Possibilities to apply friction stir lap welding to some couples of aluminum – copper dissimilar materials

R. Cojocaru [a*] And L. N. Boţilă [b]

National Research& Development for Welding and Material Testing - ISIM Timisoara, România

E-mail: [a]rcojocaru@isim.ro, [b]lbotila@isim.ro*

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1. Introduction

Friction stir welding (FSW) is a purely mechanical solid state joining process, which is based on frictional heating and plastic deformation of the materials to be welded, performed at the interaction between a non-consumable welding tool, which rotates on the contact surfaces of the joints. The welding tool is moved at the welding speed along the joint line. The base material, which is brought in a plasticized state, is transferred behind the tool, creating a welded joint [1, 2, 3].

The maximum temperature reached in the joints is approximately 0.8 of the melting temperature of materials to be joined. Unlike conventional friction welding, a heating effect overlaps on a mechanical mixing effect of the materials to be welded.

As a result of the friction between the welding tool shoulder and the base materials, a quantity of heat is locally released, which has the effect of plasticizing the materials to be joined. At this point, the welding tool is engaged in a translational movement by means of the welding equipment. As the rotating active element is moved in the welding direction, the material in front of the pin is softened due to conduction heating, being driven into the space behind the welding tool, left free by the advance of the tool. The back of the tool shoulder forges the deformed material, leaving behind a smooth weld (Figure 1). The local deformation process is assimilated to a continuous extrusion process along the joint length [2].

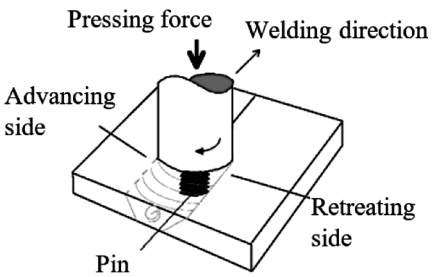


Figure 1. Principle sketch of the FSW process.

Although researches on the FSW process have intensified in recent years, it has been found that generally butt joining is studied, there is researches that have been extended to other joining geometries.

As a result, there has been increased the interest in friction stir lap welding, especially for the assembly of components and products in the aeronautical and automotive fields.

Friction stir lap welding (Figure 2) differs from friction stir butt welding by the arrangement of the parts to be joined, placed and fixed on top of each other, which involves additional complications related to ensuring of heat transfer between the two materials to be joined and the special construction of welding tool [3, 4, 5].

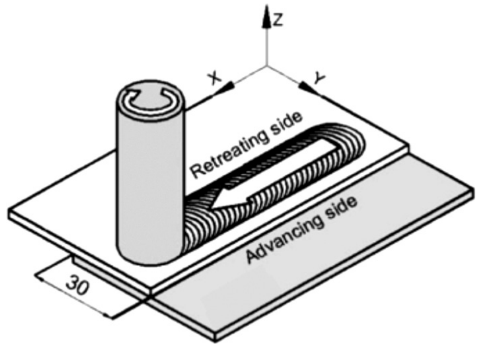


Figure 2. Friction stir lap welding.

Friction stir lap welding is becoming increasingly usable for joining of aluminum and copper components and products, replacing technologies that use fasteners. This is because rivet holes are potentially crack initiators and can also cause corrosion problems. Moreover, the elimination of fasteners contributes to the reduction of mass of components and costs reduction.

2. General considerations

Lap and butt welding are co mmon types of welding configurations.

It is important to be mentioned that the knowledge gained for friction stir butt welding cannot be fully extended to friction stir lap welding. This is because there are some particularities of friction stir lap welding compared to friction stir butt welding of sheets.

For butt welding the surfaces to be effectively welded are placed in a vertical position, while for lap welding there are placed horizontally, the interface being between the bottom part of the upper component and the upper part of the lower component.

The plastic and mechanical behavior of the materials to be welded differs completely in the case of FSW lap welding compared to FSW butt welding.

The material flow in the FSW lap welding process is the most relevant aspect for obtaining the desired mechanical properties of the welded joint. Thus, in terms of material flow, an important vertical component is required to obtain welded joints with appropriate characteristics.

As a result, the welding tools need have also other configurations and the parameters used must be reconsidered in order to obtain a proper flow of the material to ensure the lap welded joint.

When optimizing the welding process, in order to obtain the best results in terms of the amount of heat introduced into the process and the mixing effect of the materials to be welded, must be taken into account the process parameters, the geometric parameters of the tool as well as welding surfaces condition.

