Aspects regarding friction stir welding of Cu99 copper

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1. Introduction

Welding of copper is difficult using conventional fusion welding process, due to very high thermal conductivity that is 10-100 times higher than that of steels and of nickel- based alloys.

From this reason, the quantity of heat necessary in the process is very high, that determine using a relatively low welding speed.

For the welding of copper and its alloys, the friction stir welding is an alternative for these methods.

Until this moment studying the welding of pure copper and its alloys was quite limited in the FSW field. It is very important to choose the correct welding parameters, material and geometry for the welding tools, as well as theoretical understanding of factors that have influence on the weldability of copper and its alloys.

Analyzing the FSW welding of copper the following aspects are retained:

• First, the material and welding tool geometry exerts a significant effect on the feasibility of the welding process on sheet copper, especially for thick ones [1], [2].

• Welding parameters have a considerable influence on the quality of the welded joint [3].

• Specialists' opinions are different regarding the micro-structural zones. While some researchers confirm the existence of three microstructural zones in FSW joint of pure copper [1], others say that in the FSW welded joints for copper distinct TMAZ thermomechanicaly affected zone does not appear [4].

2. Materials to be welded

Chemical composition of Cu 99 sheets is presented in Table 1 and mechanical characteristics in Table 2.

Table 1. Chemical composition of Cu 99

Alloying element	Cu	Zn	Al	Si	Mg
Percent (%)	98.80	0.1458	0.0326	0.0235	0.008

Table 2. Mechanical characteristics of Cu 99.

Characteristics	Value
Mechanical resistence, R_m	260 MPa
Ultimate strength, $R_{p0.2}$	206 MPa
Vickers hardness, HV_1	85 HV1
Elongation, A_5	40 %

Copper is a metal with a low hardness and density of 8.96 g/cm^3. Having a good heat and electrical conductivity it is the second after silver in terms of electrical conductivity and thermal conductivity.

Copper presents high melting point (1083°C), which causes a restricted use as pure metal. It can be easily allied with other metals: Zn, Sn and Ni, forming alloys: brass, bronze, respectively constantan, with improved properties and low melting points. Copper is very malleable and can be easily laminated (thin copper foil are blue-green).

As areas of use, the following, can be presented: valves, sheet metal roofing, coins, electrical cables and conductors, copper pots, printed circuit boards, manufacturing heat installations, site, statues, making car radiators, auto parts, etc.

In the experimental program for friction stir welding of copper Cu 99, that is the base of the results presented in this paper, metal sheets with thickness s = 5 mm and 250x110mm size were used.

3. Welding tools. Welding parameters

Due to the continuous widening of the possibilities for application of the FSW welding, geometry of the welding tools used to join new materials, having different thickness, but also for realization of new types of joints, was permanently developed [5].

For example, for welding of aluminium alloy sheets with thickness less than 12 mm, the most used types of tools are with cylindrical threaded pin, due to the relatively simple geometry, which provides an easy technology for their execution. Design of the welding tools based on a quantitative understanding of the material flow is not fully mastered yet.

FSW welding tools are designed depending on the welding material characteristics (chemical composition, physical and mechanical properties, thickness of materials, etc.) and have as a result the necessary information regarding:

– Establishing material for the tool;
– Welding tool geometry;
– Tool active elements sizes (tip and shoulder).

The initial estimated force intensity that develops during welding, and the correlation with the type of tools is useful in the design of tools for materials with high hardness. Such estimates are extremely useful considering plastic flow in the thermal model [7]. Errors that may result due to ignoring of plastic flow of the material in the welding tool tip area for alloys with high thermal conductivity are lower than for low thermal conductivity materials (steels). Largest errors are in the area around the vicinity of the tool (tip and shoulder), where knowledge of the actual temperature is very important to conduct the optimum FSW process.

The quality of the welds is significantly influenced by the welding parameters [6], [8]. Shoulder – tip assembly speed, welding speed, pressing force and design (geometry) of the welding tool must be optimised for obtaining homogeneous welded joints. FSW characteristics can be altered by choosing different types of welding tools and tool parameters: diameter and geometry of the shoulder and the tip.

