Experimental investigations of tungsten inert gas assisted friction stir welding of pure copper plates

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Abstract. Welding copper and its alloys is usually difficult to join by conventional fusion welding processes because of high thermal diffusivity of the copper, alloying elements, necessity of using a shielding gas and a clean surface. To overcome this inconvenience, Friction Stir Welding (FSW), a solid state joining process that relies on frictional heating and plastic deformation, is used as a feasible welding process. In order to achieve an increased welding speed and a reduction in tool wear, this process is assisted by another one (WIG) which generates and adds heat to the process. The aim of this paper is to identify the influence of the additional heat on the process parameters and on the welding joint properties (distribution of the temperature, hardness and roughness). The research includes two experiments for the FSW process and one experiment for tungsten inert gas assisted FSW process. The outcomes of the investigation are compared and analysed for both welding variants. Adding a supplementary heat source, the plates are preheated and are obtain some advantages such as reduced forces used in process and FSW tool wear, faster and better plasticization of the material, increased welding speed and a proper weld quality.

1. Introduction

Friction Stir Welding is a solid state joining process that relies on frictional heating and plastic deformation realised at the interaction between a non-consumable welding tool that rotates on the contact surfaces of the workpieces. The welding tool is positioned vertically on the material and then moved at 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].

The final disposal canister for spent nuclear fuel is the most critical application for FSW of copper. The other available welding method for sealing the corrosion barrier canister is electron beam welding (EBW). The microstructure and mechanical properties (especially tensile strength and elongation to fracture) of copper FSW welds are very similar to those of the hot worked base materials and superior as compared to EB welds [2].

The microhardness of FSW welded joints is the mechanical property most analyzed in the scientific papers. This is due, on the one hand, to the fact that microhardness depends on the microstructural changes, the grain size and the precipitation state generated by the welding process, and on the other hand, because there is a good correlation between the microhardness profile and the profile of the other mechanical properties (Rp0.2, Rm, A%, ...) [3], these correlation is making from the microhardness a marker of mechanical properties.

Research in this field has shown that FSW welding microhardness values are different depending on the nature of the joined materials. For cooper alloys' increasing the heat input leads to annealing softening and lower hardness. Lowering the heat input leads to refined grain size and eventually to equal or even higher hardness of the welds as compared to the base material [4 - 7].

The aim of this paper is to identify the influence of the additional heat generated from tungsten inert gas source on the process parameters, especially on welding speed, in order to identify the possibility of increasing the productivity of the process and on the welding joint properties (temperature distribution, hardness and roughness).

2. Experimental program

2.1. Experimental stand

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 analyzing the temperature and axial force recorded values throughout the process.

During the process, the temperature was measured by using a high-speed and high-sensitivity thermographic infrared camera (FLIR A40M). The used camera has a field of temperature measurement between -40 [^{0}C] and + 2000 [^{0}C]. The compressive force was measured with a mechanical device that has a fixed force transducer, type AM, with range between 0 [KN] and 20 [KN], assembled on the main spindle. The FSW machine and the information captured are extracted using a special soft.

