Effective Dynamic Coefficient of Friction between Rotating Rod and Aluminum Alloy Plate Evaluated by Thermal Method*

by Toshio Tomimura**, Taichi Ikeda *** and Shigeki Hirasawa ****

In the early heating stage by friction of friction welding, friction stir welding, spot friction welding, surface modification, and so on, conductive heat transfer plays an important role in formation of temperature field in the system, which would have direct effects upon the successive plastic flow process. In the heat transfer process of such systems, the effective dynamic coefficients of friction $\mu$ between a rotating rod and a metal plate is regarded as one of essential key parameters. However, almost no coefficients for various important industrial materials seem to have been obtained so far. In the present study, from experiments on unsteady-state friction heating and corresponding numerical calculations, the effective dynamic coefficients of friction $\mu$ using a rotating rod with a spherical tip of high speed tool steel have been evaluated for the aluminum alloy A2024, A5052 and A6061.

Key Words: Dynamic coefficient of friction, FSW, Friction welding, Spot FSW, Surface modification, Aluminum Alloy, Unsteady-state heat conduction, Experiment, Numerical calculation

1. Introduction

In friction stir welding (FSW), which was developed by The Welding Institute (TWI) in 1991 [1-3], the effective dynamic coefficient of friction $\mu$ between a rotating rod and a metal plate is regarded as one of essential key parameters for studying unsteady-state heat transfer in the rotating rod and the metal plate. Further, this effective dynamic coefficient $\mu$ is also quite important in the fields of friction welding, spot friction welding, surface modification, and so on. Unsteady-state conductive heat transfer in the rod and plate system could be clarified by performing numerical calculations using the effective dynamic coefficient $\mu$, and further the calculated results could be given as the initial condition for the successive plastic flow process.

In the field of FSW, for example, extensive studies have been done to simulate the FSW process. And the temperature field and the flow behavior of metal after initiation of the plastic flow have been gradually clarified[4-11]. On the other hand, concerning conductive heat transfer in the early heating stage by friction of FSW, friction welding and so on which would have direct effects upon the successive plastic flow process, few studies have been done, and almost no effective dynamic coefficients for various important industrial materials seem to have been obtained so far except for the first approximate values on the industrial pure aluminum A1100, the aluminum alloy A7075, the copper Cu, the stainless steel SUS304 and the nickel Ni[12].

In this study, as is the same way in the previous study [12], experiments on unsteady-state friction heating of an aluminum alloy plate by the rotating rod with a spherical tip of high speed tool steel and numerical calculations corresponding to the experimental system have been conducted. And from the curve fitting between the measured and calculated temperature histories, the effective dynamic coefficients of friction $\mu$ between the rotating rod and the aluminum alloy plates of A2024, A5052 and A6061 have been evaluated. This time, however, in consideration of the previous experiences [12] of appearance of chattering vibrations and increase in errors by inevitable automatic range change of temperature measuring system, and further, to evaluate the effective dynamic coefficient $\mu$ more correctly, the curve fitting method was applied for 30 seconds after the start of friction heating.

2. Experiments

2.1 Experimental apparatus

Figure 1 shows the experimental apparatus, which was made by rebuilding a milling machine. A rotating rod made of tool steel is supported with a chuck of the milling spindle, and the vertical load $F$ is applied on it by making use of turning moment produced by a weight suspended with a fine wire of an arm.

The holding block is made entirely of stainless steel. A hole of 50mm diameter is bored through the center of the upper stainless plate, and a specimen applied a black paint to its bottom surface was screwed up on the plate. Inside of the holding block, a stainless mirror is fixed at an angle of 45°, and through the hole...
of the upper plate and the mirror, the bottom surface temperature of a specimen was measured with an infrared thermometer.

2.2 Experimental conditions

The dimensions and the thermophysical properties of the rotating rod and the aluminum alloy at the absolute temperature 300K used in the present study is listed in Table 1. As for the aluminum alloy, although its length and width are both 70mm, an equivalent radius $r_s$ of the square plate is shown for taking correspondence to the numerical analysis into consideration. Here, $N$ is the number of rotations per minute of the rotating rod, and $F$ is the vertical load exerted on the aluminum alloy plate.