Also, the wear resistance of the tool is a determining factor in FSW, in particular when welding hard metals.

It can be concluded that the size and shape of the welding tools, as well as the material used for making them have a decisive role in achieving quality welds.

Material characteristics for making welding tools are very important in FSW, but the choice of material depends on the welding parts material and the estimated tool life [9].

4. Experimental program welding

The experimental program for welding Cu99 was carried out on the FSW machine of ISIM Timisoara with the following features:

- tool rotation: 400 – 1450 rev/min;
- welding speed: 0 – 500 mm/min;
- tool rotation engine power: 4KW;
- fitted with monitoring system using infrared thermography.

At FSW of Cu99 the welding parameters were mainly influenced by:

- physical and mechanical properties and characteristics of the welded material;
- technical characteristics of the welding system used in the experimental program.

Due to the large forces that develop during the welding process it was necessary to limit the welding speed to below 120 mm/min.

When designing welding tools it was first considered the fact that shape design influences the heat generation, plastic flow, the forces that develop during the process and the uniformity of the welded joint. The shoulder generates the greatest amount of heat and prevents the expulsion of the plasticiezed material on welded parts, while both (shoulder and tip) affect the flow of material.

It was found that the tools with threaded tip (conical screw threaded cylindrical tip) load more quickly with copper even from the start phase of welding materials.

For this reason, there is a risk of rupture (tip shear) when the effective welding process starts.

During the FSW experiment using threaded conical tip made from C 120 steel treated at 42-45 HRC, its shearing occurred at 1mm away from the shoulder in a section comprising the bottom of the thread.

Tip shearing was due to Cu99 core material deposited on the threaded area and also onto the welding tool shoulder. Similarly, when using the tool with grooved conic spiralled tip, it broke at the beginning of the welding process. The same thing happened when using M6 threaded cylindrical tip made from heat treated steel C120 at 42-45 HRC. The tip broke at the start of the longitudinal displacement movement of the welding tool.

Taking into consideration the inappropriate behaviour when welding copper using threaded tip welding tools made from steels thermal treated to 42 – 44 HRC, it was decided to design and make tools with the shoulder made from steel and the tip made from tungsten alloys. Tools were made with a shoulder diameter of Ø20 and Ø25 mm and cylindrical tip with diameters of Ø4 and Ø5.5 mm with a length of 4.8 mm.

In the case of using the tip with a diameter of Ø4 mm (welding speed 95 mm/min, tool rotation 950 rot/min) it sheared at the shoulder level after approximately 50 mm long weld.

In Figure 1 the image resulted after the X-Ray examination is presented, in the case of using the tip with Ø5.5 mm in diameter (welding speed 118 mm/min, tool rotation 950 mm/min) and Figure 2 shows the results from the macroscopic analysis for different areas of the welded joint.

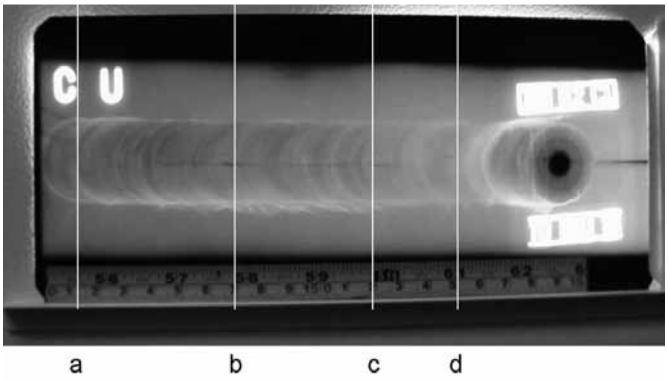

Figure 1. X-Rays testing - joint D.

The X-Ray radiography reveals areas with defects which are also highlighted by the macroscopic aspect (Figure 2a – Zone A) of the sample extracted from zone b and also zones without defects placed at the start and at the finish of the welded joint (Figure 2b).

