Study on the influence of technological parameters on the friction stir butt welding process of pure copper plates

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Abstract. Friction stir welding - FSW is a relatively new welding process, which is increasingly used in industry, due to the advantages which it has in relation to conventional processes (by melting and adhesions). The advantages of the FSW welding process (as a solid phase welding process) are all the more obvious in the case of joining copper and its alloys, because they have a high melting temperature and high thermal diffusivity. The influence of the technological parameters of the process, the tool rotational speed and the welding feed, on the temperature and the axial force, as well as on the quality of the joint surface is presented. The study shows that the stabilization of the process takes place after a certain time from the beginning of the advance stage and highlighted the major influence of the tool rotational speed on the process temperature, surface defects and the roughness of the joint surface.

1. Introduction

Copper and copper alloys offer unique combinations of electrical and thermal conductivity, mechanical strength, formability and corrosion resistance, nonmagnetic behaviour, which makes them used in a wide range of engineering applications.

In industry, the joining of copper and copper alloys is usually done by various classical processes of: fusion welding (arc shielding gas, acetylene flame, laser, etc.), adhesion joining (brazing, soldering) or solid-state welding (electrical resistance and pressure end-to-end, ultrasound, friction stir welding). Due to the problems generated by melt welding (cracks, pores, oxides) and the relatively low strengths obtained by adhesion joining, solid state welding processes are preferred in many situations.

Friction stir welding - FSW is a relatively new welding process [1], which is increasingly used to join copper structures and its alloys. The FSW process is able to perform thick welds, with mechanical properties superior to melt welding, reliably and reproducibly [2 - 5], which is why this welding process is in full growing.

Scientific research on the joining of copper and its alloys through the FSW process is mainly focused on the study of the influence of technological parameters and the shape of the tool (rotating active element) on the quality of the joint [6 - 11], the possibility of combining different structures and types of alloys, inclusive dissimilar [7, 12 - 15] or the possibility of using external heat sources - the application of hybrid processes [16 - 18]. For this purpose, different theoretical-experimental research techniques and/or numerical modelling techniques and simulation were used.
The research on FSW joining of copper alloys has shown that due to the relatively high melting temperature and high thermal diffusivity of copper alloys, their FSW joining is limited to a narrow range of technological parameters. The temperature during the FSW process has a decisive role on the quality of the joint (appreciated by its microstructure and mechanical properties), and the axial pressure force influences the morphological aspect of the joint, but also the defects in the weld seam.

This paper presents the main results of the experimental research of the FSW joining process of a structure consisting of two similar pieces positioned butt-to-butt. The two welded parts are made of Cu-DHP, a material commonly used in the automotive industry, in the construction of radiators and air conditioning system elements. This study presents an analysis of the dependence of the process parameters, temperature and axial force, on the technological parameters of the process, the rotational speed of the rotating active element (tool) and welding feed. Also, the surface quality of the joints is evaluated by visual morphological analysis and through the roughness parameters.

2. Experimental procedure

2.1. Materials joined and experimentation
In the experiments, two plates of Cu-DHP (chemical composition: Cu 99.9% and P 0.015 - 0.04%), of dimensions 100x250x3 mm, having the mechanical characteristics from the table 1, were joined by FSW butt-welding process, figure 1.

![Figure 1. FSW butt-welding: (a) process scheme, (b) dimensions of the welding tool.](image)

| Table 1. Mechanical characteristics of Cu-DHP. |
|-----------------------------------------------|
| Mechanical characteristics | Tensile strength, Rm [MPa] | Yield strength, Rpo.2 [MPa] | Vickers hardness, HV0.3 [N/mm²] | Elongation, A5 [%] |
| Value | 260 MPa | 206 MPa | 81 | 55 |

In order to analyse the influence of the technological parameters: rotational speed - n, and welding feed - w, on process characteristics, several experiments were performed, with different values of these technological parameters, table 2.

