1. INTRODUCTION

Certain physical properties of copper and aluminum, like the high electric and thermal conductivity, enable their common application in electronics, thermo-technique and other areas, in the form of bimetal. The necessity for their joining is indispensable in joining copper and aluminum electric conductors or the cable endings. Studying and improvement of advanced welding technologies of various metals and their alloys, mainly Al, Ti, Mg and different types of steels, are at present in focus of the modern research. The friction by welding plays a significant role in those researches, whether the matter is rotational continuous friction welding (when the cylindrical elements are welded) or the FSW (when the welded elements are plates or thin sheets). Friction welding of various materials was the subject of these authors previous research [1-3], as well as of certain other authors [4-11]. In those articles, it was shown that successful joining by friction welding could be done for different classes of steel [1-5], steels and other metals [6] or the light metals [7-10]. In addition, joints realized by classical friction welding, considered in this paper, can be compared to joints obtained by the friction stir welding procedure [11-14]. Joints obtained by either of the two mentioned friction welding processes exhibit advantages, compared to joints executed by some other welding procedure and it was proven that they could withstand successfully both static and dynamic loads in exploitation [13, 14].

The procedure of continuous friction welding of parts made of aluminum and copper is presented in this paper. The purpose was to determine the influence of the basic welding parameters (friction time, friction pressure and compacting pressure) on the mechanical and microstructural characteristics of the weld, since the bimetal joint characteristics depend on them.

2. BASIC CHARACTERISTICS, PHASES AND PARAMETERS OF THE FRICTION WELDING PROCESS

The friction welding process is very complex. When observing on the micro level, the mechanism of the joint realization is based on forming the metal bond (solid solution) between the base metals, all due to the diffusion process. That bond is created when the metal clean surfaces are coming close at distances that are of the order of magnitude of the crystal lattice parameters. At the beginning of welding, the contact of the welded parts is being realized only at the roughness tips, while the increase of the contact area is achieved by the plastic deformation of by friction of the heated contact surfaces. The physical essence of the process is in...
transformation of the mechanical energy into heat, which is released because of friction at the joining spot, i.e. in the contact zone of elements that are being joined. The released heat is supposed to soften and to plasticize the near-the-contact layers of materials, but the melting temperature of the easier melting material must not be exceeded. In the considered case that is aluminum, which means that the joint weld should be formed at temperature little below of 600 °C. The quantity of the released heat depends on the nature of the base metals, thermo-mechanical properties and the friction coefficient.

In the first phase, one part is rotating (aluminum) while the other part (copper) is not moving (Figures 1a, 2a). In the next phase, when the aluminum part reaches sufficient angular velocity, the copper part is being brought into contact by the axial force. The friction pressure ($p_f$) increases up to the maximum (Figures 1b, 2b). Then the heat is released and with maximum friction pressure, the conditions are achieved for realization of the joint. After the process is finished, rotation of the rotating part stops, what represents the third phase (Figures 1c, 2c) in which the maximum compacting pressure is being introduced ($p_c$). At that point, the extrusion of the plasticized material occurs, so at the rim of the joint a "wreath" of the extruded material is formed, the so-called "mushroom". After the cooling, the solid joint is obtained.

Quality of the joint is determined by the three basic variables, which influence mechanical and microstructural properties of the welded joint. Those are the relative speed (number of rpms), pressure and time. The friction speed influences, to the great extent, the character, shape and magnitude of the realized plastic deformation, as well as the heat generating process. It has been proven that within the range of the small angular velocities the plastic deformation process is being realized at larger depth. Unlike that, at large values of speed, either the complete welding cannot be realized, or the joints are of the poor quality.

The pressure during the friction phase has a strong influence on the thermo-deformation phenomena. There are two different pressures – the friction pressure ($p_f$) and the compacting pressure ($p_c$). The friction pressure action during the heating causes intensive deformation of material, heat release and temperature increase. The friction welding cycle could be realized by different variations of pressure vs. time, while as the optimal is considered the step-wise variation cycle [7].

The time depends on other factors that are influential in the welding process, like base metal properties, friction speed and pressure, shape and sizes of the welded parts. The friction time is the time needed for the contact surfaces to heat up to the maximum temperature.

The complete influence and dependence of the friction welding parameters, during the process, are presented in diagram in Figure 3.

Technological parameters of the friction welding were adopted based on experience, literature recommendations and large number of trials. The proper selection of parameters affects the output characteristics of the joint, so accordingly, it is necessary to select the optimal parameters. The adopted parameters were:

- number of rpms $n = 2500$ rpm,
- welding time $t = 4 – 15$ s,
- friction pressure $p_f = 50$ MPa,
- compacting pressure $p_c = 150$ MPa.
Estimate of the selected parameters optimality is done experimentally by the tensile test, hardness measurement and analysis of the joint's microstructure.