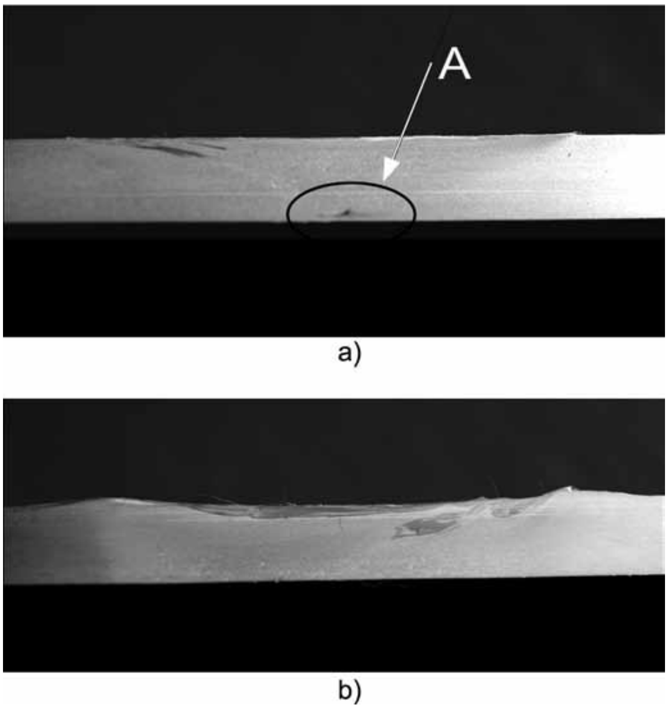

Figure 2. Macroscopic aspect of the joint.

Areas with tunnel like defect are formed due to inappropriate geometry of the tool tip, which does not favour efficient material flow and mixing (Figure 3 – Zone B).

Inconclusive results obtained at FSW of Cu99 with the tools presented have determined conception of tools with new geometries and new materials.

Welding tools were manufactured from sintered tungsten carbide P20S. The P20S material is a quaternary carbide made from a mixture of tungsten carbides WC, titanium carbides TiC, tantalum TaC, niobium NbC and cobalt CoC carbides.

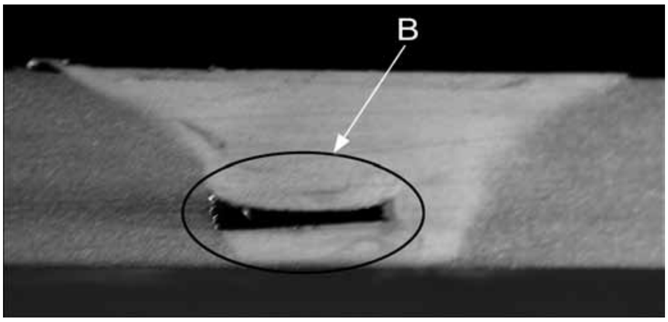

Figure 3. Macroscopic analyses - joint C.

If the non-sintered material in the form of powder has a density of 2.65 g/cm^3, after sinterization at 1400^{o}C the obtained material has a density of 12.05 g/cm^3.

P20S material has a hardness rating of 1500 HV and maintains its properties up to 1200 - 1300^{o}C and is very resilient to wear.

Due to this material, the adherence factor of the copper in the active areas of the welding tools has reduced significantly.

The following shape and geometry of welding tools were used:

– Tool shoulder - smooth with diameters of Ø20 mm and Ø18 mm;

– Tool tip - smooth conical with a length of 4.8 mm.

Very good results were obtained using the following technological parameters values: welding speed 80-118 mm/min, welding tool rotation 950 – 1000 rot/min, welding tool with a shoulder diameter of Ø20 mm and smooth conical tip with a length of 4.8 mm.

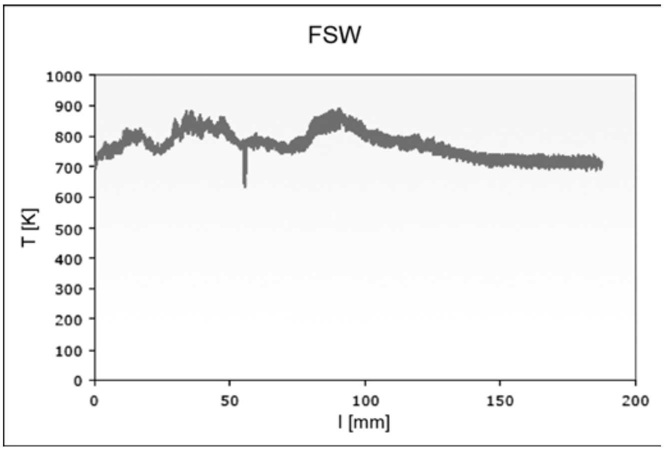

Figure 4. Variation of the temperature during the FSW welding process of Cu99.