| Table 2. Experimental plan of FSW of process. |
|-----------------------------------------------|
| Exp. no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Rotational speed, n [rpm] | 1200 | 1000 | 1200 | 1000 | 800 | 800 | 1000 |
| Welding feed, w [mm/min] | 90 | 90 | 150 | 150 | 90 | 150 | 120 |

2.2. Process parameters measurement and welds surfaces analysis
The experiments were performed on a specialized welding machine, FSW 4-10, figure 2. The welding process was monitored throughout its evolution, by recording the values of temperature and axial force.
The process temperature was measured using the infrared thermography method, using an infrared thermographic camera of the type FLIR A40M (temperature measurement range -40°C...+2000°C, accuracy of data measurement ±2°C, 76800 pixels, 60 fps). The thermographic data measured during the welding process were recorded and processed on a laptop, using the specialized software ThermaCAM™ Researcher. The positioning and fixing of the thermographic camera were done with the help of a special device, which allowed its positioning behind the active element (tool), at a constant distance from it, monitoring the joint area in the immediate vicinity of the tool throughout the process evolution.

The axial process force was measured using a force sensor mounted on the main shaft of the welding machine head, a sensor that includes a WIKA compression transducer, model F1211 (force measurement range 0 - 20 kN and relative linearity error of ±0.3% * Fnom). The acquired data were recorded and processed on a laptop, using the GRAPHTEC midi LOGGER GL240 system.

![Figure 2. Experimental stand of Friction Stir Welding process.](image)

The roughness of the FSW joints was determined on specimens taken from the end area of the joint, using a portable digital roughness-meter, type MAHR PS-10. The roughness measurement was performed in three areas of the specimen, in a direction parallel to the welding direction using a stylus method.

3. Results and discussions

The evolution of the temperature and the axial force during the FSW process were represented superposed on the same diagram, over the sampling scheme of the specimens from the welded structure. This allowed to highlight the moment when the process becomes stable: the temperature and the axial force remain approximately constant during the process. Equally, this helped to highlight local process conditions in which the joint was made, respectively, the conditions associated with the areas from which the different specimens used in the study were collected.

Figure 3 shows as an example such a diagram for experiment 6. It is found that the process becomes stable after a distance of about 70 mm from the beginning of the joint. On the whole of the experiments performed, the distances from which the FSW process becomes stable are between 60 and 90 mm.
The average values of temperature and axial force in the process stability area are presented in table 3 and are represented graphically, depending on the technological parameters n and w, in figure 4, respectively, figure 5.

Table 3. Average values of temperature and axial force in the process stability area.

| Exp. no. | 1       | 2       | 3       | 4       | 5       | 6       | 7       |
|----------|---------|---------|---------|---------|---------|---------|---------|
| Technological parameters (n, w) | (1200,90) | (1000,90) | (1200,150) | (1000,150) | (800,90) | (800,150) | (1000,120) |
| Average temperature, [°C] | 693 | 466 | 580 | 550 | 476 | 500 | 596 |
| Average axial force, [kN] | 12.5 | 9.7 | 11.8 | 13.2 | 12.6 | 12.6 | 10.3 |

Figure 3. Experience no. 6 (n = 800 rpm, w = 150 mm/min): (a) evolution of temperature and axial force in the FSW process, (b) appearance of the welded joint.

Figure 4. Dependence of average process temperatures on technological parameters.
From the analysis of the values in table 3 and of the graphs in figures 4 and 5, the following can be deduced:

- The average temperature values are between 466 and 693 °C and represent between 44% and 64% of the copper melting temperature (values similar to those found in other scientific studies);
- The process temperature is significantly influenced and in the same way by the tool rotational speed, while the welding feed has a smaller influence and depends on the value of the tool rotational speed. Thus, increasing the tool rotational speed produces a significant increase in the process temperature. Instead, increasing the welding feed causes a slight increase in the process temperature at low tool rotational speeds and a decrease in the process temperature at high tool rotational speeds. These influences of the technological parameters on the process temperature are due to the ratio in which are the velocities of the points on the periphery of the shoulder / tool pin produced by the two technological parameters: the velocities generated by the speed are between 50265 - 75400 mm/min at the shoulder periphery, and between 7539 - 11309 mm/min at the periphery of the pin, while the velocities generated by the welding feed are between 90 - 150 mm/min. Therefore, the effects produced by them (heat development due to friction at the shoulder-part interface and inside the joint by mixing of materials produced by pine) are different.