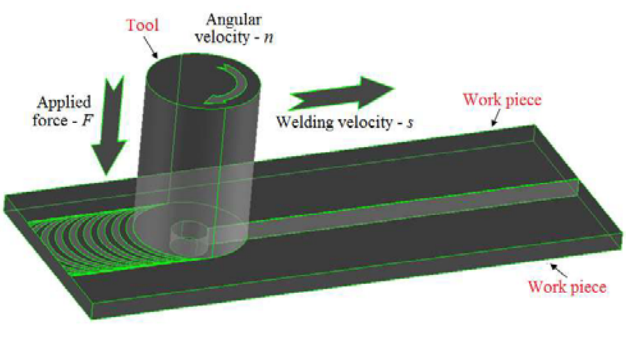


Figure 1. A schematic presentation of the friction stir butt welding process

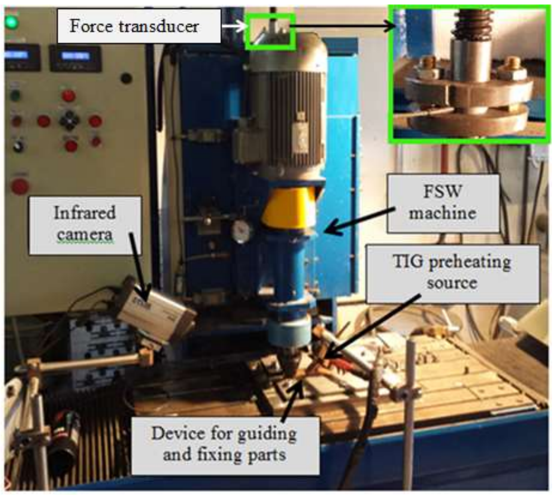


Figure 2. Experimental stand of TIG assisted friction stir welding process

2.2. Welded material

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. Other properties of copper are including high thermal and electrical conductivity, formability, and corrosion resistance [8]. Because of high thermal conductivity, welding copper and its alloys is usually difficult to join by conventional fusion welding processes but this characteristic makes it feasible for solid state joining processes such as FSW.

The effective chemical composition of the Cu-DHP (phosphorus–deoxidized copper) sheet used in the experimental program is provided in the table 1 and the effective mechanical properties in the table 2.

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 at break, A5	40 %

All the workpieces were cut by having the same rolling direction and more precisely with the side which the joint will be made parallel to the rolling direction of the initial blank, figure 3.

2.3. *Welding tool*

The welding tool used has a classical monoblock structure with conical pin and is made of **P20+S** (carbide of sintered tungsten), figure 3.

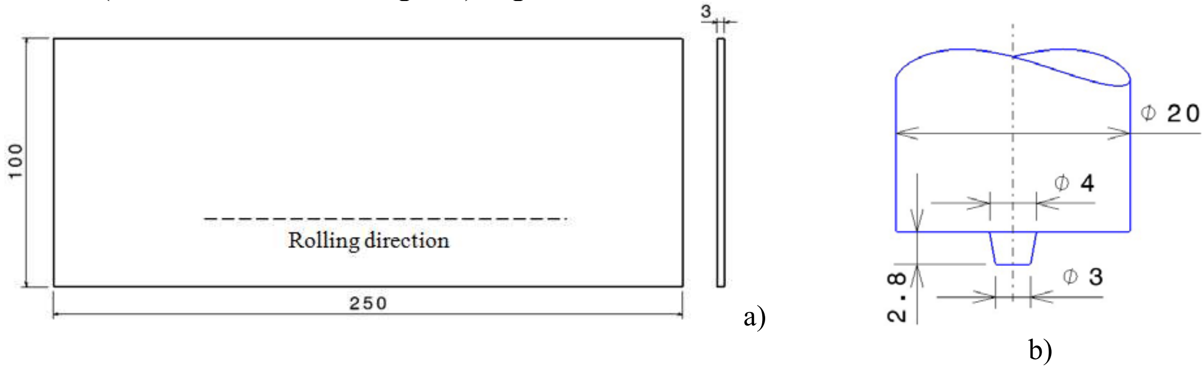


Figure 3. Geometry and dimensions of the workpieces (a) and of the welding tool (b)

2.4. *Experiments*

The experiments on FSW and TIG assisted FSW processes were developed for butt welding Cu-DHP sheets, table 3. The process' parameters which were varied are the rotational speed of the tool [rpm] and the welding speed [mm/min].

Table 3. Experimental plan of FSW and TIG assisted FSW processes

Exp. Nb.	Rotational speed [rpm]	Welding speed [mm/min]	TIG welding current [A]	Exp. Cod.
1	800	150	-	I.6
2	1200	150	-	I.3
3	1000	250	100	II.3

2.5. *Sampling of specimens*

From the welded joints, samples were cut for macroscopic and microscopic analysis, for measurement of microhardness and roughness, but also for traction and bending attempts. This paper presents and analyzes the results regarding the distribution of temperature, axial force, hardness and roughness values resulted from experiments. The relative positioning of the samples which microhardness and roughness were measured according to the geometry of the welding bead is shown in figure 4 and figure 5. These were cut from the beginning and from the end of the joint for highlight how microhardness and roughness are affected by process stability and local process parameters.