Monitoring of the welding process was performed using infrared thermography technique, which provided real-time information on the quality of the welded joints [10]. For each welding experiment using both optimized welding tools and technology (which have obtained the best characteristics of the welded joints), the infrared thermography system has provided data on the stability of the welding process and the average temperature optimum, by which the actual process of welding was conducted.

Figure 4 shows the temperature variation during the welding process, recorded with the infrared thermography camera.

The average temperature value measured during the stabilized welding process was approx. 525^{o}C and the peak temperature reached cca. 610^{o}C.

The macrostructure of the obtained welded joints certify that welds without defects / imperfections and with a well-consolidated nucleus have been obtained (Figure 5).

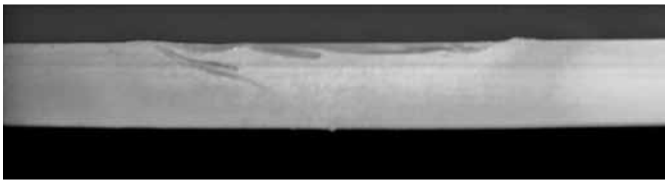

Figure 5. Macrostructure of the FSW welded joint of Cu99.

The performed microstructures revealed that the base material has a structure made up of polyhedral (twinned) grains with annealing twins (see Figure 6).

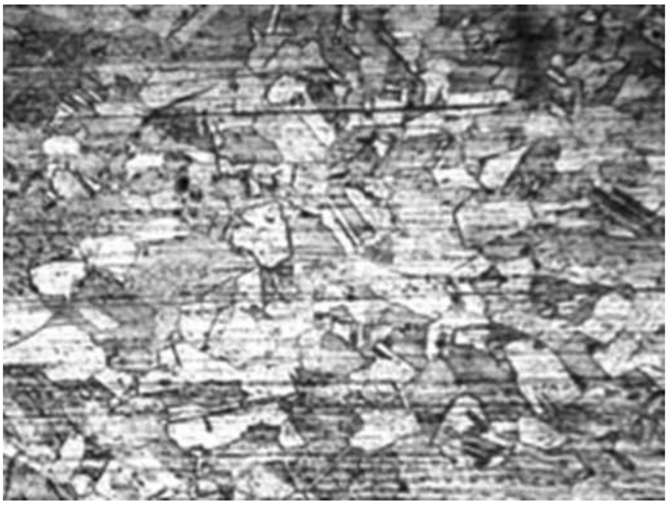

Figure 6. Microstructure of the base metal (MO, 100x).

In the heat affected zone, the structure presents the specific characteristics of high temperature, which led not only to a beginning of recrystallization, but also to grain size increase, compared to the base material (Figure 7).

Figure 7. Microstructure of the heat affected zone (MO, 100x).

Analyzing the heat affected zone that is related to the advancing part of the tool, respectively to the withdrawing part of the tool, no significant differences are observed. The zone affected by both heat and strain (on the withdrawing part of the tool) has a fine structure, with flowing strips, where the grains were strongly deformed on the direction of flow of the material (Figure 8).

