Orientation of process parameter values of TIG assisted FSW of copper to obtain improved mechanical properties

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Abstract. Welding copper and its alloys is usually difficult to achieve by conventional fusion welding processes because of high thermal diffusivity of copper, which is at least 10 times higher than most steel alloys. In order to reduce the increased temperature loss, it would be advantageous to use a process that is carried out at lower temperatures. Friction Stir Welding (FSW) is a solid state joining process that relies on frictional heating and plastic deformation and was explored as a feasible welding process. In order to achieve an increased productivity this process is assisted by another one, TIG (tungsten inert gas), which generates and adds heat to the process. The aim of this paper is to determine the progress direction of the process parameter values in order to maintain the productivity of the hybrid process and also to increase the values of the mechanical properties. Are analysed the evolution of the temperature, of the plunging force, of the microhardness and of the tensile strength in order to evaluate the changes generated by the application of the hybrid process. Then changes to the process parameter values of the hybrid process based on the evaluation of the previously mentioned properties are suggested in order to improve its mechanical properties.

1. Introduction

Friction Stir Welding is a solid state joining process that relies on frictional heating and plastic deformation made by a non-consumable welding tool that is rotating on the contact surfaces of the workpieces. The welding tool is positioned perpendicularly on the material and is moving with the welding speed along the joint line. The plasticized material is transferred behind the tool, forming a welded joint, figure 1. FSW involves the joining of two metal pieces at the molecular level without melting. Due to its solid state nature FSW has many benefits over fusion welding techniques. The main advantage of this is its ability to weld alloys which are mostly non-weldable using fusion welding methods due to problems with oxidization, solidification, shrinkage, sensitivity to cracking and the resultant porosity problem [1]. Because of the interest shown by the industry towards this process, extensive research has been carried out to improve its productivity, thus this process is assisted by another one, TIG, which generates and adds heat to the process.

In most analysed scientific papers, the main advantages of the TIG assisted FSW process for the joining of copper are summarized as: increased productivity, faster and better plasticization of the base material, reduced FSW tool wear and clamping forces [2]. But the same time with the temperature increasing, which is the factor that facilitates the occurrence of all these advantages, the mechanical properties of the joint are decreasing, behaviour that is also identified in the literature but for hybrid
FSW of dissimilar materials (Cu-Al) joints [3]. To obtain good mechanical properties for FSW of pure copper joint, it is recommended that the temperature during the process to be between 460 °C and 530 °C [4].

The aim of this paper is to promote and support certain hypotheses about changing the process parameters in order to maintain the productivity of the hybrid process and also to increase the values of the mechanical properties. The research includes two experiments for the FSW process and two experiments for TIG assisted FSW process. The different process parameters affect the temperature’s profiles, the cooling rates and consequently the welded joints’ properties.

Research in this field has shown that for FSW welds of copper alloys, microhardness and tensile strength depend on the condition of the base material (annealed or work hardened) as well as on the heat input of the welding. Increase of the heat input leads to an annealing softening and to a decrease of microhardness and tensile strength. Lowering the heat input (lower rotational speed of the tool or higher welding speed) leads to a decrease in grain size which consequently leads to equal or even higher microhardness of the welds compared to the base material [5–8], increased yield and tensile strength values and reduced ductility [5,6].

2. Experimental program
The experimental stand includes a FSW welding machine, a TIG welding head, an orientation and fixing device, and various data acquisition, recording and monitoring systems, figure 2. Welding processes are monitored by analysing the temperature and axial force values throughout the process.

