Joining of Alumina (Al2O3) with Metals by the Friction Welding Method

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Abstract

The paper presents the results of welding the Al2O3 type ceramics with Al and Cu by friction energy. The welded materials were: corundum ceramics of 99.9% Al2O3 content, aluminum of 99.9% Al content and electrolytic copper of 99.9% Cu content. The samples used for welding were of the cylindrical shape, 10 mm in diameter and 25 mm in length. The welding process was carried out on a friction welding machine for metals, of the RSM 210 H+W type.

The basic welding parameters were given, namely the number of sample rotations, amount of welding pressure, welding time and the swelling effect under the conditions of additional heating of the samples. The joints obtained as a result of friction were characterized by quite high mechanical strength, homogeneous microstructure of Hume-Rothery phases and higher hardness, as well as distinct diffusion and deformation zones.

Keywords:
Friction Welding; Ceramics, Metals.

1. The state of research

The research so far has shown that friction welding is basically a process where considerable deformations take place in welded materials which are also mutually displaced [1,2].

The description of the main factors behind the processes may concern both metals capable of considerable plastic strain, composites and non-metallic alloys less susceptible to plastic deformation. In either case the plastic material will have constituted at least one third of the formed joint. The process of friction welding involves the transformation of kinetic energy into thermal energy by means of friction. What is the basic phenomenon causing higher temperature and then plastic deformation of the welded materials, or only one of them, is friction.
The friction coefficient is expressed by the following relationship:

\[ \mu_s = \frac{F_s}{P} \]  

(1)

where: \( F_s \) - is the force needed to start sliding, \( P \) - axial force applied to the faying surface.

One distinguishes static friction coefficient (\( \mu_s \)) and dynamic friction coefficient (\( \mu_d \)), where \( \mu_s > \mu_d \). For calculation purposes the mean value of friction coefficient can be defined by the following relationship:

\[ \mu_t = \frac{k_p}{(n)^2} \]  

(2)

where: \( k_p \) is the factor of proportionality = 0.067, \( n \) - rotational speed in r.p.m, \( r \) - distance from the roll axis in mm.

However, it is well-known that the friction coefficient is dependent on the temperature in the welding zone, the temperature, in turn, depends, i.e. on the number of revolutions and welding pressure (Fig. 1).

If we assume that the friction coefficient is constant and independent of rotational speed and unit pressure only, then the mean density of thermal flux can be expressed by the following formula:

\[ q = k_p \cdot p \cdot \mu_t \cdot r \cdot n \]  

(3)

where: \( q \) - the density of thermal flux [W/m²], \( p \) - unit pressure [N/m²], \( \mu_t \) - friction coefficient, \( n \) - number of revolutions [rpm], \( r \) - distance between the zone in question and the axis [m], \( k_p \) - constant of proportionality (# \( k_p \sim 2.8 \cdot 10^{-3} \)).

As the temperature increases so does the plastic deformation of a metal in the mating zone until appropriate temperature and higher friction pressure are achieved, after which welded materials are considerably deformed, their surfaces brought very close and mutually displaced to be permanently welded.

From the point of the kinetics of motion, friction can be divided into sliding and rolling, where the speed of the bodies in contact is either different or the same. Friction results depend, to a large extent, on the friction area which, in turn, depends on the real surface. In the process of friction welding, the sum of the touching surfaces constitutes the bearing surface, and consequently the sum of elementary joining surfaces can be expressed by the formula:

\[ S_r = \frac{N}{\sigma_{pl}} \cdot c \]  

(4)

where: \( N \) - normal load, \( \sigma_{pl} \) - yield point of the lower-melting material, \( c \) - coefficient dependent on the shape and size of a joining protrusion.

The formation of strong joints during the friction of bodies in the solid state has been accounted for by a number of hypotheses. One of the most important ones are adhesive, diffusive and power-related.

The adhesive hypothesis - correctly assumes that obtaining a strong joint depends on adhesive forces acting on adjoining surfaces, which can be achieved by

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Table 1. Friction coefficients for different materials [4]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perfectly pure metals in vacuum</td>
<td>Galling ( \mu &gt; 5 )</td>
</tr>
<tr>
<td>Pure metals in air</td>
<td>0.8-2.0</td>
</tr>
<tr>
<td>Pure metals in humid air</td>
<td>0.3-1.5</td>
</tr>
<tr>
<td>Steel after dry metals and bearing metals (e.g. lead, bronze)</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Steel after ceramics (e.g. sapphire, diamond)</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>Ceramics after ceramics (e.g. carbides after carbides)</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>Polymers after polymers</td>
<td>0.05-1.0</td>
</tr>
<tr>
<td>Metals and ceramics after polymers (e.g. after PVC)</td>
<td>0.04-0.5</td>
</tr>
<tr>
<td>Limiting metal lubrication</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>High-temperature lubrication (e.g. MoS(_2), graphite)</td>
<td>0.05-0.2</td>
</tr>
<tr>
<td>Hydrodynamic lubrication</td>
<td>0.001-0.005</td>
</tr>
</tbody>
</table>

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Fig. 1. The relationship between friction coefficient and temperature in friction welding of low carbon steel [3]: a) varying rotational speed and \( p \)=const, b) varying unit pressure and \( n \)=const.
plastic strain of micro-ridges. Moreover, plastic strain leads to an increase in free energy of the material in its entire volume. An increase in free energy of the material results in higher temperature, which, in turn, increases the adhesion coefficient. Fig. 2 shows changes in the adhesion coefficient as a function of temperature [4].