As shown in Table 2 of the sequence number list of experiments for the aluminum alloy A2024, six rotating rods were prepared, and to each rotating rod, three specimens were tested successively for the purpose of investigating the effect of tip conditions on the effective dynamic coefficient of friction $\mu$.

3. Numerical calculations

Figure 2 illustrates the physical model and the coordinates system. Here, a vertical dash-and-dotted line shows the rotation axis. With the number of rotations per minute $N$ (the corresponding angular velocity $\omega=2\pi n$, where $n=60/N$) and the vertical load $F$, a spherical tip shaped rotating rod of the radius $r_t$ and the length $l_t$ is pushed against a specimen of the radius $r_s$ and...

---

**Table 1** Dimensions and thermophysical properties of rotating rod and aluminum alloy A2024, A5052 and A6061 (at 300K)

<table>
<thead>
<tr>
<th></th>
<th>Rotating rod</th>
<th>A2024</th>
<th>A5052</th>
<th>A6061</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_t$, $r_s$ [mm]</td>
<td>10</td>
<td>39.5 (Equivalent radius of 70 x 70 plate specimen)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_t$, $l_s$ [mm]</td>
<td>50</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$c_t$, $c_s$ [kJ/(kg*K)]</td>
<td>0.461</td>
<td>0.880</td>
<td>0.90</td>
<td>0.896</td>
</tr>
<tr>
<td>$\rho_t$, $\rho_s$ [kg/m$^3$]</td>
<td>7830</td>
<td>2770</td>
<td>2680</td>
<td>2700</td>
</tr>
<tr>
<td>$\lambda_t$, $\lambda_s$ [W/(m*K)]</td>
<td>45.1</td>
<td>120.0</td>
<td>137.0</td>
<td>180.0</td>
</tr>
<tr>
<td>$a_t$, $a_s$ [mm$^2$/s]</td>
<td>12.5</td>
<td>49.2</td>
<td>56.8</td>
<td>74.4</td>
</tr>
</tbody>
</table>

**Table 2** Sequence number list of experiments for aluminum alloy A2024

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Tip radius [mm]</th>
<th>$N$ [rpm]</th>
<th>$F$ [N]</th>
<th>Rotating Rod No.</th>
<th>Specimen Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2024</td>
<td>75</td>
<td>1160</td>
<td>972</td>
<td>1</td>
<td>2024-1</td>
</tr>
<tr>
<td></td>
<td>445</td>
<td>972</td>
<td>550</td>
<td>2</td>
<td>2024-4</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>1160</td>
<td>972</td>
<td>4</td>
<td>2024-10</td>
</tr>
<tr>
<td></td>
<td>445</td>
<td>550</td>
<td>6</td>
<td>5</td>
<td>2024-16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2024-17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2024-18</td>
</tr>
</tbody>
</table>
were assumed adiabatic. On the other hand, some amount of heat could be released not only from the side surface of the rotating rod and the top surface of the specimen by natural convection and thermal radiation but also from the top surface of the specimen by thermal conduction and thermal radiation. However, since the whole quantity of the heat released from the rotating rod and the specimen has been confirmed negligible compared with the heat accumulated in them from the previous theoretical investigation\textsuperscript{14)}, the side surface of the rotating rod and the top surface of the specimen were also assumed adiabatic. As for the initial condition, the system was put under the initial temperature $T_0$.

The heat $q_{fr}$ generated by friction per unit time and area at the radius $r$ is given by the following equation\textsuperscript{12)}.

$$q_{fr} = \mu_0 \rho \omega r = 2 \pi \mu_0 \rho \omega r$$

where $\mu$ is the effective dynamic coefficient of friction, and is assumed constant. The $p_m$ included in Eq. (1) is the friction pressure. Although the pressure changes with the radius $r$, it was given in the present study by the following mean value for simplicity.

$$p_m = F \left( \frac{\omega r^2}{2} \right)$$

As to the generated heat by friction $q_{fr}$, the following condition is required at the interface ($z=0$) between the rotating rod and the specimen.

$$q_{fr} = -\lambda_z \frac{\partial T_s}{\partial r} + \lambda_t \frac{\partial T_t}{\partial r} \quad (0 \leq r \leq r_f)$$

Further, in the region $r_f < r < r_s$, at the interface, an adiabatic condition was applied to the rotating rod and the specimen.