### Figure 3. Dependence of friction welding parameters of welding process phase

#### Table 1. Physical and mechanical properties of aluminum and copper

<table>
<thead>
<tr>
<th>Property</th>
<th>Al</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point, ºC</td>
<td>660.4</td>
<td>1083</td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>222</td>
<td>395</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>2.699</td>
<td>8.96</td>
</tr>
<tr>
<td>Coefficient of linear expansion, 1/ºC</td>
<td>23.9</td>
<td>16.5</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>50 ÷ 80</td>
<td>150</td>
</tr>
<tr>
<td>Hardness, HB</td>
<td>15 ± 20</td>
<td>25</td>
</tr>
<tr>
<td>Elasticity modulus, MPa</td>
<td>71000</td>
<td>127000</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>30 ÷ 45</td>
<td>52</td>
</tr>
<tr>
<td>Plasticity</td>
<td>good</td>
<td>good</td>
</tr>
</tbody>
</table>

Al-Cu alloys on the aluminum side solidify as the binary system with eutectics that contains 33 % of Cu and consists of Cu (α) solid solution crystals and the brittle intermetallic phase Al₂Cu (θ). One should keep in mind that copper, as an alloying element, significantly increases the resistance properties of aluminum. For instance, the alloy consisting of Al + 1 % Cu has the strength for 5 % higher that the pure aluminum [7].

#### Figure 4. Technical drawing and physical appearance of initial and welded Al-Cu samples

When the copper content is larger than 5.7 %, both brittle phases can exist, Al₂Cu and Al₄Cu₉.

#### Figure 5. Equilibrium phase diagram Al-Cu

### 4. EXPERIMENTAL INVESTIGATIONS

Quality and properties of the realized joints were determined experimentally by the tensile test, hardness measurement and analysis of the microstructure of the joint's characteristic zones.

#### Tensile test

For this test, the cylindrical samples were prepared made of the welded Al-Cu joints (Figure 6(a)). Samples were obtained in different conditions – the duration of the welding process was varied what directly influences the tensile properties of the joint.

On samples welded by friction, the breaking occurred mainly on the aluminum part, Figure 6(b) or in the zone of the Al-Cu joining, what is a very important indicator that the friction welding parameters were adequately selected.
Figure 6. Sample for tensile test (a) and high-quality welded joint after test – fracture in base metal (b)

Results of tensile tests of the base metals and heterogeneous welded joints are shown in Table 2 in terms of the friction time.

Table 2. Tensile strength of the base metal and friction welded joints’ samples

<table>
<thead>
<tr>
<th>Time, s</th>
<th>$R_m$, MPa</th>
<th>Breaking spot</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>61</td>
<td>WJ</td>
</tr>
<tr>
<td>6</td>
<td>69</td>
<td>WJ</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>Al</td>
</tr>
<tr>
<td>8</td>
<td>85</td>
<td>Al</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>Al</td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>WJ</td>
</tr>
<tr>
<td>12</td>
<td>75</td>
<td>Al</td>
</tr>
</tbody>
</table>

Based on results presented in Table 2 one can conclude that the shorter welding time results in obtaining the joint with properties that are worse than those of the base metals. This is why the recommendation is that the welding should last longer (> 7 s), for the welded joint to obtain better mechanical properties (higher strength).

Measurement of hardness and microstructure analysis. Hardness measurement was performed to determine the homogeneity of the welded joint, namely the presence of the undesired brittle phases ($\theta$–CuAl$_2$ and $\delta$–Cu$_{9}$Al$_4$). Hardness was measured along the three directions and at 5 points along the sample axis, according to Figure 7(a). The measurement points are distributed like this: direction I coincides with the welded sample's axis, direction II is at a distance of 3 mm from the axis and direction III is 8 mm away from the axis.

Obtained results for four tested samples are shown in Table 3, while the distribution hardness for sample # 1 is shown in Figure 8, with microstructures of the joint's characteristic zones. In majority of samples, hardness was pretty uniform and evenly distributed. As expected, the highest increase of hardness was recorded in the zone of melting/diffusion, where, besides the achieved high temperature, the Al melting occurred what created conditions for intensive diffusion of Cu and appearance of the intermetallic phases of high hardness. That was confirmed also in [7]. The $\theta$ (CuAl$_2$) phase has the body centered cubic (BCC) lattice. By increasing the Cu content in the alloy, it crosses into the $\theta$-phase area, where the $\theta$-phase transforms into the body centered tetragonal (BCT) lattice. Microhardness of such a $\theta$-phase is 450 to 650 HB.