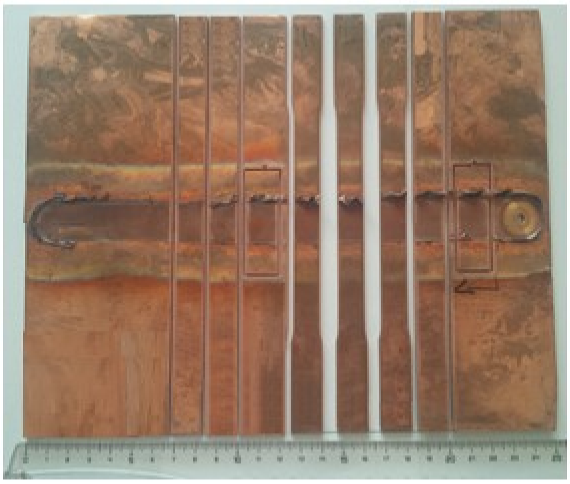


Figure 4. Photo with the samples cutted from the resulting welded joint

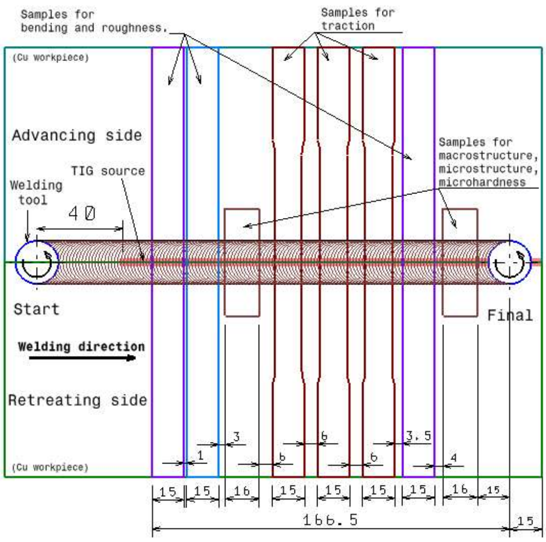
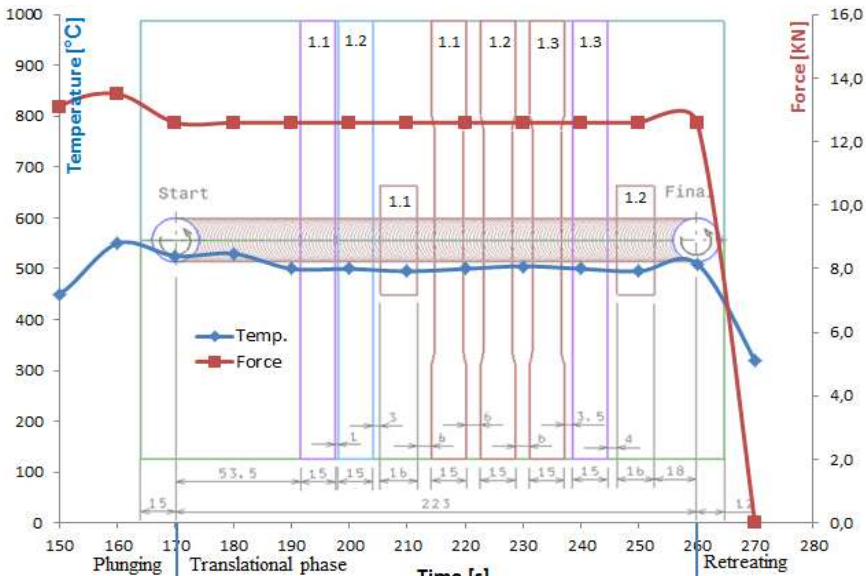


Figure 5. The relative position of the specimens used to determine microhardness and roughness

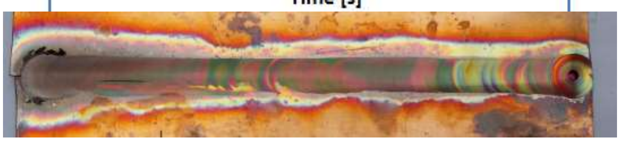
3. Results and discussions

3.1. Temperature and Plunging force analysis

In order to highlight the local conditions which the joining was made in the areas where the microhardness and roughness was determined, but also to highlight the moment from which the values of the compressive force become approximately constant during the experiments (and more precisely the moment when the process becomes stable), the two process parameters, the temperature and the axial force, were represented on the same diagram, having as background the specimen sampling scheme, figures 6 - 8.



(a)



(b)

Figure 6. Experiment 1: (a) evolution of the temperature and axial force during FSW process; (b) welded joint.