The basic equation applied to the rotating rod and the specimen is the two-dimensional unsteady-state heat conduction equation in cylindrical coordinates. In this study, taking the abovementioned boundary and initial conditions, the condition given by Eq. (3) satisfied at the contact interface, and the basic equation into consideration, thermal network method was applied to perform numerical calculations effectively.

### 4. Result and discussion

A series of experiments and the corresponding numerical calculations for the aluminum alloy plates of A2024, A5052 and A6061 have been performed, and by applying the curve fitting method between measured and calculated temperature histories, the effective dynamic coefficients of friction have been evaluated using the data for 30 seconds after the start of friction heating.

Hereafter, the results obtained for the aluminum alloy A2024 are shown as a representative example, since the page-length is limited, and in addition, almost all the same behaviors were observed for the aluminum alloy of A2024, A5052 and A6061.

Figure 4 shows one example of the curve fitting method. Here, the closed circle shows the measured transient temperature variation, $T_b$ and $T_s$ represent the central temperature on bottom surface and the initial temperature, $t$ is the time, and $r_f$ is the
radius of the actual contact circle. The solid and broken lines show the numerical results for various effective dynamic coefficient $\mu$ calculated under the corresponding experimental conditions. From this figure, the $\mu$ in the present example can be evaluated about from 0.25 to 0.30.

Figure 5 shows evaluated ranges of the effective dynamic coefficients of friction $\mu$ obtained for 18 specimens of aluminum alloy A2024. Here, the vertical axis shows the evaluated effective dynamic coefficient $\mu$, and its range is shown by a black band, which at the same time means estimated error band of the $\mu$. On the other hand, Fig. 6 shows the evaluated results by applying the previous method, where the $\mu$ was evaluated by using the data for 120 seconds after the start of friction heating and the numerical calculations were performed by the fixed contact radius of $r_{fr} = 2\text{mm}$. As clearly seen from these two figures, by

Fig. 4 Example of curve fitting method

Fig. 5 Evaluated ranges of the effective dynamic coefficients of friction $\mu$ obtained for 18 specimens of aluminum alloy A2024 (In the case of measured contact radius)

Fig. 6 Evaluated ranges of the effective dynamic coefficients of friction $\mu$ obtained for 18 specimens of aluminum alloy A2024 (In the case of fixed contact radius of 2 mm)
introducing the time range of 30 seconds and the actually measured contact radius, more reliable effective dynamic coefficients of friction $\mu$ can be evaluated.

From Fig. 5, almost no effect of tip conditions on the effective dynamic coefficient of friction $\mu$ can be observed. And from all of those measured results, the evaluated mean value of the effective dynamic coefficient $\mu$ is about 0.29.

Figures 7, 8 and 9 show the effects of the tip radius of the rotating rod, the number of rotations per minute $N$ and the vertical load $F$ on the effective dynamic coefficients of friction $\mu$, respectively. As seen from the figures, little effects of the abovementioned factors on the effective dynamic coefficient $\mu$ were observed under the present experimental conditions.

5. Conclusions

The effective dynamic coefficients of friction $\mu$ between the rotating rod with a spherical tip of high speed tool steel and an aluminum alloy plate has been evaluated for three kinds of specimens A2024, A5052 and A6061. The major findings of the present study are summarized as follows:

1. The evaluated effective dynamic coefficients of friction of A2024, A5052 and A6061 are about 0.29, 0.29 and 0.33, respectively.
2. Almost no effect of tip conditions on the effective dynamic coefficient of friction $\mu$ can be observed.
3. Little effects of the tip radius of the rotating rod, the number of rotations per minute $N$ and the vertical load $F$ on the effective dynamic coefficients of friction $\mu$ were observed under the present experimental conditions.

Reference

1) US Patents 5460317 and 5813592 (Japan Patents 2712838 and 2792233), 1995.