![Figure 1. A schematic presentation of the friction stir butt welding process.](image1)

![Figure 2. Experimental stand of TIG assisted friction stir welding process.](image2)

The chemical composition and the effective mechanical properties of the Cu-DHP (phosphorus–deoxidized copper) sheets used in the experimental program are provided in tables 1 and 2. Copper has a face-centred cubic (fcc) crystal structure and it doesn’t undergo phase changes after solidification. Melting point of copper is 1084 °C. Because of high thermal conductivity, welding copper and its alloys are usually difficult to join by conventional fusion welding processes but this characteristic make them feasible for solid state joining processes such as FSW.

| Table 1. Chemical composition of Cu-DHP. |
|----------------------------------------|
| Alloying element | Percentage [%] |
| Cu | 99,9 |
| P | 0,015 - 0,04 |

| Table 2. Mechanical characteristics of Cu-DHP. |
|-----------------------------------------------|
| Name of the characteristic | Value |
| Tensile strength, Rm | 260 MPa |
| Yield strength, Rp0,2 | 206 MPa |
| Vickers hardness, HV0,3 | 81 HV0,3 |
| Elongation, A5 | 40 % |
For butt welding Cu-DHP sheets were developed experiments using FSW and TIG assisted FSW processes, table 3. The process parameters which varied were the rotational speed of the tool [rpm], the welding speed [mm/min] and the axial force [KN] which was manually adjusted until a value that presented a suitable visual aspect of the joint, while the current intensity of the TIG preheating source (for the hybrid process) [A] remained constant. All workpieces were cut in order to have the same rolling direction, parallel with the welding direction, figure 3. The welding tool has a classical mono-block structure with conical pin and is made of P20+S (carbide of sintered tungsten), figure 4.

**Table 3.** Experimental plan of FSW and TIG assisted FSW processes and average values measured for axial force and for temperature.

| Exp. No. | Rotational speed [rpm] | Welding speed [mm/min] | TIG welding current [A] | Average axial force [KN] | Average temperature [ºC] |
|----------|------------------------|------------------------|------------------------|--------------------------|--------------------------|
| 1        | 1200                   | 90                     | -                      | 12,45                    | 693                      |
| 2        | 800                    | 90                     | -                      | 12,55                    | 476                      |
| 3        | 1000                   | 250                    | 100                    | 11,7                     | 868                      |
| 4        | 1000                   | 350                    | 100                    | 12                       | 845                      |

Samples from the welded joints were cut for macroscopic and microscopic analysis, for measurement of microhardness and roughness, but also for tensile and bending tests, figure 5. This paper presents and analyses the results regarding the evolution of temperature, axial force, microhardness and tensile strength values.

**Figure 3.** Dimensions of the workpieces.

**Figure 4.** Dimensions of the welding tool.

**Figure 5.** The relative position of the specimens used to determine the weld properties.

3. Results and discussions

3.1. Temperature and Plunging force analysis
In order to highlight the local conditions in which the joining was made in the areas where the microhardness and tensile strength was determined, but also to highlight the moment when the process becomes stable, the temperature and the axial force, were represented on the same diagram, having as background the specimen sampling scheme, figures 6 - 8.
Figure 6. Experiments 1 and 2: (a) evolution of the temperature and of the axial force during FSW process; (b) Exp.1 - welded joint; (c) Exp.2 - welded joint.

Figure 7. Experiment 3 (a) evolution of the temperature and of the axial force during TIG assisted FSW process; (b) welded joint.
The analysis of the temperature’s evolution and of the axial force from the previous diagrams highlights the following aspects:

- If we perform a comparative analysis between experiments 1 and 2 we notice that the temperature is increasing with increasing of tool’s rotational speed and for experiments 3 and 4 we observe that the value of the temperature is increasing with the decreasing of the welding speed. The highest temperature was found, as expected, in TIG assisted FSW process, table 3.

- The axial force used in the experiments has an approximately equal value for all experiments, which leads to compliance with temperature variation laws, depending on the process parameters, table 3. This must have a value that assures a certain penetration of the tool in the welding materials in order not to cause channel defects (insufficient plunging) or excessive burr (too much plunging).