Current research in the field is aimed both at welding of similar materials (welding parts made of the same material), but especially of dissimilar materials (welding parts made of different materials), used mainly in the construction of parts that are specific to the aerospace industry, transports and the automotive industry.

The category of materials welded by using friction stir welding process generally includes: aluminum alloys, magnesium alloys, titanium alloys, steels, composites, copper and copper alloys.

Friction Stir Welding (FSW) is an innovative method of joining materials in a solid state at low temperatures below the melting temperature. This allows the joining of different types of metals with totally different chemical, physical and mechanical properties and at the same time avoiding the formation of intermetallic (unwanted) phases that co mmonly occur during the fusion welding process [5].

Research to date has shown that FSW process engineering depends significantly on the configuration of the joint, in other words, for different sets of process parameters it is obtained the maximize of the mechanical performance for butt joints, respectively for overlapping joints.

Friction stir lap welding requires specific fastening and tightening systems to ensure the proper relative position of the components to be welded. In order to fix the components in the case of lap welding, the tightening system must avoid any relative movement of the components during the welding process.

3. Research base / research support

The complex research programs developed at ISIM Timisoara, regarding friction stir lap welding of aluminum alloys and copper as couples of dissimilar materials, were based on the use of solid and validated application techniques, but also the results obtained by friction stir lap welding of aluminum alloys and copper as couples of similar materials.

3.1. Experimentation technique

Since 2008, ISIM Timisoara has started to use specialized welding equipments and devices within the research programs in the field of friction stir welding. Those equipments and devices for friction stir welding were developed in the frame of some research projects financed within some national research programs [6]. The equipment and related devices have been continuously improved and modernized, depending on the requirements of specific research programs (Figure 3). These have also been completed by innovative systems for real-time monitoring of friction stir welding processes (e.g. the use of infrared thermography).

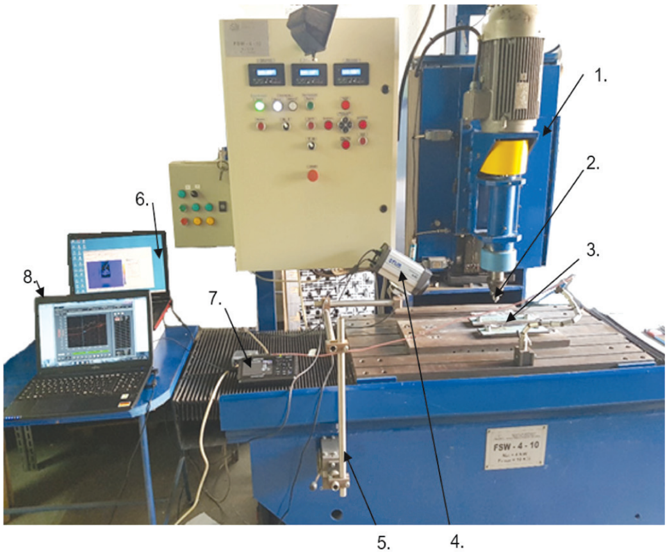


Figure 3. FSW welding complex system.

The complex welding system is composed of:
1. FSW 4-10 welding machine;
2. Welding tool with tool holder device;
3. Device for positioning and fixing of welding materials;
4. Thermographic camera;
5. Thermographic camera positioning and fixing device;
6. Temperature evolution monitoring system;
7. Fz force measurement and control system;
8. Fz Force evolution monitoring system.

Also, a wide range of constructive solutions of welding tools have been conceived and designed in close correlation with specific applications. Figure 4 shows two constructive solutions of FSW welding tools: tool with conical pin and four flat chamfers, respectively welding tool with threaded cylindrical pin.

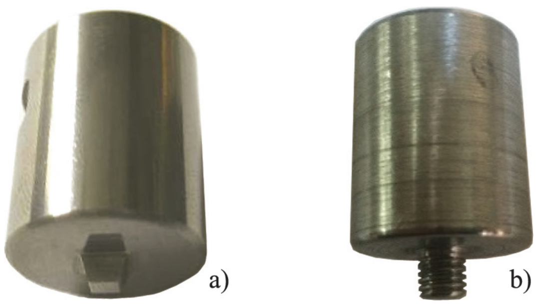


Figure 4. Constructive solutions for welding tools:
a) Tool with conical pin and four flat chamfers;
b) Tool with threaded cylindrical pin.

These tool variants are used for a wide range of couples of materials.

