and C1100 pure copper), and thermal elastic–plastic stress analysis was conducted by using the finite element method.
2 Experimental process

2.1 Concept of the new technology

In the new process, the IM settles between the specimens and generates heat by moving against the specimen surfaces. Once the specimen interface has been softened, the IM is quickly removed from between the specimens. In the next process, the specimens are pressed together and joined under an upset pressure. The total duration of the process is 0.15 s (0.05 s for removing the IM; 0.1 s for contacting the specimens under the upset pressure).

The quantity of heat produced on each side of the specimens can be controlled in two ways: by fabricating the IM from two materials with different friction characteristics or by changing the friction pressure on each side. The joining of similar materials does not require changing the IM or the friction pressure on each side.

We adopted an orbital motion for the IM, which ensures constant angular velocity at each location and time. Furthermore, the upset pressure is applied when the interfaces of both specimens are judged to be fully softened. The judgement is made by thermometer measurements.

2.2 Experimental equipment

Figure 2 shows the setup of the specimens, IM, oscillation motor of the IM, torque meter, and device used to apply the upset pressure. Also shown are the chucking parts of the specimens and the device that moves the specimens aside, separating them from the IM.

The operation of the IM is demonstrated in Fig.3. The rotation of a servomotor (Mitsubishi Electric, HA-LFS15K2) is transferred to a small pulley though a flexible joint, a large pulley, and a timing belt. The rotational motion of the small pulley is then converted to uni-directional translation through a slider-crank mechanism that operates a linear guide. The orbital motion is obtained by a double slider-crank mechanism with a phase difference of \( \pi/2 \) rad.

The equipment specifications were as follows: maximum number of IM rotations per minute = 6000; displacement from the center of rotation of the orbital motion = 0.8 mm.

Figure 4 shows the area in which the specimen moves relative to the IM's motion.

The maximum friction and upset pressures are 70 MPa and 700 MPa, respectively.

![Fig.2 Experimental equipment and setup of new friction welding procedure](image-url)
2.3 Test materials

The test specimens were aluminum alloy (2017-T4) and pure copper (C1100-H), and the IM was made of S50C. The shapes and dimensions of the specimens are shown in Fig.5. The IM dimensions are \( w \times 34 \text{ mm} \times l_{27} \text{ mm} \times t_{6} \text{ mm} \).

The chemical compositions of A2017-T4 and S50C are shown in Table 1. C1100-H consists of 99.94% Cu and 0.05% oxygen. In a tensile test, the tensile stresses of 2017-T4 and C1100-H were confirmed to be 426 MPa and 350 MPa, respectively. The thermal conductivities of C1100-H, A2017-T4, and S50C are 403 W/m-K, 164 W/m-K, and 63.3 W/m-K, respectively.
2.4 Experimental conditions

The friction and upset pressures and modes of the orbital motion are listed in Table 2. The surface temperatures of the specimens 2 mm from the interface were measured by radiation thermometers (KEYENCEFT-H40) and thermocouples.

<table>
<thead>
<tr>
<th>Friction pressure</th>
<th>(MPa)</th>
<th>9-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Friction time</th>
<th>(s)</th>
<th>1-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation number of IM</td>
<td>(rpm)</td>
<td>3000-4000</td>
</tr>
<tr>
<td>Rotation radius of IM</td>
<td>(mm)</td>
<td>5.8</td>
</tr>
<tr>
<td>Upset pressure</td>
<td>(MPa)</td>
<td>200</td>
</tr>
</tbody>
</table>

2.5 Thermal elastic–plastic stress analysis by the finite element method

To identify the suitable friction and upset conditions, we conducted thermal elastic–plastic stress analysis by the finite element method by using ANSYS mechanical design software (ANSYS Inc.)\(^1\). The solution was obtained by coupling unsteady heat transfer analysis to non-linear structural analysis, thus accounting for any heat transfer or radiation of friction heat to the specimens, IM, and atmosphere. The details are presented below.