3.2. Microhardness analysis

Microhardness profiles were measured over the transverse cross-section of Cu-DHP FSW welds with hot-rolled base material, figure 9. From each joint were extracted two samples, one from the beginning of the joint and the other from the end of the joint to highlight how microhardness is affected by the process stability, figure 5. These samples were subjected to an automatic grinding and polishing. The microhardness was measured with an electronic microhardness tester, type InnovaTest Falcon 500. The Vickers microhardness values of the welded specimens were determined under the load of 300 g during 10 s of penetration time.

The weld’s microhardness depends on the heat input generated in the process. Increasing the heat input leads to lower hardness. Lowering the heat input leads to refined grain size and approximately equal or even greater hardness of the welds as compared to the base material, figure 10.

Regarding the evolution of microhardness profile according to the local conditions registered on the samples, are ascertained the following:

- In experiment 2 the values measured on the sample taken from the beginning of the joint are...
slightly higher than those measured on the sample taken from the end of the joint, figure 10. This is explained by the temperature’s differences in these two areas, lower in the beginning and higher in the end, figure 6.

- In experiments 3 and 4, the values measured on the sample taken from the beginning of the joint are lower than those measured on the sample taken from the end of the joint, figures 11, 12. Although the temperature values in the two areas are approximately equal or even bigger for the samples taken from the end of the joint, figures 7, 8. These differences can be attributed to different cooling rates. At the end of the process the additional TIG heat input is interrupted and consequently the second sample benefits from a faster cooling.

- The same explanation may be given for exp. 1 which also shows smaller values of microhardness for the first sample, figure 10, although the temperature in its area was lower than that in the area of the second sample, figure 6. Exp. 1 was the first done experiment and at that time the whole experimental stand had the room temperature. Once the welding was completed, in the absence of the heat input generated by the tool, the area of the specimen from the end of the joint cooled faster. This behaviour of copper is also identified in other scientific papers, in which the TIG assisted FSW joints (but for dissimilar materials) have undergone forced cooling [3].

3.3. Tensile strength analysis

The transverse tensile tests of 3 mm thick Cu-DHP FSW welds were performed according to the standard SR EN 10002-1, the standard is for fusion welds, but it is also proper to FSW joints. Three tensile strength samples were extracted from each joint, at the dimensions presented in SR EN ISO 6892-1, using the abrasive waterjet method followed by milling the calibrated area of the specimens, figure 13. All of these samples were cut from the end of the welded joint where the process became more stable, to result values of tensile strength that accurately characterize the set of process
parameters used, figure 5. The tests were performed using an INSTRON 8800 testing machine which presented a maximal traction force of 250 KN, using a strain rate of 8 mm/min. Tensile strength of specimen presents higher values for the classic FSW process and lower values for the TIG assisted FSW process, figure 14. By making a correlation between the temperatures and tensile strengths it is observed, as in the case of microhardness, that with the increasing of the temperature the tensile strength is decreasing, table 4. The highest value of tensile strength and microhardness is identified for exp. 2, the experiment with the lowest temperature, which is comprised within the range specified in the literature (460- 530 °C) as presenting copper FSW welds with good mechanical properties [4].

![Figure 13. Geometry and dimensions of the tensile test samples.](image)

![Figure 14. Tensile strength of samples.](image)

### Table 4. Average values measured for microhardness and for tensile strength.

| Exp. No. | Average microhardness HV/0.3 | Average tensile strength [MPa] |
|----------|-----------------------------|-------------------------------|
| 1        | 66.61                       | 193.2                         |
| 2        | 79.57                       | 216.6                         |
| 3        | 62.69                       | 135.8                         |
| 4        | 63.87                       | 147.8                         |

3.4. **Orientation of process parameter values of TIG assisted FSW of copper**

As it can be seen from this study, mechanical properties are negatively influenced by the increase over a certain limit of the temperature recorded during the process. So intervention on process parameter values is required in order to obtain lower temperatures and consequently to increase the values of the mechanical properties, but in the same time maintaining the productivity of the hybrid process.

