Dynamics of temperature distribution during friction stir welding of butt joints of copper and aluminum

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Abstract. A mathematical model of temperature distribution in the process of friction stir welding (FSW) of dissimilar butt joints has been developed. The model makes it possible to take into account the geometric dimensions of the tool, the thermophysical properties and the temperature distribution in the sample during the transition of the welded material into the superplastic state. Temperature measurements were carried out at various points of the sample from the side of aluminum and copper during the FSW. This model is used to estimate the linear velocity of the FSW associated with the thermophysical properties of materials. The calculation results are in satisfactory agreement with the experimental data.

1. Introduction

Due to the large differences in physical and chemical properties, the formation of high-quality copper-aluminum compounds or their alloys is usually associated with various difficulties. Friction stir welding (FSW) is one of the solid-phase welding methods that allows you to join dissimilar materials with anomalously different physical, chemical and mechanical properties, in numerous combinations of metals, such as Al-Mg, Al-Fe, Al-Cu, etc.

Some aspects of the FSW process are still poorly understood and require further research. Most of the available research on determining the technological parameters of the FSW (rotation speed tool, welding speed and penetration tool, its displacement relative to the butt line) was experimental [1-4]. The smallest part of the works oriented for these purposes was of a numerical nature [5-9].

Mathematical modeling can be useful for understanding the influence of technological parameters on the process of formation of a welded joint during FSW. Visualization and analysis of metal flows in a superplastic state, temperature fields, stress and strain fields associated with the FSW process can be easily obtained using simulation. Therefore, to achieve the best mechanical properties of the weld joint, simulation allows you to adjust and optimize the process parameters and geometry of the tool [10].

One of the main directions of research in FSW is the assessment of temperature distribution in the area of the welded joint [11-13]. The temperatures occurring during the FSW are below the melting points of the materials being welded, but high enough for the formation of intermetallics. Therefore, it is very important to know the evolution of the temperature field of the weld. Usually, with FSW, the temperature at certain points of the sample is measured using thermocouples [12, 13]. However, the process of measuring the temperature in the zone of a welded joint using a plurality of jacked thermocouples is technically challenging. In this case, numerical methods based on a suitable
mathematical model can be very effective and convenient for this kind of research. This approach to studying FSW has been used over the past few years [13, 14]. In work [15] M. Riahi and H. Nazari presented numerical results based on the assumption of a linear dependence of the friction coefficient on temperature. It is shown that the highest temperature gradient is in the area under the shoulder. In the work of Schmidt et al. [16], an analytical model of heat generation in welded samples is presented, based on assumptions about the state of contact between the rotating surface of the tool and the welded part.

2. Experimental technique

Dissimilar joints of copper M1 and aluminum AD1 with a thickness of 3 mm were obtained by FSW. The plates were cut into blanks with a size of 250 × 250 mm. The copper sheets were annealed at about 650 °C, held for 1 hour, and then cooled in air. Before welding, the plates were placed on the base plate of the machine and rigidly fixed with clamps along the welding direction to prevent their mutual displacement.

Welding was carried out on a vertical milling machine with a rotation speed of 600 rpm to 1200 rpm and a welding speed of 25 mm / min to 60 mm / min. We used a cylindrical steel tool with a working part made of VK8 hard alloy with a shoulder 13 mm in diameter and a pin in the form of a truncated cone with a diameter of 6 mm at the base, and 4 mm in the truncated part and a generatrix length of 2.9 mm. With FSW the tool was installed with an inclination angle of 1–5 degrees from the normal to the surface of the welded plates. In the studies, samples of butt joints were welded.

To confirm the temperature distribution in the sample at FSW, 4 thermocouples were installed. The temperatures of ring elements with inner radius \( r_0, r_1, r_2 \) and \( r_3 \) were measured by the thermocouple method using a device and a personal computer (figure 1). We used chromel-alumel thermocouples of the GTHA-0.8-500m type, which were attached to the surface of the specimen being welded by capping at a distance of 2, 4.5, 6.7, and 10 mm from the heat input axis. The measurements were repeated three times and the average temperatures were taken into account.