Each side of the specimen and the IM was analyzed to minimize the calculation time. The computational grids were constructed from parametric elements using mesh morphing, and 2828 nodes (in total) were formed for the specimens and IM. To ensure convergence at each time step, the time-step \( \Delta t \) was set to \( 2.5 \times 10^{-2} \) s. Figure 6 shows the computational grid setup of the analysis.
The generated friction heat depends on the motion of the IM around radius $R$. Therefore, the friction heat $H$ is given by Eq. (1):

$$H = F_p \mu R \omega \pi r^2,$$

where

$$R = \alpha + r,$$

and $F_p$ is the friction pressure, $\mu$ is the friction coefficient, $\alpha$ is the radial difference between the orbital motion and specimen, $r$ is the radius of the specimen, and $\omega$ is the angular velocity.

The friction heat generated at the interface is conducted to the specimens and the IM. The specimens and IM also lose heat to the air by radiation and convective transfer.

The heat $P$ radiated to the air is given by the Stefan–Boltzmann law:

$$P = \sigma \varepsilon (T_s^4 - T_a^4),$$

where $\sigma$ is the Stefan–Boltzmann constant, $\varepsilon$ is the emissivity, $T_s$ is the surface temperature of the specimen, and $T_a$ is the air temperature.

$T_s$ and $T_a$ were initialized as 22 C (295 K), and the $\varepsilon$ values of Al/air and steel/air were set to 0.1 and 0.8, respectively.

The convective heat transfer $Q$ was computed by Eq. (4):

$$Q = h A (T_s - T_a),$$

where

$$h = Nu k / L,$$

and $Q$ is the amount of heat transfer, $h$ is the heat transfer coefficient, $A$ is the cross-sectional area, $Nu$ is the Nusselt number, $k$ is the thermal conductivity of the fluid, and $L$ is the representative length.

For air around a horizontal cylinder, $Nu$ can be calculated by Eq. (6):

![Computational grids (mesh quality 0.38)](image)
\[ Nu = 0.53 \left( Gr \times Pr \right)^{0.25}. \]  

(6)

Moreover, we have

\[ Gr = g\beta L^3 \left( T_s - T_a \right) / \nu^2 \]  

(7)

and

\[ Pr = \nu / Da, \]  

(8)

where \( Gr \) and \( Pr \) are the Grashof and Prandtl numbers, respectively; \( g \) is the gravitational acceleration; \( \beta \) is the thermal expansion of the air; \( \nu \) is the kinematic viscosity; and \( Da \) is the thermal diffusivity of the fluid.

The value of \( \beta \) at each temperature was calculated to approximate a straight-line fit to the thermal expansion data of air, passing through the points 1.0 (0 ℃) and 0.11 (600 ℃). Similarly, \( Da \) at each temperature was calculated to approximate a straight-line fit to the thermal diffusivity data of air, passing through the points 1.91 \( \times 10^{-5} \) (0 ℃) and 1.41 \( \times 10^{-4} \) (600 ℃).

For the nonlinear structural analysis, we adopted the Newton–Raphson method, in which we repeatedly iterated Eq. (9):

\[ \left[ K^T_i \right] \{ \Delta u_i \} = \{ F_{\text{app}} \} - \{ F_{\text{nr}} \} \]  

(9)

Equation (9) was iterated by updating \( \left[ K^T_i \right] \) and \( \{ F_{\text{app}} \} - \{ F_{\text{nr}} \} \) at each step.

Here \( \left[ K^T_i \right] \) is the tangent stiffness matrix, \( \{ \Delta u_i \} \) is an incremental displacement vector, and \( \{ F_{\text{app}} \} \) and \( \{ F_{\text{nr}} \} \) denote the load and restoring vectors, respectively.

The elastic–plastic deformation was approximated by the two straight lines method. In the elastic region, the Young’s modulus is constant, and the tangent modulus in the plastic region was determined by using Eq. (10):

\[ H’ = \frac{d\sigma}{d\varepsilon}, \]  

(10)

where \( H’ \) is the tangent modulus of plasticity, and \( \sigma \) and \( \varepsilon \) are the equivalent plastic stress and strain increments, respectively.

The yield point was obtained by the von Mises yield criterion, which states that yield occurs when the principal stresses satisfy a particular relation. The yield stress is determined at each temperature.