This intervention is proposed for each process parameter for a clearer identification of its influence:

- Increasing the welding speed is a known and proved way of lowering the process temperature by making a comparison between exp. 3 and 4, from which it is also noticed that this decrease is very small (23 °C) compared to the established target (320 - 400 °C), although a significant increase in feed rate is achieved (100 mm/min). To achieve this objective by varying this parameter is thus impossible due to the limitation imposed by the rigidity of the tool pin.

- Decreasing the rotational speed of the tool is also a known and proved way of lowering the process temperature by making a comparison between exp. 1 and 2, where a decrease of 217 °C in the temperature is recorded for a reduction of 400 rpm in the rotational speed. This hypothesis represents a feasible option of lowering the temperature to values that show good mechanical properties.

- Decreasing the heat input generated by the TIG source can also be a feasible option of lowering the temperature, but with a certain consequence in reducing the productivity of the hybrid process.
Thus the most advantageous variant of temperature reduction in the hybrid process is represented by decreasing in the rotational speed. But it should be taken into consideration that with decreasing in the temperature also the process productivity will be decreasing due to increasing in plastic stress of the copper, so it must be prioritized the quality or the productivity of the weld according to the application in which it is used. However, analyzing the plunging force exerted on the parts for the two processes, it is noticed that this is not very much increased for the classic process (0.85 KN) although the temperature of the parts is up to 392 ° C lower. This indicates a slight variation of the plastic stress in the analyzed temperature range and thus possibility to achieve hybrid FSW joints at low temperatures with high productivity. In the literature was also analysed the TIG assisted FSW with forced cooling which presents improved mechanical properties of the joint, but for dissimilar materials. An approach that can be also used for copper weld, especially that the microhardness values determined for the specimens that benefited of a faster cooling has shown superior values and this variant does not significantly affect the productivity of the process.

4. Conclusions
As a result of the researches carried out, the following main conclusions are presented:

1) The temperature is increasing with increasing of tool rotational speed and decreasing of the welding speed, thus respecting the laws of variation presented in the literature.

2) The axial force used in the experiments has an approximately equal value for all experiments, fact that indicates a slight variation of the plastic stress in the analysed temperature range.

3) Decreasing the heat input leads to equal or even higher microhardness of the welds as compared to the base material and also to higher values of tensile strength. The best properties of the welded joints of Cu made in these researches were recorded for experiment 2.

4) Most advantageous way of increasing the mechanical properties of the hybrid process, with less influence on its productivity, is the decrease of the rotational speed.

5) Forced cooling of the welded joint represents another way of increasing the mechanical properties of the hybrid process with minimal influence on its productivity.

On future researches, the indicated changes on the process parameters and the forced cooling will be experienced and analysed for TIG assisted FSW of pure copper plates.

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5. References
[1] Dawes J and Thomas M 1996 Friction stir process welds aluminium alloys Welding J. 31-45
[2] Scutelnicu E, Birsan D and Cojocaru R 2011 Research on friction stir welding and tungsten inert gas assisted friction stir welding of copper Recent Advances in Manufacturing Engineering 1 97-102
[3] Mehta K P and Badheka V J 2017 Hybrid approaches of assisted heating and cooling for friction stir welding of copper to aluminium joints J. of Materials Processing Technology 239 336-45
[4] Hwang Y M, Fan P L and Lin C H 2010 Experimental study on friction stir welding of copper metals J. of Material Processing Technology 210 1667-72
[5] Xie G M, Ma Z Y and Geng L 2007 Development of a fine-grained microstructure and the properties of a nugget zone in friction stir welded pure copper Scripta Materialia 57 73-6
[6] Surekha K and Els-Botes A 2011 Development of high strength, high conductivity copper by friction stir processing Materials and Design 32 911-6
[7] Cam G 2011 Friction stir welded structural materials: beyond Al-alloys International Materials Reviews 56 1-48
[8] Savolainen K Mononen J Saukkonen H and Koivula J 2005 Friction stir weldability of copper alloys Tribologia 24 15-33