Improving the quality of Cu99 welded joints using friction stir welding process in shielding gas environment

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1. Introduction

Copper welding is difficult to be achieved by using conventional fusion welding processes, due to the very high thermal conductivity, which is 10-100 times higher than steels and nickel alloys.

That is why the amount of heat required to be introduced into the process is very high, which determines a very low welding speed.

As an alternative to these processes, the friction stir welding process FSW can be also used for welding copper and its alloys.

Until a few years ago, the study of welding pure copper and copper alloys was limited in the field of FSW. It is very important to choose the correct welding parameters, the material of the welding tools and their geometry, as well as the theoretical understanding of the factors that influence the FSW weldability of copper and its alloys.

Using the FSW process can bring important benefits. For example, compared to TIG welding, the FSW welding produces net lower residual shrinkages and angular deformations, which recommend this process for the manufacture of parts and subassemblies with good dimensional accuracy.

When FSW welding copper alloys, strength characteristics comparable to those of the base metal are obtained.

For FSW welding of pure copper, the tensile strength is slightly lower than in the base metal [1-4]. The strength of FSW joints for copper increases with the decrease of the tool shoulder diameter and the tool rotation speed, respectively with the increase of the welding speed [2].

ISIM Timisoara obtained good results when joining copper, especially by using ultrasonic welding processes [5], respectively by means of soldering and brazing [6].

FSW copper welding has been part of the ISIM Timisoara research program in recent years. Notable results were obtained by welding copper Cu99, but also in joining pairs of dissimilar materials [7]-[9].

In order to improve the quality of welded joints, ISIM Timisoara proposed the development with its own contributions of the FSW welding method in inert gas environment (FSW - IG).

This paper presents the comparative results obtained by ISIM Timisoara within an experimental research program, aiming in welding the classical FSW, respectively FSW - IG of copper Cu99.

2. FSW welding in inert gas environment

ISIM Timisoara has notable contributions in the development of the FSW process, including through the proposal and development of new methods of application (of the procedure):

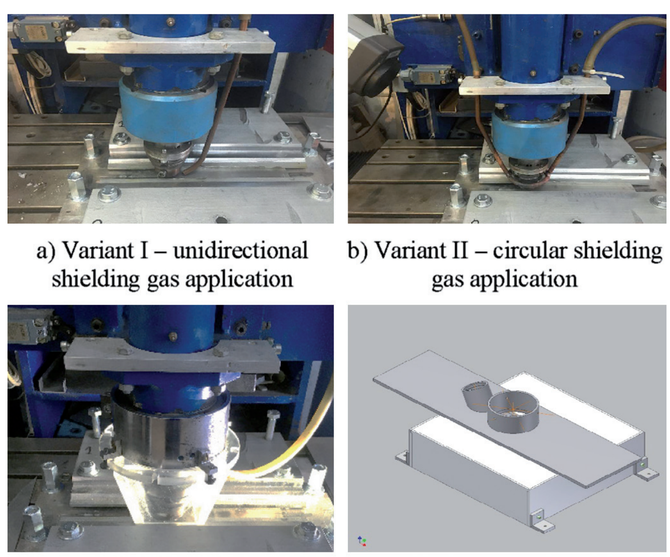
- FSW-TIG welding (Patent No.123349/28.10.2011)
- FSW-US welding [10].

It has been shown that these extensions of the friction stir welding process FSW can have beneficial effects on the quality of the welded joint, provided that optimized process parameters are used, established in correlation with the characteristics of the materials to be welded.

Depending of case, it is possible to obtain: the improvement of the mechanical characteristics of the welded joints, an increase of the welding speeds and, through this, an increase of welding productivity, a lifetime increase of welding tools.

Experimenting and using the FSW-IG welding method, involves first of all the provision of the necessary techniques for application: the completion of the welding machine with modules / devices, needed to ensure inert gas in the work area, assuring the conditions for real time monitoring of the welding process (in case of usage of the infrared thermographic technique).