3.2. Friction stir lap welding of aluminum alloys

In previous research, an experimental program for welding and characterization of welded joints was developed in order to obtain results that would lead to the development of friction stir lap welding technologies for similar materials in the category of aluminum alloys.

For example, the experimental program demonstrated that the EN AW 1200 aluminum alloy with 3 mm/3 mm and 4 mm/4 mm thickness can be welded by friction stir welding process in the "overlapped sheets" variant provided that optimal welding parameters are used (Figure 5).

a) 3mm/3mm

b) 4mm/4mm

Figure 5. Friction stir lap welding of EN AW 1200 sheets.

Depending on the thickness of the materials to be welded, the geometry and dimensions of the welding tools and the process conditions, it was possible to establish optimized parameters for friction stir lap welding of EN AW 1200 sheets.

For couples of overlapped sheets of EN AW 1200 (thickness 3 mm/3 mm and 4 mm/4 mm) good results were obtained using welding tool with M6 threaded cylindrical pin (pin length 5 mm and 6.5 mm), respectively welding parameters – welding speed 70-300 mm/min and tool rotation speed 1200-1300 rpm (counterclockwise rotation sense).

The depth of penetration of the welding tool pin into the package of overlapped materials was ~83-88% of its thickness, respectively ~66-75% of the thickness of the lower sheet.

Another example of a positive result was friction stir lap welding of aluminum alloy EN AW 6082 having 6 mm/6 mm sheet thicknesses.

It has been shown that EN AW 6082 aluminum alloy (6 mm thickness) can be joined by using friction stir lap welding, if the basic conditions established by experiments, regarding the tool and welding parameters are respected (Figure 6).

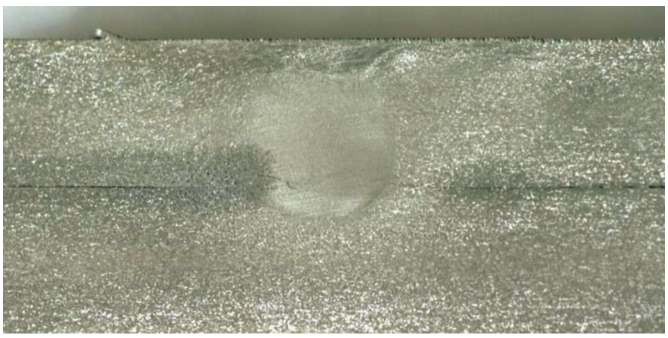


Figure 6. Friction stir lap welding of EN AW 6082 sheets (6 mm/6 mm).

In this case, good results were obtained using a welding tool with M6 threaded cylindrical pin (pin length 7.5 mm), welding speed 180 mm/min and tool rotation speed 1200 rpm (counterclockwise rotation sense).

The depth of penetration of the welding tool pin into the package of overlapped materials was ~ 75% of its thickness, respectively ~ 33% of the thickness of the lower sheet.

3.3. Friction stir lap welding of copper alloys

Other previous research has shown that for friction stir lap welding of similar Cu99 sheets (2 mm/2 mm/2 mm thickness), joints without defects (Figure 7) and with good mechanical characteristics can be obtained using:

- a welding tool made of sintered tungsten carbide P20S, with conical pin having four flat chamfers, 5.5 mm pin length and Ø 20 mm smooth shoulder (pin penetration ~ 5.5 mm in the welding materials),
- process parameters - tool rotation speed n = 1450 rpm and welding speed v = 60-80 mm / min.

In this case, the depth of penetration of the welding tool pin into the package of overlapped materials was ~ 92% of its thickness, respectively ~ 75% of the lower sheet thickness.

Figure 7. Friction stir lap welding of Cu 99 (2 mm/2 mm/2 mm).

4. Aluminum – Copper welding experiments

At ISIM Timisoara, experimental researches have been developed for the welding of couples of dissimilar materials with possibilities of application in industry.

Complex researches have been performed for the application of the friction stir lap welding process of couples of aluminum-copper dissimilar materials.

4.1. Friction stir lap welding of EN AW 1200 aluminum alloy and copper Cu 99

Joining of aluminum-copper couple of dissimilar materials is of particular interest, especially in applications that involves to make electrical connections.

The possibilities of friction stir lap welding for the combination of materials EN AW 1200 aluminum alloy with pure co mmercial copper (SR EN 573-3:2019 and SR EN 1652:2000) were analyzed.

Depending on the thickness of the "package" of the materials to be welded, a welding tool with pin length L_{pin} = 3.8-5.5 mm and smooth shoulder with diameter $Ø_{shoulder}$ = 18-20 mm was used.