![Fig. 2. The influence of heat on the adhesion coefficient for: 1) copper, 2) magnesium, 3) titanium.](image)

The adhesive hypothesis fails both in the case of hard materials resistant to plastic strain and the joints of high mechanical strength.

The diffusion hypothesis assumes that joints are formed when materials, brought together within their atomic forces, create first spanning bridges on their sliding surfaces, due to adhesion. In these places, the material is heated even up to its melting point, which is manifested by so-called "temperature flashes" [1], which, in turn, contributes to a higher diffusion coefficient. In addition, this coefficient is increased by the pressure rise. It seems that the diffusion of atoms or ions can be the main phenomenon observed while sealing ceramic materials with metals.

The power hypothesis - put forward by Sieniev [5] - assumes that if two elements of the welded metal are brought together so that their crystallographic microstructure is compatible then less energy should be used to join them. So for the welding to be effective one should increase the energy of atoms on sealed surfaces to reach the so-called critical level of welding. The value of this energy is different for different materials and depends on temperature and surface condition. According to the author of the power hypothesis, the first spanning bridges of the seal are formed on the faying surface of the joined materials and grow dramatically on this surface as a result of supplied energy equal to the power welding threshold. The atoms of the material give off excess energy after the load has been removed and then assume the position similar to the one in a highly deformed crystal lattice.

None of the hypotheses sketched above explains entirely the mechanism of joint formation in the process of friction welding. However, the analysis of the existing hypotheses about the formation of strong seals in the solid state allows us to conclude as follows [2]:

- to obtain joints in the solid state it is necessary for the surfaces of contact to be clean,
- in the faying area, sufficient load must be provided to bring the two surfaces close enough for their atomic forces to interact,
- the higher the temperature in the welding area the lower the load required to obtain a joint
- the ability of materials to be welded in the solid state depends on their physical properties and the straining conditions.

An important factor affecting the welding in the process of friction is the surface temperature of joined materials and its distribution throughout welded elements. Assuming that in welding (elastic) ceramics and plastic materials an important role is played by in-diffusion of atoms in ceramics besides plastic strain, one must note that it is the temperature that controls these two phenomena. Temperature distribution in welded materials can be measured by the thermo-visual method or precisely located micro-thermal elements.

Generally, however, temperature distribution can be analytically defined by the conductivity equation.

\[
\frac{\partial T}{\partial t} = \frac{Q^2}{\rho \gamma v^2}, \text{ at } Q^2 = \frac{k}{\rho \gamma}
\]  

where: \( t \) - time, \( v \) - distance from the welding place, \( k \) - thermal conductivity coefficient of the welded material, \( g \) - specific gravity of the welded material, \( \gamma \) - specific heat of the welded material.

To make sure that obtained measurement results are sufficiently precise one can solve the conductivity equation by analytic methods. Boundary and initial conditions, which can be fulfilled in the case of friction welding, sufficient for solving the conductivity equation are the following:

1. \( T_{10}=h(v) \) - is the function obtained from the measurements at time \( t=0 \),
2. \( T_{00}=f(t) \) - is the function obtained at \( v=0 \), i.e. on the welding surface,
3. \( T_{25}=h(25) = \text{constant} \ y=0 \)
4. \( Q^2 = \frac{k}{\rho \gamma} = \text{constant} \)

Under these conditions one can solve the conductivity equation by the analytical or graphical method.
Table 2. Friction welding conditions for Al₂O₃ and Al as well as Al₂O₃ and Cu

<table>
<thead>
<tr>
<th>Type of welded materials</th>
<th>Welding conditions</th>
<th>Pressure in the friction phase</th>
<th>Pressure in the forge phase</th>
<th>Braking time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Friction time [ms]</td>
<td>Forge time [ms]</td>
<td>Rotational speed [N/min]</td>
<td>[MPa]</td>
</tr>
<tr>
<td>Al₂O₃ - Al</td>
<td>2500</td>
<td>2500</td>
<td>10000</td>
<td>2.5</td>
</tr>
<tr>
<td>Al₂O₃ - Cu</td>
<td>3000</td>
<td>2500</td>
<td>16000</td>
<td>4.0</td>
</tr>
</tbody>
</table>

2. The course of experiments

Corundum ceramic rods were chosen for the experiments, containing 99.9% Al₂O₃, 10 mm in diameter and 25 mm in length, as well as aluminum rods (99.9% pure Al) and Ø10 mm x 25 mm electrolytic copper. The welding tests were carried out on the RSM2 type machine made by the HWH company.