To provide the supply of inert gas in the welding area, ISIM Timisoara proposed several variants of technical solutions [11], which are shown in fig. 1.



a) Variant I – unidirectional shielding gas application

b) Variant II – circular shielding gas application

c) Variant III – gas application enclosure, mounted on the main shaft of the FSW machine

d) Variant IV - gas application enclosure, mounted on the table of the FSW machine

Figure 1. Variants of technical solutions for gas application to FSW-IG.

For FSW-IG welding of copper Cu99, the constructive solution shown in fig.1c was used.

Within a research project (which is underway), ISIM Timisoara has developed experimental research programs to analyze the effects of applying the FSW welding method in inert gas environment (FSW-IG) to materials with very different properties, characteristics and uses:

- - Cu99 - copper;
- - DD13 - steel;
- - TiGr2 - titanium alloy;
- - AZ31B - magnesium alloy,

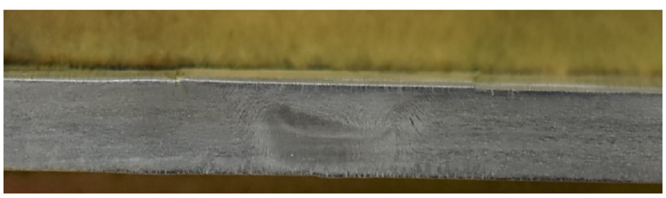
in order to compare the performances of welds made using FSW-IG with those made by the classical FSW process.

Figure 2 shows the macroscopic appearance of butt welds made by friction stir welding in inert gas environment, in the case of DD13 steel (fig. 2a), TiGr2 titanium alloy (fig. 2b) and of AZ31B magnesium alloy (fig. 2c).

The partial results obtained so far have highlighted positive aspects and benefits that can be capitalized by implementation in industrial applications.

a) FSW-IG welded joint - DD13 steel

b) FSW-IG welded joint - TiGr2 titanium alloy



c) FSW-IG welded joint - AZ31B magnesium alloy

Figure 2. Macroscopic appearance of FSW-IG welded joints.

The paper presents some results obtained when joining copper Cu99, by applying the two joining methods by classical FSW welding, respectively by FSW welding in inert gas environment (FSW-IG).

3. Experimental program for FSW-IG welding of copper Cu99

3.1. Welding materials and process parameters

For butt welding in inert gas environment, at FSW-IG shielding gas and FSW welding, a Cu99 copper sheet measuring 250 x 100 x 3 mm was used. The chemical composition of copper Cu99 is shown in tab. 1.

Table 1. Chemical composition of copper Cu99.

Alloying element	Cu	Zn	Al	Si	Mg
Percentage [%]	98.80	0.1458	0.0326	0.0235	0.008

Copper is a metal with a density of 8.96g/cm^3, low hardness and has a high melting point (1083^0C). It is a good conductor of electricity and heat, being second only to silver in terms of electrical conductivity and caloric conductivity. It can be easily alloyed with other metals (e.g. Zn, Sn) thus forming brass and bronze type alloys, with improved properties and lower melting points. Copper is a very malleable material and can be easily laminated, having good hot formability properties and excellent cold formability.

As joining methods, copper Cu99 can be easily joined by soldering and brazing processes, the welding being more difficult to apply (e.g. electric arc welding with shielding gas, respectively oxy-acetylene welding).

The mechanical properties of Cu99 used within welding experiments are shown in tab. 2.

Table 2. Mechanical properties of copper Cu99.

Mechanical properties	Value
Tensile strength, Rm	255 MPa
Yield strength, $R_{p0.2}$	206 MPa
Vickers hardness, HV1	85 HV1
Elongation at break, A_5	40 %
Bending angle at break	$82\text{-}89^0$

In the experimental program, as technological welding parameters speeds of 950 - 1000 rot/min were used, as well as welding speeds between 20 - 120 mm/min, the direction of rotation of the tool being counterclockwise. For the FSW-IG welding experiments, argon was used as an inert shielding gas, with a flow rate of 16 l/min. The technological parameters of welding are shown in tab. 3.

Table 3. Technological process parameters.