- In connection with the axial force in the process, it was not possible to establish its dependence on the two varied technological parameters in this study, n and w. This is caused by the complex mechanisms that influence the evolution of the axial force and which is done at the same time: on the one hand, the plasticization of the material (determined by the increase of the process temperature - which is influenced differently by the two technological parameters) leads to the decrease of the axial force, on the other hand, the increase of the friction between the tool and the welding material (also determined differently by the two technological parameters) leads to the increase of the axial process force.

The stabilization area of the welding process is also highlighted by the visual morphological analysis of the joint structure, figure 6. At the same time, this analysis provides important information on the production of surface defects of the joint, which are presented below:

- **Channel defect** (visible in all experiments): this occurs especially in the first part of the joint and is caused by insufficient reinforcement of the material on the advancing side. The appearance of this defect is due to insufficient plasticization of the material (low process temperature) and / or insufficient penetration of the tool in the joint structure (improper adjustment of the technological system). Once the FSW process stabilizes, the first cause is eliminated. The second cause can be highlighted on the joint structure by the existence of specific circular tracks, smaller than the diameter of the tool shoulder.

- **Excessive burr defect** (highlighted in exp. no. 1): this is caused by welding materials in too hot working conditions. When the process temperature is too high (above 650 °C), excessive
plasticization of the material and its mixing causes the appearance of these burrs, more prominent on the retreating side.

Figure 6. Visual morphological aspect of the surface’s joints.

The roughness of FSW joints is influenced by:
- the kinematics of the process that determines the appearance of “circular tracks”: the spacing and height of the circular tracks specific to the FSW process depend on the tool rotational speed and the welding feed;
- the deformations caused by the friction of the tool shoulder with the upper surface of the parts and process temperature, which favours excessive plasticization of the material.

Figure 7. Dependence of average samples roughness on technological parameters.

The dependence of the average values of the roughness of the parts joined by the two technological parameters considered in the study, n and w, presented graphically in figure 7, highlights the fact that the roughness of the joint increases with increasing values of the two technological parameters:
- the increase of the feed rate, w, kinematically determines the increase of the surface roughness. This increase is more accentuated with the increase of the tool rotational speed, which causes the increase of the process temperature and, thus, the plasticization of the material;
- the increase of the tool rotational speed, n, leads to the increase of the process temperature and, thus, to the plasticization of the material, which also produces the increase of the surface roughness;
- the increase of the tool rotational speed influences the roughness of the joined surfaces to a greater extent than it influences the increase of the welding feed.

4. Conclusions
The main conclusions regarding the dependencies of the process parameters and of some characteristics of the welded joints by the technological parameters of the FSW process are summarized below.

The temperature in the FSW process depends on the two technological parameters, increasing with the increase of the tool rotational speed and with the reduction of the welding feed, the tool rotational speed having a major influence in this dependence. The axial force in the process does not show an explicit dependence on the two technological parameters, due to the two complex mechanisms that influence it and which is done at the same time: the material plasticization and friction between the tool and the material.

The FSW joints present two categories of surface defects: channels and excessive burrs. The channel type defect is determined by the insufficient penetration of the tool in the joining structure (improper regulation of the technological system) and by the low process temperature, while the excessive burr type defect is caused by too high process temperatures. Therefore, the temperature of the process is particularly important in relation to the occurrence of these defects:
- a high temperature ensures a better mixing of the material (creating the premises to avoid channel defects);
- increasing the temperature to values higher than 650 °C leads to excessive plasticization of the material and, thus, to the appearance of excessive burrs and to the increase of roughness.

FSW joints roughness depends on the two technological parameters, increasing as their values increase, the tool rotational speed having a greater influence in this dependence as well.

The study will continue through the structural and mechanical characterization of the joints and an analysis of the influence of defects on their mechanical behaviour.
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