What concerns the microstructure, it could be said that it depends largely on the welding parameters, since during the friction welding of copper and aluminum occurs creating and breaking of micro joints, as well as surfacing of copper layer on the aluminum front surface in the initial phase. That causes the friction plane to move away from the joining plane, while the microstructural processes occur within the mixing zone (Figure 8, position 3). From microstructure analysis of joints, it was established that the diffusion zone width was within range 2 to 10 $\mu$m, while the grain size was 0.1 to 0.2 $\mu$m.

4.1 The welding time influence on the plastic deformation and the samples’ lengths

Investigation of the welding time influence was done at the end, since due to friction, the samples are shortened and the part of material is lost into the so-called "mushroom". During the welding of Al and Cu, a very intense plastic deformation of the coupled parts occurs both in the radial and axial direction, of both materials, especially aluminum, as the weaker and softer one. By monitoring the dimensions’ changes with time, the relationship was established between the process duration and the samples’ deformation (Fig. 9).

Measurements results show that length reduction of the aluminum part is much bigger than that of the copper one. The difference, depending on the welding parameters, could reach even 10:1 ratio.
Deformation in the radial direction is much harder to measure since the "mushroom" is formed on the front side of the aluminum element. During the welding process the softened aluminum layers are being extruded from the friction plane towards the periphery so the big "mushroom" is formed, which is partially transferred to the frontal part of copper, over the whole perimeter [7]. The wreath diameter is increasing with extension of the welding time.

4.2 The welding time influence on the plastic deformation and the samples' diameter

Deformation in the radial direction is harder to monitor due to formation of a "mushroom" which is created at the frontal side of the aluminum element. During the welding process, the aluminum layers are moving out of the friction plane towards the periphery; they are extruded into the wreath and the big 'mushroom' is formed, which covers the frontal side of copper over the whole perimeter (Fig. 4).

The wreath diameter is changing with variation of the friction time. Increase of time causes enlargement of the wreath's diameter (Fig. 9). Depending on the friction time, as well as on the friction and compacting pressures, the wreath diameter can be increased within range 2 to 40 % with respect to the initial diameter of the aluminum part.

5. CONCLUSION

Joining of Al and Cu can be successfully performed by the friction welding; however, to obtain the welded joint, which fulfills all the required technical conditions, it is necessary to pay special attention to selection of the process parameters.

Analyses of the experimental results have shown that the basic process parameters significantly influence joint's structural and mechanical characteristics. If the optimal welding conditions were applied, it is possible to achieve the joint's strength, which is at the level of the aluminum strength, which means that during the tensile test the break must occur outside the joint zone. If that was achieved, then the bimetal Al-Cu friction welded joint is considered as the high quality joint.
However, the welding time influence should also be kept in mind. With increase of the welding time the tensile strength increases, while the shortening of the sample, especially the Al part, is much bigger. In addition, increase of hardness in the joint zone is expected, where it could reach 130 HV, as well as the grain size increase to 0.1 to 0.2 μm, with the diffusion zone width of 2 to 10 μm.

The presented results can be especially useful in designing the parts, joined by the friction welding procedure, when it it is necessary to obtain the precise desired length and strength of the joined elements.

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NOTE:
The shorter version of this research was presented at the "TEAM 2015" Conference, reference [9].

REFERENCES

УТИЦАЈ ПАРАМЕТАРА ЗАВАРИВАЊА ТРЕЂЕЊЕМ НА СВОЈСТВА AL-CU СПОЈА

Н. Ратковић, Д. Арсић, В. Лазић, Р. Николић, Б. Хадзима, П. Палчек, А. Седмак

У овој раду је дата теоријско-експериментална анализа споја алуминијума и бакра оствареног заварињем трењем. С обзиром на то да се овакви биметални спојеви Al-Cu у великој мери применују у индустријској прaksi, експериментална анализа у овом раду је изведена на конкретним елементима који се користе у електроници. Чинићена да је реч о спајању два различита материјала указује на сложеност проблема, пошто феномени који се јављају у зони спајања изузетно утиче на физичке, механичке и структурне карактеристике завариваних основних материјала. Поред теоријске анализе основних фаза и механизма процеса завариња трењем, истрживање је обухватило и експерименталну анализу промене геометрије услед пластичне деформације, анализу промене структуре.
и тврдоће у зони споја, као и основних механичких карактеристика Al-Cu споја. Овај рад даје значајне резултате који указују на могућност остваривања поузданих заварених спојева два различита метала.