Process	Rotation speed n [rot/min]	Welding speed v [mm/min]	Tool rotation direction	Shielding gas flow rate [l/min]
FSW-IG	950	20-40-80	Counter-clockwise	16
	1000	20-60-90-120		16
FSW	950	20-40-80		-
	1000	20-60-90-120		-

3.2. Welding technique

An ISIM existing welding system was used (fig. 3):

- welding equipment FSW (1);
- shielding gas supply system (2);
- shielding gas enclosure (3);
- FSW welding tool (4);
- parts to be joined (5).

Figure 3. FSW welding system with enclosure type device for shielding gas application.

A detail regarding the enclosure used, to ensure the shielding gas in the welding area, is presented in fig. 1c.

Previous research has shown that the use of tools with cylindrical threaded pin, in correlation with optimized welding parameters can result in obtaining quality joints (without defects and imperfections).

The high temperatures required for the plasticization of the materials to be joined make that the critical element for welding to be the durability of the material from which the welding tool is made. The material from which the welding tool is made must ensure that the welding process can be carried out properly.

Due to the particularities of the materials to be joined, respectively their high plasticization and melting temperatures, when apply FSW-IG and FSW to welding of them, it is very important to make a right choice of the welding tools materials.

In order to be able to test and verify the effects of using shielding gas for FSW copper welding, a welding tool was used in the experimental program which proved to be a good solution only for certain process conditions / parameters that are used – tool with smooth conical pin, made of sintered tungsten carbide P20S (fig. 4).

Figure 4. Welding tool with smooth conical pin.

P20S is a quaternary carbide made by sintering at 1400^0C and contains a mixture of WC tungsten carbides, TiC titanium carbides, TaC tantalum and NbC niobium carbides, as well as cobalt Co. Table 4 shows characteristics / properties of P20S sintered carbide.

Table 4. Characteristics / properties of P20S sintered carbide.

Hardness	1500 HV
Thermal stability	$1200\text{-}1300^0C$
Wear resistance	very high
Particles dimensions	2 mm
Mechanical strength	$1650\ N/mm^2$
Sintering temperature	1400°C

Also, in order to carry out the welding process in good conditions and to obtain a suitable welded joint, it is necessary to correlate the length of the welding tool pin with the thickness of the materials to be welded.

The welding tool used in the experimental program has a pin length of 2.85 mm and a shoulder diameter of 22 mm.

3.3. Welding experiments

In order to be able to make a comparative analysis between the performance of classical FSW welding, respectively FSW–IG in the experimental program, for both welding methods the same conditions and technological process parameters were used, according to tab. 3.

The surface appearance at the top and at the root of the welded joint FSW classic and FSW-IG are presented in fig. 5 and fig. 6.

Figure 5. Surface/root appearance - welded joint FSW copper Cu99.

Figure 6. Surface/root appearance - welded joint FSW-IG copper Cu99.

Analyzing the welding surface, no visible defects are highlighted in the area of the welded joint. The different aesthetic appearance of the welded surface in an air working environment is observed (fig. 5) compared to the welded surface in inert gas environment (fig.6). It is possible that the thermal influence and the corrosion related phenomenon can be more pronounced in the case of using classical FSW, compared to FSW-IG. It was found (fig. 6) that the thermally influenced areas are more extensive compared to the case where FSW-IG was used.

The appearance at the root of the weld reveals that the weld is penetrated on the entire thickness of the sheets to be welded (in both analyzed cases).

Samples were taken from the welded joints for structural analysis and hardness measurements, as well as for tensile and bending tests, for both FSW and FSW-IG methods.

The macroscopic appearance of the FSW welded samples taken from areas where welding speeds of 40 mm/min and 80 mm/min respectively were used is shown in fig. 7. The formation of a “tunnel” type defect can be observed, defect that occurred when using both welding speeds (zones A and A´). The defect has formed at the interface between the nugget (N) and the heat affected zone (HAZ), towards the root of the weld.