![Figure 1. Arrangement of the device for measuring the temperature in the sample at FSW: 1- personal computer; 2- universal milling machine 6T80SH; 3- tool; 4- thermocouples; 5- microprocessor](image)

3. Mathematical model of the dynamics of the temperature field at FSW

Let us consider a mathematical model of temperature dynamics during butt welding of a product made of two dissimilar metals. We represent the product in the form of a composite disk of relatively small thickness \( h \). Its axis coincides with the axis of rotation of the tool (pin with shoulder). To increase the efficiency of the FSW of dissimilar metals in the process of welding, the pin axis is slightly shifted by \( \delta p \) relative to the contact line of the two metals. We assume that \( \delta p \) is positive if the displacement occurs to a material with high thermophysical parameters (copper alloy) [1-5,17].

The technological parameters of the FSW process are presented in table 1.
Table 1. Technological parameters of welded materials.

| Welded materials | Temperature of conversion to SPS, $T_{\text{sp}}$ (K) | Friction coefficient, $\mu$ | Yield shear stress, $\tau$ (MPa) | Applied vertical force, $F$ (kN) | Tool angular rotation speed, $\omega$ (rad min$^{-1}$) | Linear welding speed, $v$ (mm/min) |
|------------------|---------------------------------|-----------------|-------------------------------|-------------------------------|----------------------------------|-------------------------------|
| AD1              | 543                             | 0.47            | 6 (13-15)                     | 2600                          | 900                              | 25                            |
| M1               | 543(570)                        | 0.35            | 36-38                         | 3500                          | 900                              | 21.5                          |

As a result of the interaction of the rotating tool with the workpiece in the central cylinder with a radius equal to the radius of the pin $r_0$, as well as in the concentrically adjacent cylindrical ring, heat power is released, which is a certain function of time: $P = P(t)$. This results in an almost radial heat flux in the composite disk, since the tangential fluxes are small.

Let us select concentric cylindrical surfaces inside the disk with increasing radius $r_0$, $r_1$, $r_2$, ..., $r_N$, where $r_N$ is the radius of the outer cylindrical end. They split the disk into $N$ component annular sections separated from each other by these surfaces (see figure 2).

Figure 2. Scheme for selecting semi-circular elements of a composite disk.

Since the temperature gradients decrease with distance from the axis disk, we assume the radii of the cylindrical surfaces to grow exponentially:

$$r_k = a^kr_0, \quad a = \left(\frac{r_N}{r_0}\right)^{1/N}.$$  \hspace{1cm} (1)

Thus, outside the pin, the disk turns out to be divided into $N$ annular elements, consisting of two parts, which are close to half rings at a small displacement $\delta\rho$ of the axis pin. By the temperature of such semicircular elements we mean the values of and the absolute temperature on their inner cylindrical surface with a radius of $r_k$ ($k = 0, 1, ..., N-1$).

The enthalpy of semicircular elements is expressed as

$$H_{1k} = m_{1k}c_1T_{1k} + \text{const} \quad \text{and} \quad H_{2k} = m_{2k}c_2T_{2k} + \text{const}.$$  \hspace{1cm} (2)

Here $c_1$ and $c_2$ are the specific Isobaric heat capacities of the 1st and 2nd metals. The masses of semi-circular elements, taking into account the increasing radii in geometric progression (1), are respectively equal to:

$$m_{jk} = \frac{\pi}{2}r_0^2 h\rho_j a^{2k}(a-1)\left[1+a-(-1)^{1/2}\frac{4\delta\rho}{a_0}\right]a^{-k}, \quad j=1, 2.$$  \hspace{1cm} (3)
where $\rho_1$ and $\rho_2$ are the densities of the 1st and 2nd metals.