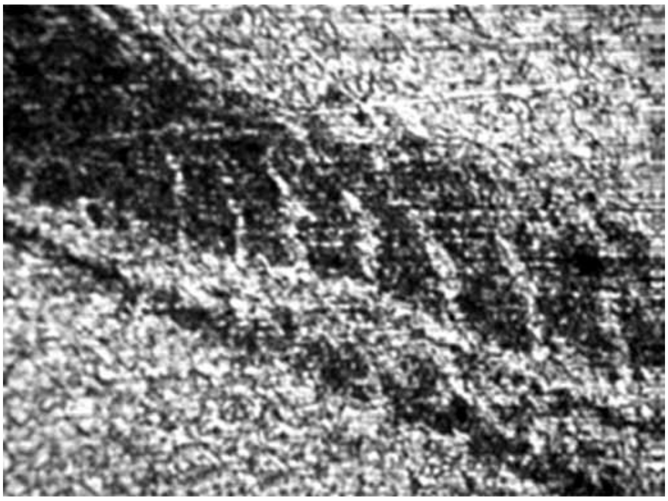

Figure 8. Microstructure of the zone affected by both heat and strain (MO, 100x) on the withdrawing part of the tool.

The zone affected by both heat and strain (on the advancing part of the tool) has a fine structure, with flowing strips, where the grains were strongly deformed on the direction of flow of the material, similar to that of the withdrawing part of the tool (Figure 9). Typical for this zone is the serrated form of a part of the material entrained in the flow.

Figure 9. Microstructure of the zone affected by both heat and strain (MO, 100x) on the advancing part of the tool.

In the nucleus zone, the microstructure of the joint presents the appearance of fine grains with less plastic deformation, due to the effect of the thermal field, which has removed, by a certain extent, the effect of the strain field (Figure 10).

The evolution of hardness in the cross section marks the characteristic zones of the joint. A small reduction in hardness values in the nucleus zone was observed, due to the heat field effect developed during the welding process. In the heat affected zone, a slight decrease in hardness values is also observed. The existence of a strip of material with a slight hardening by approximately 10% (compared to the base material) was also revealed, between the heat affected zone and the nucleus area, in the thermo-mechanically influenced zone, probably as a consequence of the plastic deformation that the material was subjected to (grain finishing).

Figure 10. Microstructure of the nucleus zone (MO, 100x).

By comparing the behaviour on the static tensile test, it was found that the ultimate strength of the welded joint was 97% of the ultimate strength of the base material. Static bending test showed that the welded joints presented a maximum degree of deformability (similar to the base material).

The very good results that have been obtained with the welding of copper 99 are due to the optimised welding parameters, the material the welding tool was made of (which contributed to the attenuation of the phenomenon of adhesion of copper onto the active surfaces of the tool), as well as, last but not least, the geometry of the tapered smooth pin tool, made of sintered tungsten carbide.

5. Conclusions

● The experimental program for welding of Cu99 copper alloy sheet, of 5 mm thickness, showed that joints free of defects and with good mechanical characteristics can be obtained, if the following conditions are provided:

– A welding tool made of P20S material is used, having a smooth tapered pin, length 4.8 mm, and smooth shoulder, diameter Ø20 mm;

– Optimal welding parameters are applied;

• Tool rotating speed n = 950-1000 rev/min;

• Welding speed v = 80-118 mm/min;

• The average temperature during the FSW process on the surface of the welding parts must be kept approximately 550^{o}C.

● It is necessary to pay particular attention to the contriving and design of the welding tools, in terms of geometry, dimensions, as well as materials of which they are manufactured.

● It is recommended to avoid thread or groove-machined pin of the welding tool, in order to avoid the pin to get charged with copper. Charging copper onto the tool can cause quick snap of the pin.

● The dimensions and geometry of the tool (shoulder and pin) must be correlated with the nature and thickness of the material to be welded, as well as with the optimum welding parameters (welding speed and tool speed).

● It is recommended that the welding tool is made of materials that can withstand high temperature (about 1000^{o}C) and reduce the tendency of charging up with copper. From this point of view, P20S carbide is a viable solution for the manufacturing of tools for welding copper, providing good durability.

- Experimental research programs have shown that tapered smooth pin tools sized appropriately for each specific application and made of sintered tungsten carbide can be viable solutions for welding overlapped sheets of copper alloys.
- Monitoring of the welding was conducted with infrared thermographic technique, which provided real-time data on the quality of the performed welded joints (data on the stability of the welding process and optimum average temperature, by which the actual welding process was conducted).
- The obtained results can promote industrial applications in the domains: automotive, electrical, rail and water transport, aircraft and food industry.

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