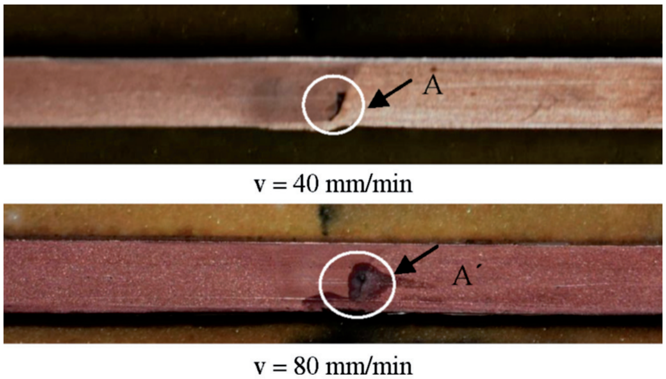


Figure 7. Macroscopic appearance of FSW Cu99 welding.

Figure 8 shows the macroscopic appearance of the welded joints in the case of using argon as shielding gas at FSW-IG welding, for welding speeds of 40, 60, 80 and 120 mm/min.

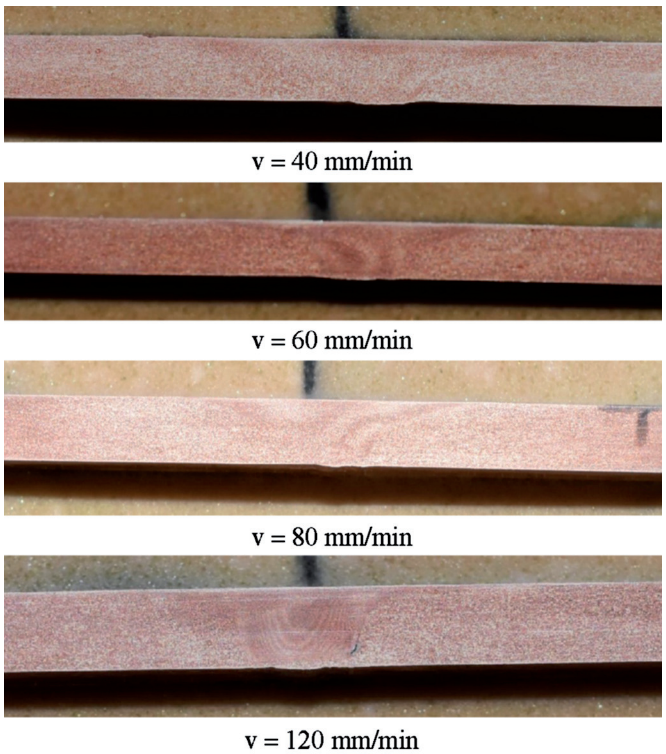


Figure 8. Macroscopic appearance of FSW-IG welds - Cu99.

Higher welding speeds compared to the conventional FSW welding process were also used, to highlight the application limits of the FSW-IG method.

Analyzing the macroscopic appearance of the joint, it can be observed that a "clean" welded joint was obtained, without defects or imperfections, for welding speeds of 40-80 mm/min. With the considerable increase of the welding speed, the formation of a defect of "non-adhesion" type was observed at the interface between the nugget (N) and the thermomechanically affected zone (TMAZ), area corresponding to the advancing side of the welding tool.

The aspect of the welds, from a macroscopic point of view, was influenced by the geometric and dimensional characteristics of the welding tool, characteristics that in the case of copper Cu99 do not favor the use of high welding speeds.

The microscopic investigations performed (MO, 100x) for the FSW and FSW-IG welded samples are presented in fig. 9.