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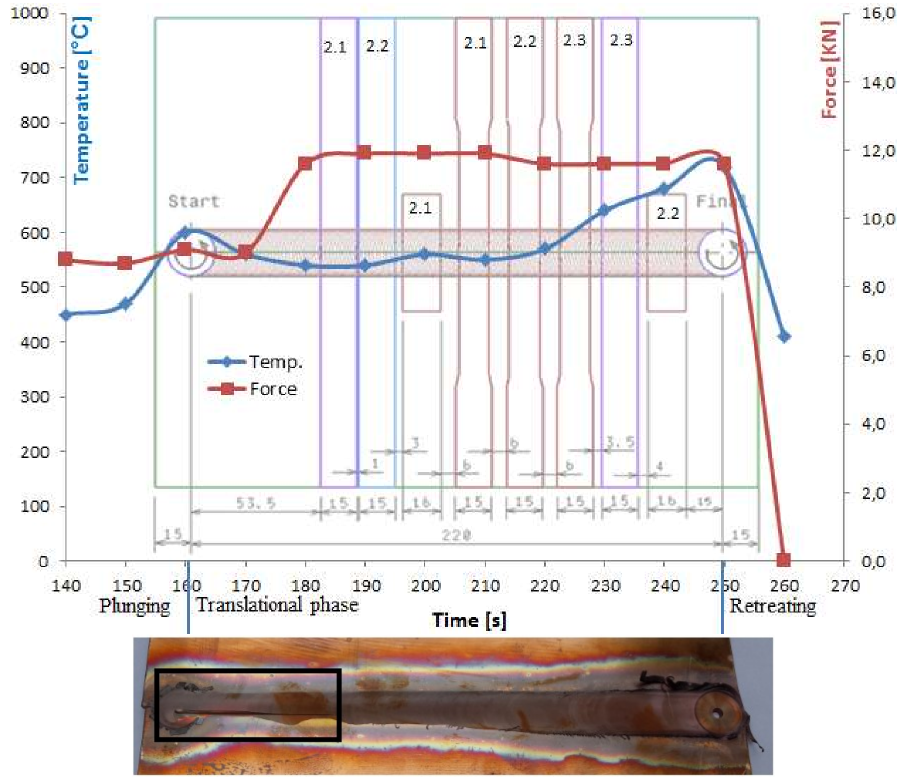
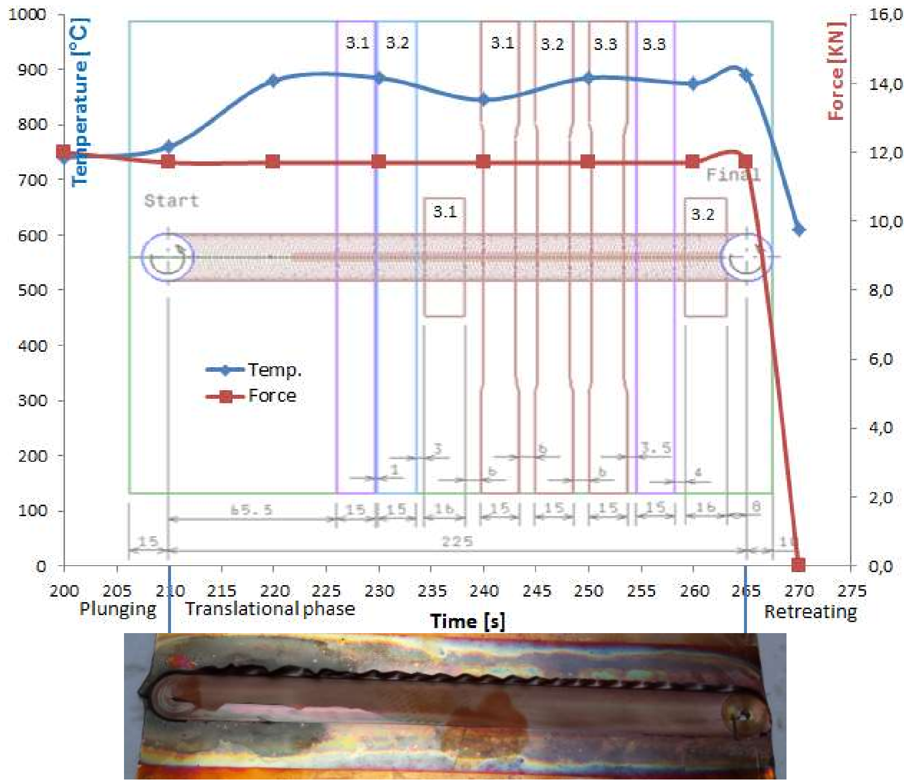


(a)

(b)

Figure 7. Experiment 2: (a) evolution of the temperature and axial force during FSW process; (b) welded joint.