The rates of change in the enthalpy of the semicircular elements of the selected $k$-th bimetallic ring can be represented in the form of energy balance equations:

$$
\frac{dH_{jk}}{dt} = w P_1 \delta_{k,0} + (1-w)P_j \delta_{k,1} + P^a_{jk} \delta_{k,1} + P^b_{jk} \delta_{k,0} + P^e_{jk},
$$

(4)

Here $P_1$ and $P_2$ are the heat powers released in the first and second metals, respectively ($P_1 + P_2 = P$); $w$ - the fraction of the power released in the area of contact of the pin with the first ring element, and $(1-w)$ - the fraction that is released in the area of contact with the shoulder. $\delta_{k,k'}$ - the delta symbol Kronecker. The ratio of $P_1$ to $P_2$ is a variable parameter of the model, approximately equal to $P_1/P_2 \approx (\pi \rho_1 + 2 \delta \rho)/(\pi \rho_2 - 2 \delta \rho)$.

The terms $P^a_{jk}$ and $P^b_{jk}$ on the right side of equations (4) represent the amount of heat received per unit of time, respectively, from the $(k-1)$ th and $(k+1)$ th half rings as a result of heat transfer. In accordance with the law of thermal conductivity, we obtain the expressions for them:

$$
P^a_{jk} = (\pi \rho_k + 2 \delta \rho) h \chi_1 j \frac{(T_{jk(k-1)} - T_{jk})}{(r_k - r_{k-1})} (1 - \delta_{k,0}),
$$

(5)

$$
P^b_{jk} = (\pi \rho_{k+1} + 2 \delta \rho) h \chi_2 j \frac{(T_{jk(k+1)} - T_{jk})}{(r_{k+1} - r_k)},
$$

(5a)

where $\chi_1$ and $\chi_2$ are the thermal conductivity coefficients of the 1st and 2nd metals. Positive values of these quantities correspond to the supply, and negative values correspond to the loss of energy by the semicircular element.

The power loss of energy semi-rings on thermal radiation as absolutely gray bodies are equal:

$$
P^e_{jk} = -2 \left[ \frac{1}{2} \pi (r_{k+1}^2 - r_k^2) - 2 \cdot (-1)^j \cdot (r_{k+1} - r_k) \delta \rho \right] \sigma (T_{jk}^4 - T_c^4),
$$

(6)

where $\epsilon_1$ and $\epsilon_2$ - the radiation absorption coefficients of the 1st and 2nd metals, $\sigma$ - constant the Stefan-Boltzmann, $T_c$ - the ambient temperature.

The powers lost by the outer surface of the half rings due to heat exchange with the environment are presented in equations (4) by the last terms equal to:

$$
P^e_{jk} = -2 \left[ \frac{1}{2} \pi (r_{k+1}^2 - r_k^2) - 2 \cdot (-1)^j \cdot (r_{k+1} - r_k) \delta \rho \right] \omega (T_{jk} - T_c),
$$

(7)

where $\omega$ -coefficient heat transfer the metal-to-air.

Substituting expressions (5) - (7) into equations (4), describing the energy balance of the semicircular elements of the sample, we obtain, after transformations, the equations for the dynamics of the temperature of the semi-circular elements of the $k$-th bimetallic ring in the form:

$$
\frac{dT_{jk}}{dt} = Q_{jk} + \kappa^a_{jk} (T_{k(k-1)} - T_{jk}) + \kappa^b_{jk} (T_{j(k+1)} - T_{jk}) + P^e_{jk} \frac{r^4_c-t^4_{jk}}{r^4_c-T_{jk}},
$$

(8)