Technological process parameters were used in the following ranges: welding speed v_s = 30-100 mm/min and tool rotation speed n = 1200-1300 rpm.

Samples were taken from representative areas of each welded joint, for structural analysis (macro and micro), for mechanical shear and tensile tests, as well as for static bending tests.

The best results were obtained using low welding speeds (v_s = 30 - 40 mm/min) at a tool rotation speed n = 1300 rpm, respectively using a welding tool made of sintered tungsten carbide P20S, with conical pin having four flat chamfers and smooth shoulder.

Figure 8 shows the macroscopic aspect of a welded joint made with optimized technological parameters.

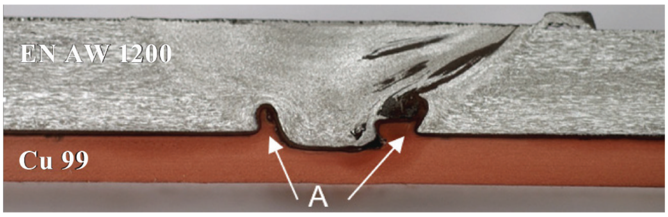


Figure 8. Macroscopic analyze of FSW weld
EN AW1200 - Cu 99.

Analyzing the macroscopic aspect, it was observed that:

- there was a better mixing of materials;
- defects in the welded joint have been considerably reduced;
- the two materials migrated to each other;
- the “mechanical fastening”, characteristic in this type of applications, was formed when applying the FSW process (areas A).

At the interface EN AW 1200 - Cu 99 appears a dark area (after attack with metallographic reagents) in which there are layers of intermetallic compounds along it, and in Cu 99 large fragments appear near the mixing area.

It was found that the hardness in the nugget, measured in the areas related to each material, have values close to the hardness of the corresponding base materials.

The shear breaking tests were performed using a specially device designed and made by ISIM Timisoara for this type of test (Figure9).

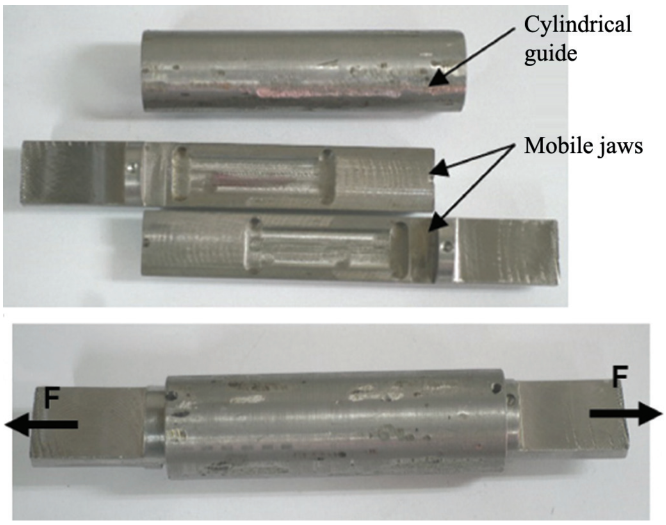


Figure 9. Device for shear breaking test.

Depending on the friction stir welding process parameters used and on the dimensional characteristics of the welding tool, values of shear strength in the range t_f = 133 - 150 N/mm^2 were obtained.

At the S-bending test, the welded joint performed very well, the specimens bending into the base materials, the weld being not affected (Figure 10).

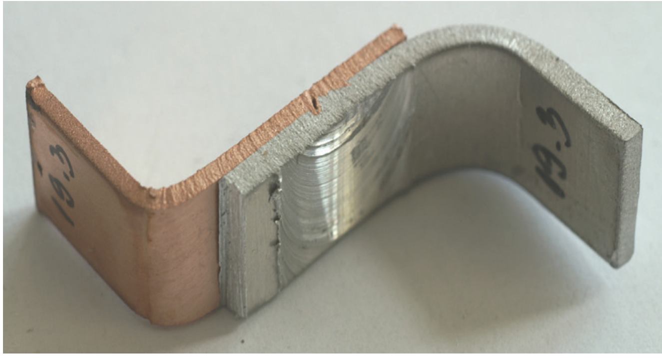


Figure 10. S-bending test (EN AW1200 / Cu 99).

The results obtained in the experimental program of friction stir lap welding of EN AW 1200 and Cu 99, demonstrate the good behavior of these materials when applying the process, respecting some basic conditions regarding the positioning of materials, welding parameters, geometry and the dimensions of the welding tool, etc.