3 Experimental results

3.1 Joint efficiency

The test results are presented in Table 3. All of the joints were broken at the interface. Under the test conditions (friction pressure = 20 MPa (Cu/IM) and 9 MPa (Al/IM), friction time = 3 s, IM rotation rate = 4000 rpm, upset pressure = 200 MPa, upset time = 2 s), the maximum joint efficiency of the proposed welding method was 60%, while that of the conventional friction welding method is 50%8). The appearance of the welded joint is shown in Fig. 7.
It should be noted that, consistent with the definition given in a previous study, the joint efficiency was defined as the tensile stress ratio of the obtained joint relative to that of AA2017.

### Table 3 Test results

<table>
<thead>
<tr>
<th>Friction pressure (MPa)</th>
<th>Rotation number (rpm)</th>
<th>Friction time (s)</th>
<th>Upset pressure (MPa)</th>
<th>Joint efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Al/S50C</strong></td>
<td><strong>Cu/S50C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>① 14 14</td>
<td>3000</td>
<td>1</td>
<td>200</td>
<td>29.8</td>
</tr>
<tr>
<td>② 14 20</td>
<td>4000</td>
<td>1</td>
<td>200</td>
<td>30.2</td>
</tr>
<tr>
<td>③ 14 20</td>
<td>4000</td>
<td>2</td>
<td>200</td>
<td>55.2</td>
</tr>
<tr>
<td>④ 14 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>57.4</td>
</tr>
<tr>
<td>⑤ 12 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>57.9</td>
</tr>
<tr>
<td>⑥ 10 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>58.1</td>
</tr>
<tr>
<td>⑦ 7 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>57.6</td>
</tr>
<tr>
<td>⑧ 8 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>60.1</td>
</tr>
<tr>
<td>⑨ 9 20</td>
<td>4000</td>
<td>3</td>
<td>200</td>
<td>60.3</td>
</tr>
</tbody>
</table>

3.2 Microscopic investigation

The structure of the center section of the joint bar was observed with an optical microscope and a scanning electron microscope (SEM). Figure 8 is an optical micrograph of the structure near the joint interface. The interface is relatively smooth but exhibits noticeable plastic deformation.

To determine the presence of intermetallic compounds and metal flake involvement, we examined the structure near the interface in more detail using the SEM.

The line scan results of Al and Cu and of O are shown in Figs.9 and 10, respectively, and the corresponding SEM images are shown in Fig.11.
As shown in Fig.9, near the interface, the Al and Cu components invade the opposite sides.

As shown in Fig.10, the O content is increased at the Al side of the interface but is hardly raised at the Cu side. From the change of the O content, we could accurately locate the interface (vertical dotted line in Fig.10).

The SEM images shown in Fig.11 reveal no intermetallic compounds or metal flakes near the interface. Both features are the suspected defects caused by dissimilar joints in the conventional friction welding process.
4 Discussion

4.1 Temperature changes during friction stage

Figure 12 presents the calculated and observed temperature changes in the Al specimen in the case of Al/ S50C (IM).

The labels 0y0x, 0y5x, and 2y5x in this figure denote the center of the specimen, the interface surface, and the surface 2 mm from the interface, respectively. On the surface 2 mm from the interface, the calculated and measured temperatures coincide.
**Figure 13** exhibits equivalent results obtained for Cu/S50C (IM).

These results confirm that the computational method simulates the actual measured values.

**Figures 14 and 15** show the calculated changes of the temperature distribution at one side of the specimen and in the IM during the friction stage. The results are plotted at 1.0 s, 2.0 s, and 3.0 s. The calculation conditions were as follows: friction pressure = 20 MPa (Cu/IM) and 9 MPa (Al/IM), friction time = 3 s, orbital motion of IM = 4000 rpm, upset pressure = 200 MPa, and upset time = 2 s. Under these conditions, the joint efficiency was 60%.

In the case of Al/S50C (IM), the heat generated by friction was transferred from the friction region into an 11.6-mm-diameter region in the IM (see **Fig.14**). Moreover, the temperature was slightly higher in the IM than it was in the Al specimen, because the thermal conductivity of the IM was lower than that of Al.