For a set of values $k = 0, 1, ..., (N-1)$, obtain a pair of systems according to $N$ equations (8), which describe the temperature dynamics of the semi-circular elements of the sample. Taking into account formulas (1), we express the coefficients of the systems of equations (8). As a result, obtain the following expressions for the heat release coefficients:

$$
Q_{kj} = \frac{2[w \delta_{k,0} + (1-w) \delta_{k,1}] P_j}{\pi_0^2 h \rho_j c_j a^{2k} (a-1) \left[ 1 + a - (-1)^j \cdot \left( \frac{4 \delta \rho}{\pi_0} \right)^{a-k} \right]},
$$

(9)
For the coefficients heat transfer between the semi-circular elements, the following expressions are obtained:

\[
\kappa_{jk}^a = \frac{2\chi_j \left[a + \left(\frac{2\delta p}{\sigma_0}\right)a^{-(k-1)}\right](1 - \delta_{k,0})}{r_0^2 \rho c_j a^{2k}(a - 1)^2 \left[1 + a - (-1)^j \left(\frac{4\delta p}{\sigma_0}\right)a^{-k}\right]},
\]

(10a)

\[
\kappa_{jk}^b = \frac{2\chi_j \left[a + \left(\frac{2\delta p}{\sigma_0}\right)a^{-k}\right]}{r_0^2 \rho c_j a^{2k}(a - 1)^2 \left[1 + a - (-1)^j \left(\frac{4\delta p}{\sigma_0}\right)a^{-k}\right]},
\]

(10b)

The radiation loss coefficients are:

\[
\beta_{jk}^r = \frac{2\varepsilon_j \alpha}{c_j \rho_j h}.
\]

(11)

The coefficients for heat transfer to the environment are:

\[
\gamma_{jk}^e = \frac{2\omega}{c_j \rho_j h}.
\]

(12)

The pair of systems of equations (8) is not closed, since the equations of the dynamics temperature \(T_{1N}\) and \(T_{2N}\) on the outer cylindrical surface are not determined either. Therefore, we select a semi-ring of very small thickness \(\delta r (\delta r \ll (r_N - r_{N-1}))\) near this surface, which can be limited to taking into account the energy losses for radiation and heat transfer only through the outer cylindrical surface of the sample. The energy balance conditions for such boundary elementary semi-rings lead to the equations:

\[
\frac{dT_{jN}^N}{dt} = \kappa_{jN}^a (T_{N-1} - T_N) + \beta_{jN}^r (T_{N-1} - T_{jN}^a) + \gamma_{jN}^e (T_{N-1} - T_{jN}^a),
\]

(13)

The coefficients on the right side of these equations are expressed as follows:

\[
\kappa_{jN}^a = \frac{\chi_j}{c_j \rho_j r_0 a^{N-1}(a - 1)\delta r},
\]

(14a)

\[
\beta_{jN}^r = \frac{\varepsilon_j \alpha}{c_j \rho_j h \cdot \delta r},
\]

(14b)

\[
\gamma_{jN}^e = \frac{\omega}{c_j \rho_j h \cdot \delta r}.
\]

(14c)

The resulting pair of systems of \(N + 1\) equations (8) and (13) is closed. The solution of this system for given \(N + 1\) initial values of the temperature of the elements \(T_k(0)\), where now \(k = 0, 1, \ldots, N\), determines the time dependence of the temperature of the semicircular elements.

3.1 Numerical simulation of temperature dynamics

The power released as a result of the rotation of the instrument depends on the temperature in the area of its contact with the sample material (see figure 4). It was calculated using the modified Schmidt formula [16].

\[
P_Q = \left[\frac{2\pi}{3} \rho \delta r + (1 - \delta) \mu \rho \right] \times \left[(R_S^2 - R_p^2) + R_p^2 \left[1 + \frac{R_0}{R_p} + \left(\frac{R_0}{R_p}\right)^2\right]\sqrt{R_p^2 + (R_p - R_S)^2}\right],
\]

(15)
where $\delta$ - the coefficient of slip between the shoulder and the workpiece ($\delta = 0.31$), depends on the surface treatment;

$P_\text{s}$ - the pressure exerted by the tool shoulder on the workpiece;

$R_\text{s}$ - radius tool shoulder;

$R_\text{p}$ - the radius of the pin at the base of the tool;

$R_\text{H}$ - length tool pin;

$T$ - the absolute temperature in the area of contact of the tool with the metal.