(a)

(b)

Figure 8. Experiment 3: (a) evolution of the temperature and axial force during FSW process; (b) welded joint.

The analysis of evolution for the two process parameters (temperature and axial force) from the previous diagrams, highlights the following aspects:

- Temperature in FSW process increases with increasing tool rotational speed. The values average temperature recorded during the three experiments were: 506 ˚C for experiment 1, 596 ˚C for experiment 2 and 860˚C for experiment 3. The highest temperature was found, as expected, in TIG assisted FSW process.

- The compressive force decreases with increasing tool rotational speed (from about 13 kN in experiment 1 to about 12 kN in experiment 2). And also additional heat input (experiment 3) presenting a slight decrease in the value of the compressive force. Compressive force plays a very important role in development of FSW joints without defects, figure 7 show that the channel defect is eliminated only after increasing the compressive force.

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. These samples subsequently have been 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.

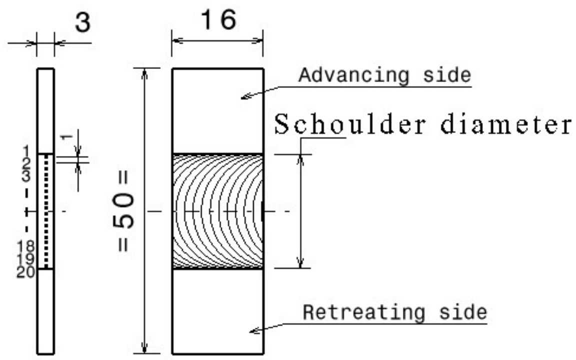


Figure 9. The location of points selected for the microhardness measurement test

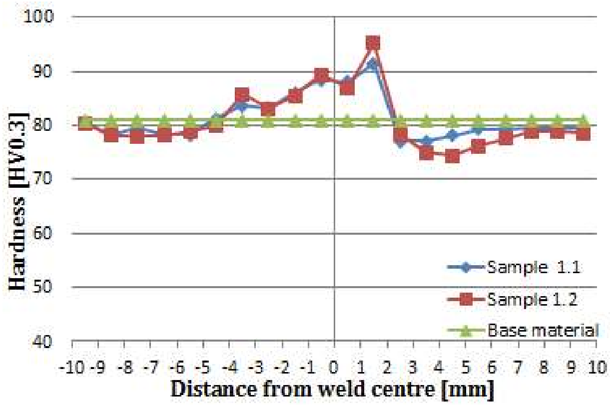


Figure 10. Measured microhardness profile of Experiment1

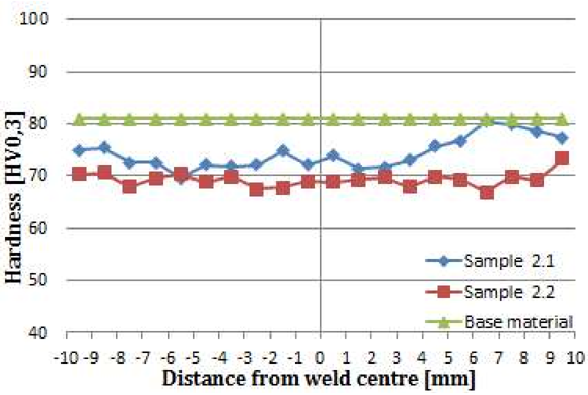


Figure 11. Measured microhardness profile of Experiment 2

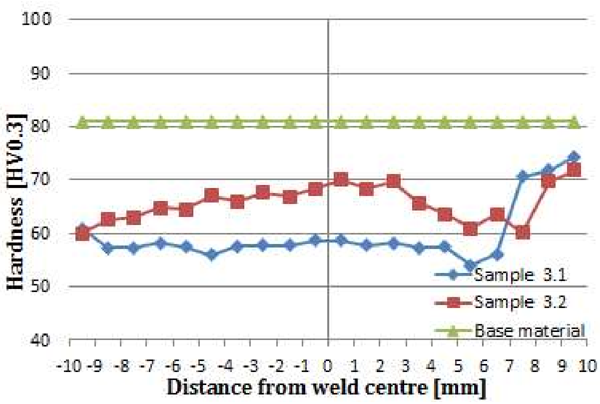


Figure 12. Measured microhardness profile of Experiment 3

Two competitive mechanisms are influencing the hardness of copper FSW welds: anneal softening and grain refinement. The weld hardness depends on the state in which the base material is found (annealed or work-hardened) as well as the heat input generated in the process. Heat input increases with increasing tool rotational speed and decreasing welding speed and leads to annealing softening and lower hardness, figures 11 and 12. So, the lowest values of the hardness were identified for the hybrid process in which the temperature recorded presents the highest values (experiment 3). Lowering the heat input leads to refined grain size and eventually to equal or even higher 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 which the determination was carried out, is ascertained the following:

- In experiment 1, there are no differences between the measured values on the sample taken at the beginning of the joint compared to the one taken at the end of this. This can be correlated with approximately equal values of the process temperature in the two areas;
- In experiment 2, the values measured on the sample taken at the beginning of the joint are slightly higher than those measured on the sample taken from the end of the joint. This is explained by the temperature differences in these two areas, lower in the beginning and higher to the end.
- In experiment 3, the values measured on the sample taken at the beginning of the joint are lower than those measured on the sample taken at the end of the joint. Although the temperature values in the two areas are approximately equal, these differences can be attributed to different cooling rates (at the end of the process, the additional TIG heat input being interrupted).

No rule of variation of the measured values on the advancing side compared to those measured on the tool retreating side has been identified.

3.3. Roughness analysis

Roughness measurement has been made on three samples for each welded joint, two from the beginning of the joint and the other from the end, figure 5. The roughness of samples was measured with the electronic roughness tester, type MarSurf PS 10. The measurements have been made in the same direction as the welding direction. For each sample there was made three measurements, the values shown in figure 13 representing their average.

Average roughness values show similar evolutions to those of microhardness, heat input also having a defining role in the variation of this parameter. So, with the temperature increase in the process, the material is more deformed and consequently has higher roughness. The smallest values is corresponding to the experiment 1 (with the lowest process temperature) and the highest values to the experiment 3, which benefits of additional TIG heat input.

Between the measured average values of roughness no dependence was identified according to the position of the sample.

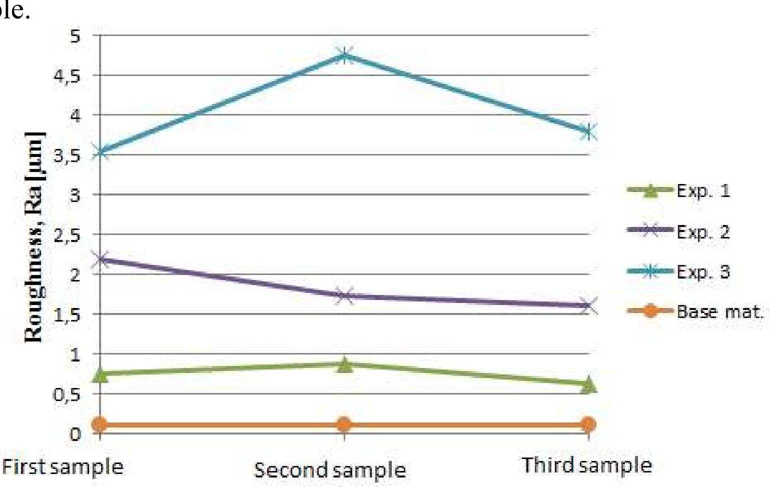


Figure 13. Measured rugosities for the experiments

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4. Conclusions

As a result of the researches carried out and the analyzes presented above, the following main conclusions are presented:

1) The best properties of the welded joints of Cu made in these researches were recorded for experiment 1, using the smallest process parameter values (rotational speed & welding speed).

2) Adding a supplementary heat source, the plates are preheated and are obtained some advantages such as reduced forces used in process and FSW, tool wear, a faster and better plasticization of the material, increased welding speed at speeds up to 2 times higher than in FSW processes. However, in case of copper, this additional heat also brings some disadvantages to the properties of the welded joint, such as the decrease in the microhardness and the increase in the roughness of the material.

3) The increasing heat input leads to annealing softening and lower hardness. The lowering heat input leads to refined grain size and consequently to equal or even higher hardness of the welds as compared to the base material.

4) Also, heat input has a defining role in the variation of roughness. As the temperature rises, the material is more deformed and presents higher roughness.

In the next researches, this study will be extend to a larger set of parameters and it will be analyzed the cooling effect on properties of TIG assisted FSW joining for pure copper plates.

Acknowledgements

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