Welding conditions were modified throughout the experiment by changing rotational speed, pressure, swelling time and initial heating temperature of ceramic samples.

The optimal friction welding conditions for Al₂O₃ corundum ceramics and Al and Cu, under which obtained joints were tear resistant to > 1 MPa, are given in Table 2.

For proper mechanical strength of the joints the welding process was also thermally activated by heating one of the welded ceramic samples up to a temperature of 350 °C. Temperature distribution in welded materials during the welding process, measured by the thermo-visual method, showed that the maximum surface temperature on welded materials was 550 °C and 900 °C for Al₂O₃-Al and Al₂O₃-Cu, respectively. Temperature distribution was much more even in metallic samples (Al and Cu) than in a ceramic element (Al₂O₃), which indicates a considerable temperature gradient in ceramic profiles (about 350 °C/mm on the average).

3. The results of structural tests

Fig. 3, 4 and 5 show joint microstructures obtained by the friction method. The figures show that the joints have a continuous structure without discontinuities. They also show that both from the metal and ceramics side one can easily distinguish the inter-phase.
4. The results of Al, Cu and O linear distributions

Fig. 6. The linear distribution of Al, Cu and O in the Al₂O₃-Al joint

Fig. 7. The linear distribution of Al, Cu and O in the Al₂O₃-Cu joint

5. Results of microhardness testing

Measurement results relating to hardness and breadth of permanent sets, deformations and diffusion depth obtained by microscopy are presented in Fig. 8 and 9, as well as Table 3 and 4.

Fig. 8. Microhardness distribution around the Al₂O₃-Al joint under the pressure of 0.4 MPa.

Fig. 9. Hardness distribution around the Al₂O₃-Al joint under the pressure of 0.25 MPa

Table 4. Depth of diffusion zone in Al₂O₃ ceramics

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mean value of diffusion zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>27.62</td>
</tr>
<tr>
<td>Copper</td>
<td>16.47</td>
</tr>
</tbody>
</table>

Table 3. Breadth measurements of the deformation zone in the case of Al₂O₃-Al and Al₂O₃-Cu joints

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1/146</td>
<td>Aluminium-Al 1375</td>
<td>980</td>
<td>389</td>
<td></td>
</tr>
<tr>
<td>2/168</td>
<td>Aluminium-Al 1250</td>
<td>625</td>
<td>385</td>
<td></td>
</tr>
<tr>
<td>3/166</td>
<td>Aluminium-Al 875</td>
<td>500</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Copper-Cu 597</td>
<td>354</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
6. Assessing the obtained results

The phenomena taking place in welding plastic and elastic materials are complex. For the sake of simplicity they can be viewed in terms of permanent deformations - elastic strain and atom or ion diffusion. The causative factors here are temperature and pressure; temperature, in turn, is influenced by rotation and the amount of pressure, and to a lesser extent, the surface condition of the welded materials and the friction coefficient.

The above mentioned phenomena and factors influence the strength and durability of the joint, which can described by the following relationship:

\[ R_m = f(\varepsilon_p + \varepsilon_d + \Delta D)k \]  

(6)

where: \( R_m \) - tear resistance, \( \varepsilon_p \) - plastic strain, \( \varepsilon_d \) - elastic deformation, \( \Delta D \) - value of diffusion coefficient, \( k \) - coefficient.

Having the output data at one's disposal (temperature, rotations, pressure, friction coefficient), one can define the above phenomena as mathematical relations known from deformation and diffusion mechanics. Basic values of rotations, pressure and temperature throughout the welding cycle are shown in Fig. 10.

As the results of the experiments presented above show:

1. By creating appropriate friction conditions at the initial heating of Al\(_2\)O\(_3\) ceramics, one can obtain strong joints of the average tear resistance of 32 MPa and 37 MPa for Al\(_2\)O\(_3\)-Al and Al\(_2\)O\(_3\)-Cu joints, respectively.
2. The obtained joint is of the deformation-diffusion character.
3. The size of the deformation zone is the function of applied pressure, equaling 250-390 \( \mu \)m for Al\(_2\)O\(_3\)-Al.
4. The size of the diffusion zone depends on the type of welded materials, e.g. in the Al\(_2\)O\(_3\)-Al joint it ranges from 10 to 28 \( \mu \)m and for the Al\(_2\)O\(_3\)-Cu joint - 8 -17 \( \mu \)m.

7. Summary

Using ceramic materials in advanced industrial products it is often required that a metal/ceramic joint should be formed or the surface of the ceramic should be modified \([1, 6-8]\) so as to combine the properties, intrinsically different, of the ceramic and the metal and to obtain a product with the desired properties and functions. The production of ceramic and metal joints is one of the most pressing issues in joining engineering. The properties of the obtained joints are adequate to the properties of the combined materials, mainly ceramics.

References