Fig. 3 shows the geometric parameters of the tool.

![Figure 3. Sketch of the welding tool.](image)

The temperature dependence of the specific heat capacity of materials, taking into account the phase transformations of metals, was modeled by a function of the form:

$$c_j(T) = c_j + \frac{\lambda_j}{\pi} \cdot \frac{\delta T}{(T - T_{\text{diff}})^2 + \delta T^2}.$$  

Therefore the coefficients of thermal conductivity of metals will also depend on the temperature:

$$\lambda_j = \frac{\lambda_j}{\rho_j \cdot c_j}.$$  

In contrast to the Schmidt model (15) [18], where the coefficient of friction $\mu$ was assumed to be a constant value, this work takes into account the temperature dependence of the coefficient of friction for each material in the form of a function

$$\mu_j(T) = \mu_{0j} \left[ 1 - \frac{1}{\pi} \arctg \left( 0.01 \cdot (t - T_{\text{diff}}) \right) \right].$$  

The effective coefficient of friction of the bimetallic sample was calculated by the formula:

$$\mu(T) = \frac{1}{2\pi R_\text{p}} \left[ \mu_1(T) \cdot (\pi R_\text{p} + 2\delta) + \mu_2(T) \cdot (\pi R_\text{p} - 2\delta) \right].$$  

Here $\delta = R_\text{p} \cdot \arcsin \left( \frac{\delta T}{R_\text{p}} \right)$ – the length of the mixing arc of the first half-ring. Formula (19) takes into account the dependence of the effective coefficient of friction on the temperature of the material in the area of contact with the tool.

Numerical solutions of the system of equations (13) determine the calculated dynamics of the temperature field in the area adjacent to the tool. In figure 4a shows the evolution of the temperature of two semirings with a radius $r_0$, and figure 4b shows the evolution of the temperature of two semirings with an inner radius $r_1$. The tool rotation time was taken in the calculations to be 40 s, after which the sample cooling process is described.
Figure 4. Dependence of temperature on time of the center of ring elements: a- from the side of the copper alloy $r_{0\text{modCu}}$ - at a distance of 3 mm, $r_{1\text{modCu}}$ - at a distance of 4.1 mm; b- from the side of the aluminum alloy $r_{0\text{modAl}}$ - at a distance of 3 mm, $r_{1\text{modAl}}$ - at a distance of 4.1 mm.

At the figure 4 shows that the maximum temperature of no more than 900 K occurs on the side of the aluminum alloy, since the material has a low coefficient of thermal conductivity compared to the copper alloy. The transition of the material to the superplastic state was no more than 10 seconds. The temperature difference between $r0$ and $r1$ was 91 K for an aluminum alloy, and for a copper alloy no more than 78 K.

Below is a comparison of the experimental and simulated temperature data during the FSW process (in figure 5).

Figure 5. Dependence of temperature on time from the center of the ring elements of a bimetallic sample of aluminum and copper alloy, remote at different distances: a - at a distance of 4.1 mm; b - at a distance of 6 mm.

The difference temperature for $r1$ and $r2$ data obtained experimentally and according to the mathematical model is no more than 5%, which indicates the adequacy of the model to the real process.

4 Conclusions
1. Mathematical model (13) thermal dynamics FSW bimetallic sample butt taking into account the temperature dependence of the generated thermal power (15).
2. On the basis of numerical realization of mathematical model (13) evaluated the linear velocity of the FSW dissimilar joints according to the programme given in [18]. This estimate is in satisfactory agreement with the experiment.
3. The FSW model proposed here allows you to establish a connection between the power consumption and the linear speed of the FSW. The experiments conducted confirm the nature of this connection.

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