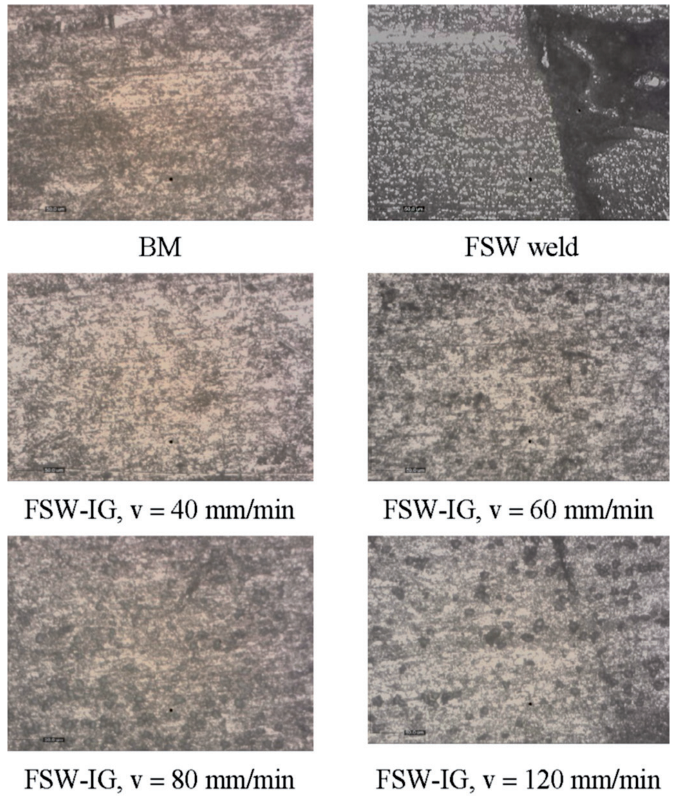


Figure 9. Microscopic analysis - FSW and FSW-IG welding.

The base material has a structure made of polyhedral grains with annealing macules.

In the heat affected zone, the structure has the specific characteristics of a high temperature, which led in addition to a beginning of recrystallization and an increase in the grain size, compared to the base material.

The thermo-deformational influenced area has a fine structure, with flow bands in which the grains have been strongly deformed in the direction of material flow.

In the nugget area, the microstructure of the joint has the aspect of fine grains, with smaller plastic deformations, due to the effect of the thermal field, which removed, to some extent, the effect of the deformational field.

HV1 hardness measurements were made in the cross section of the joint, in the median plane of the material thickness, located at 1.5 mm from the surface. The measurements were performed with a step of 1 mm, both for the welded joint area and for the base material, the measurement results being presented in tab. 5, for the FSW welded samples, respectively tab. 6 for the FSW-IG welded ones.

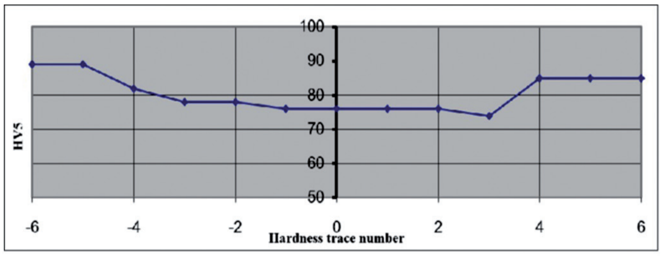
Table 5. Hardness measurement values - FSW, Cu99.

MB right Advancing side			Joint and adjacent areas							MB left Retreating side		
85	85	85	74	76	76	76	76	78	78	82	89	89

Table 6. Hardness measurement values – FSW-IG, Cu99.

MB right Advancing side			Joint and adjacent areas					MB left Retreating side		
72	74	74	72	72	69	74	72	72	72	72

The evolution of HV5 hardness is shown graphically in fig. 10a for FSW welding and in fig. 10b for FSW-IG welding of copper Cu99.



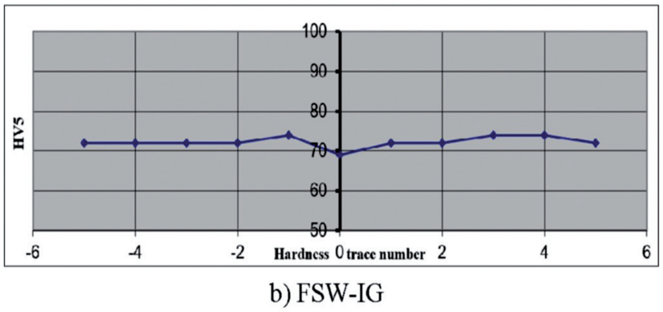


Figure 10. Hardness evolution for FSW and FSW-IG copper Cu99.