Welding experiments were also performed, in which the positioning of materials was changed, the copper sheet being placed on top.

In this experiment, for friction stir lap welding of Cu 99 and EN AW 1200 sheets (2 mm and 6 mm thickness), a P20S tool with smooth conical pin having length L_{pin} = 2.8 mm was used. The welding parameters used were: tool rotation speed n = 1000 rpm, welding speed v_s = 20 mm/min and a counterclockwise direction of tool rotation.

Figure 11 show the macroscopic aspect of the welded joint in cross section.

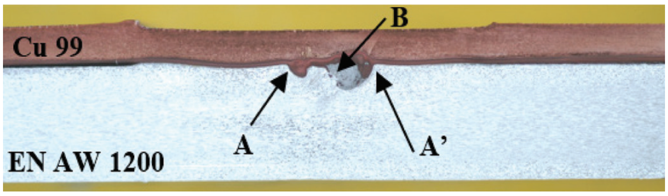


Figure 11. Macroscopic analyze of FSW weld
Cu 99 - EN AW 1200.

It is observed that a clean welded joint was obtained, without defects like “material gaps” type. There are areas where the formation of “onion rings” is distinguished, especially in the heat affected zone (HAZ), characteristic of the friction stir welded joint. It is also very clear how to “anchor” the copper (areas A, A’) in aluminum, a phenomenon that ensures mixed grip (with hybrid effect - mechanical grip - friction welding). Zone “B” was formed between the elements that ensure the mechanical fastening, probably consist of intermetallic compounds.

Tensile tests (debutonation) were performed on samples taken from different areas of the welded joint. Values of the maximum breaking force in the range F = 2520 - 3260 N, respectively breaking strengths in the range R_m = 28 - 35 N/ mm^2 were obtained.

Even if the FSW joint is “clean”, without defects, when Cu is placed on top, the shear strength is much lower compared to the case when the aluminum is placed on top.

For this reason, from point of view of the positioning of the welding materials, it is reco mmended that the aluminum be placed on top.

4.2. Friction stir lap welding of EN AW 3105 aluminum alloy and copper Cu 99

An experimental program for friction stir lap welding of the couple of materials EN AW 3105 - Cu 99 (SR EN 573-3:2019 and SR EN 1652:2000) was also performed. A P20S sintered carbide welding tool was used, with smooth conical pin having length L_{pin} = 2.7 mm and smooth shoulder of diameter $Ø_{shoulder}$ = 20 mm. The following process parameters were used: welding speed v_s = 70 mm/min and tool rotation speed n = 1200 rpm.

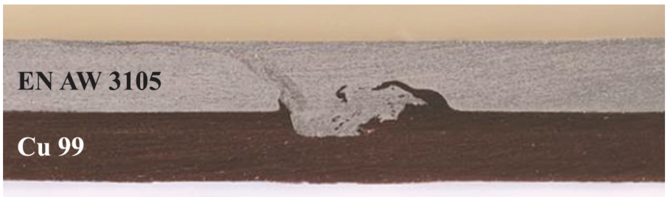
The macroscopic aspect of the welded joint was analyzed in different moments / sequences of the welding process and it was found that the nugget has a variable evolution in time, in terms of size, configuration and distribution of compounds that are characteristic of the two materials.

For example:

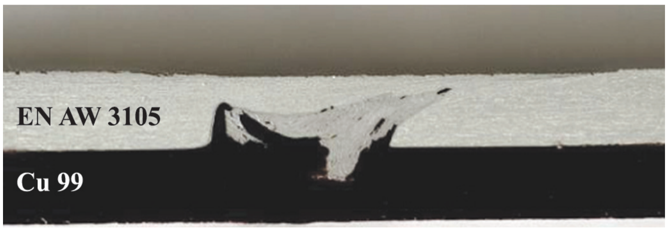
- at 60 mm from the beginning of the weld, the portion of the mixing zone (nugget) extends mainly from the aluminum alloy in copper (Figure 12a);
- after 150 mm of welding, with the increase of the temperature developed during the process, it is observed that the mixing area expands to a greater extent from the copper into the aluminum alloy (Figure 12b).

The nugget part of the aluminum alloy consists of the following areas:

- an area of the nugget, light color and placed at the top in Al,
- an area below the previous one, containing numerous particles rich in Cu and extending into the Cu base material (Figure12b).



a)



b)

Figure 12 Macroscopic aspect of FSW weld for samples taken:
a) at 60 mm from the beginning of weld;
b) at 150 mm from the beginning of weld.