Similarly, for Cu/S50C (IM), the temperature was larger in the IM than it was in the Cu specimen. However, the temperature difference between the IM and the specimen was larger in Cu/S50C (IM) than in Al/S50C (IM) because the thermal conductivity of Cu was sufficiently large to transfer the heat generated by friction, as evidenced in the specimen in **Fig.15**.
Fig.14  Calculated temperature distribution during friction stage (Al/S50C)
Fig. 15  Calculated temperature distribution during friction stage (Cu/S50C)
4.2 Welding mechanism of the new process

The experiment demonstrated that when specimens make no physical contact during the friction stage, the intermetallic compounds and metal flakes that cause cracking in the joint are avoided. For this reason, the joint efficiency was improved by using our proposed method.

To obtain a robust joint using the present combination of materials, both materials must be plastically deformed by maintaining the strength balance between A2017 and Cu near the interface. This objective was attained by changing the heat generated by the friction between A2017/IM and Cu/IM.

However, a joint efficiency of 60% is inadequate in practice. The operational conditions under which our friction welding process could realize actual products were not determined in this study.

We surmise that because the welding was made by solid bonding, increasing the heat generation would improve the joint efficiency.

We further note that an A2017/A2017 joint with more than 95% joint efficiency has been reported. Therefore, the joint efficiency is not affected by oxidation at the interface. In future work, we will exploit the oxidized region to create a functionally gradient structure.

5 Conclusions

We proposed a new welding technique for joining dissimilar materials. The technique was tested on an Al alloy (A2017) and pure Cu (C1100). The optimal welding conditions were identified by thermal elastic-plastic stress analysis. The main results are summarized below.

1) The maximum joint efficiency in the proposed method was 60% (versus 50% in the conventional welding process).
2) Micro-inspection (by an SEM) revealed an absence of intermetallic compounds and metal flake involvement in the joint welded by the proposed method.
3) The O content increased on the Al side of the interface, but was hardly altered on the Cu side.
4) The precise position of the welding interface could be determined from the change of O content near the interface.

Acknowledgement

The authors would like to thank Enago (www.enago.jp) for the English language review.

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Nomenclature

\[ A \quad \text{Cross-sectional area, m}^2 \]

\[ D_{\alpha} \quad \text{Thermal diffusivity of the fluid, m}^2/\text{s} \]

\[ d\bar{\sigma} \quad \text{Equivalent plastic stress increment} \]

\[ d\bar{\varepsilon} \quad \text{Equivalent plastic strain increment} \]

\[ F_p \quad \text{Friction pressure, Pa} \]

\[ g \quad \text{Acceleration due to gravity, m/s}^2 \]

\[ Gr \quad \text{Grashof number} \]

\[ H \quad \text{Friction heat, W} \]

\[ H' \quad \text{Tangent modulus of plasticity, N/m}^2 \]

\[ h \quad \text{Heat transfer coefficient, W/m}^2\text{K} \]

\[ k \quad \text{Thermal conductivity of the fluid, W/m-K} \]

\[ L \quad \text{Representative length, m} \]

\[ Nu \quad \text{Nusselt number} \]

\[ P \quad \text{Radiated heat} \]

\[ Pr \quad \text{Prandtl number} \]
\( Q \)  
Amount of heat transfer, W

\( R \)  
Radius of orbital motion, m

\( r \)  
Radius of the specimen, m

\( T \)  
Torque, Nm

\( T_a \)  
Air temperature, K

\( T_s \)  
Surface temperature of the specimen, K

\( \alpha \)  
Radial difference between orbital motion and specimen, m

\( \beta \)  
Thermal expansion coefficient of air, 1/K

\( \varepsilon \)  
Emissivity

\( \mu \)  
Friction coefficient

\( \nu \)  
Kinematic viscosity, m\(^2\)/s

\( \sigma \)  
Stefan–Boltzmann constant \((5.67 \times 10^{-8})\), W/m\(^2\)K\(^4\)

\( \omega \)  
Angular velocity, rad/s

\[ K^T \]  
Tangent stiffness matrix

\( \{ \Delta u_i \} \)  
Incremental displacement vector

\( \{ F_{\text{app}} \} \)  
Load vector

\( \{ F_{\text{res}} \} \)  
Restoring vector