The FSW welded sample was made with a speed of 60 mm/min, and the FSW-IG welded sample, with a welding speed of 80 mm/min.

It was found that in the case of using classical FSW, in the nugget, the hardness values have lower values than those measured in the base material (by approx. 15%). In the case of FSW-IG welding, the hardness values in all areas of the welded joint have values close to those measured in the base material.

Tensile strength tests were performed for specimens taken from the joint, taken from areas where the welding speed was 40 mm/min, respectively 80 mm/min.

The aspect of the specimens, following the tensile test for the two methods, is shown in fig. 11 and fig. 12.

In general, the specimens broke in the weld, in the TMAZ or in the nugget.

In the case of classical FSW welding, it was found that the specimens broke at values of tensile strength Rm between 195-249 N/mm^2, at an average value of 227 N/mm^2, which represents ~89 % of the tensile strength of the base material (255 N/mm^2).

The highest value of tensile strength was obtained when using the welding speed of 60mm/min (249N/mm^2), with about 5.5% higher than when using the welding speed of 120mm/min (236 N/mm^2).

When welding FSW-IG, the specimens broke at an average value Rm = 254 N/mm^2, close to the tensile strength of the base material approx. 255N/mm^2. The lowest value of tensile strength was recorded at a speed of 40 mm/min.

The elongation at breaking point of the test specimens is between 20.53-22.05%, with an average value of 21.53%, which represents 53.82% of the elongation value of the base material (40%).

There are no significant differences in tensile strength and elongation, at break point, between specimens, even if they were taken from areas of the joint where different welding speeds were used.

Bending tests were performed for specimens taken from the joint, the test results being shown in fig. 13 for the use of the classical FSW, respectively in fig.14 for the case of FSW-IG welding.

Figure 11. Aspect of tested tensile specimens – FSW welding, Cu99.

Figure 12. Aspect of tested tensile specimens – FSW- IG welding, Cu99.

Figure13. Aspect of FSW specimens tested at bending – Cu99.

Figure14. Aspect of FSW-IG specimens tested at bending – Cu99.

It can be observed that the degree of deformability is maximum even at the bending test, namely with a stretched root. There were no differences in bending behaviour between the specimens, although they were taken from areas of the joint where different welding speeds were used (for both analyzed cases).

There was only one exception to FSW-IG welding when at a welding speed of 120 mm/min, there was a cracking tendency of the material in the weld (at an angle $\alpha \sim 160^0$). This may be a consequence of the high welding speed (for copper) that was used in this case.

ISIM Timisoara has developed methods for monitoring welding processes. For example, the force monitoring showed that during the welding process, depending on the process phase, the maximum values of the pressing force were: $F_{max} \sim$ 8.400 N (in the phase of penetration of the welding tool pin into the joining materials), $F_{max} \sim$ 8.500 N (at the beginning longitudinal feed for welding) and $F_{max} \sim$ 8.200 N (during the welding process).

In the case of FSW-IG welding, Fz force values were obtained, close to those measured for classical FSW welding.

4. Conclusions

The experimental researches for FSW-IG welding of copper Cu99 were developed on the working technique conceived and realized at ISIM Timisoara.

FSW experiments, respectively FSW-IG, were performed under the same experimental conditions in terms of process technological parameters.

Following the application of the two welding methods (FSW-IG and FSW), when joining copper Cu99, using the same working conditions and the same technological parameters, we can conclude that:

- when using the classic FSW welding process, at speeds of 60 mm/min and 80 mm/min, defects of "non-adhesion" or "tunnel" type were formed in the welding;
- when using the FSW-IG welding process, the joint obtained, using speeds of 20-90 mm/min, was "clean", without defects or imperfections. At high speeds (v=120 mm/min) in the welded joint at the boundary between the nugget (N) and the thermomechanically affected zone (TMAZ) a "lack of adhesion" type defect has formed;
- as a consequence of the formation of welding defects, in classical FSW welding, the tensile strength of the weld was significantly lower compared to the FSW-IG case. The very high speed (120 mm/min) favored the formation of a defect that occurred along the entire length of the weld.

Acknowledgements

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