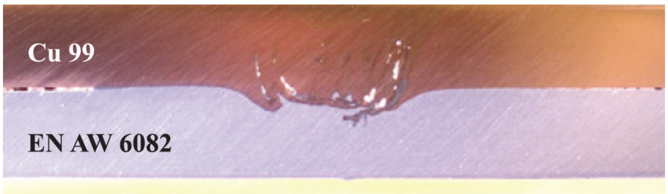
Microhardness measurements were performed in the cross section of the joined parts, in a direction parallel to the outer surfaces of the joined parts, at half on their thickness. The load used was 300 g, the step was 1 mm and determinations were made 10 points on each. Slight increases in microhardness (~15%) were found in the joint area for Cu material. The microhardness values in this area, in the Cu material are about 100 HV0.3, being slightly higher than those in the base material (approximately 87 HV0.3). Such increases were not highlighted for the Al material.

From the point of view of the residual stresses, it was found that:

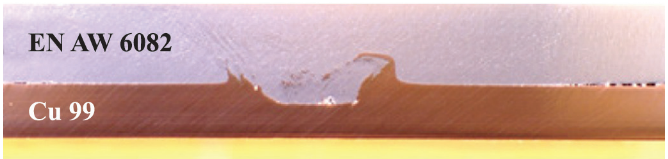
- in all measured points, there are compression;
- the residual stresses in the weld bead, in absolute value, are significantly higher in Cu than in Al and are higher than those in the base materials.

Very good results, similar to those presented in the case of friction stir welding of aluminum alloys EN AW 1200, respectively EN AW 3105 with Cu 99 copper, were also obtained in the case of couple of materials: EN AW 6082 - Cu 99 and EN AW 5754 - Cu 99 (SR EN 573-3:2019 and SR EN 1652:2000).

For example, Figure 13 presents the “clean” macroscopic aspect of the FSW welded joint, for both possible situations for positioning of the welding materials.



a)



b)

Figure 13. Macroscopic analyze of FSW weld Cu 99-EN AW 6082: a) Cu99 placed above; b) EN AW 6082 placed above.

Analyzing the macroscopic aspect, it is observed that all considerations / assessments related to the experiments presented above are also valid in this case, as well as in the case of welding of aluminum EN AW 5754 with copper Cu 99 (Figure14).

Figure 14. Macroscopic analyze of FSW weld EN AW 5754 - Cu 99.

For all couples of materials that were approached, it was found that a very important parameter with an impact on the quality of the welded joint is the depth of penetration of the tool pin into the material placed below (especially for high hardness materials). Consequently, depending on the dimensional characteristics and the nature of the materials to be welded, the optimal length of the welding tool pin is determined.

4. Conclusions

- The industrial implementation of the FSW process started with applications based on butt welding of aluminum alloys;
- The extraordinary qualities of the process encouraged the implementation for other types of joints, including the joining of overlapped sheets;
- At ISIM Timisoara, remarkable results were obtained in friction stir lap welding of aluminum alloys (e.g. EN AW 1200, EN AW 6082) and Cu 99 copper, in combinations of similar materials. In all cases, "clean" welds were obtained, without defects or imperfections;
- The experimental researches developed at ISIM Timisoara demonstrated certain possibilities for applying the friction stir lap welding of aluminum alloys EN AW 1200, EN AW 3105, EN AW 6082, EN AW 5754 with copper Cu 99;
- At all welded joints, regardless of the couple of materials aluminum-copper, a mixed joint was formed: friction welding - mechanical fastening / fixing;
- From the point of view of the positioning of the two welding materials in relation to each other, it was found that in some cases, it is more advantageous to position the aluminum above the copper;
- It was found that the following parameters and process conditions are essential for obtaining good quality welds: welding speed, tool rotation speed, geometric and dimensional characteristics of the welding tool, condition of the contact surfaces of the materials to be welded, placement / positioning of the welding materials in relation to each other;
- An essential parameter for friction stir lap welding is the length of the welding tool pin in relation to the thickness of the package of welding materials $BM_1 + BM_2$;
- Depending on the type, location and thickness of the materials to be welded, it is determined how deep the tool pin should penetrate the material below;
- Process parameters for which good results have been obtained were: welding speed with values in the range of 30-200 mm/min and welding tool speed in the range of 1000-1300 rpm, mentioning that higher speeds could be used in cases where the aluminum was placed above the copper;
- The obtained results showed that the application of friction stir lap welding to the approached couples of materials can be done with good results, implementable in production.

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