Microstructure and Properties of Copper and 5754 Aluminum Alloy Joints by Friction Stir Welding

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Welding dissimilar materials aluminum and copper by FSW are of great interest because Al and Cu are two most common engineering materials widely used in many industries. The paper analyzes the microstructure and mechanical properties obtained by butt of dissimilar material Cu - Al alloys (EN-AW-5754) by FSW. The joining by FSW process of the two samples (5 mm thickness) was performed with the pin of the tool tangential to copper plate. The values of the process parameters were the same in both cases: the rotation speed of the pin 1200 [rpm] and feed rate 60 [mm / min]. The microstructure was examined in 6 zones covering the whole thickness of the plates, Vickers microhardness was measured along a perpendicular line to the nugget and residual stresses.

Keywords: friction stir welding, dissimilar joint, microstructure, microhardness, residual stress

The use of the FSW process offers many advantages, including improved tensile and fatigue mechanical properties of the processed parts, an improved technological process, achieving the process without supplies, reducing the influence on health and environment and reduced operating costs. All these advantages have caused FSW to gain an interest in the automotive industry [1]. So far, the areas of application of FSW were located in three directions. These include extruded parts assembly to form larger elements, assembly of stamped and welded body parts, as well as assembly applications. In each of these categories FSW provides distinct advantages and reductions in production costs, which make the application of this method to be effective. Current research in the field are oriented toward both welding similar materials (welding parts are made of the same material), and especially of dissimilar materials (welding plates have different materials), mainly used in the construction of parts specific to the aerospace industry, transport, automotive industry, electrical industry.

The category of similar materials welded by the FSW method includes: aluminum alloys, magnesium alloys, titanium alloys, steel, composites, copper and copper alloys.

Using the FSW there can be joined dissimilar materials having different melting temperatures, materials which cannot be joined by other processes. Thus, different aluminum alloys are joined (aerospace industry), Al steel alloys (automotive) [2-5], Al titanium alloys, Al alloys with Mg alloys (aviation industry) [6-7], Al Cu alloys (electricity industry) [8-10]. These materials are difficult to be joined using welding methods by melting because of the great differences between physical and chemical properties, and the tendency to form fragile intermetallic compounds.

In this work, dissimilar FSW of commercial pure copper and 5754 aluminum alloy sheets was achieved and the microstructure and properties of the dissimilar joints were investigated. FSW joints were analyzed based on experimental results.

Copper has high electrical and thermal conductivity, excellent corrosion resistance, and good formability which cannot be fully utilized due to restrictions in its weldability. Copper is difficult to join using conventional fusion welding methods due to its high thermal conductivity. FSW is suitable for joining copper because the heat is created on the spot by friction between the tool and the base material [10-12].

Experimental part

In the experimental part of this investigation, the welded samples are butt joints between two plates, where the dimensions are 160 x 80 mm^2 and the thickness is 5 mm. The friction stir welds have been carried out on samples of Cu 99 and EN-AW-5754 with the composition listed in table 1.

Here, we used a cylindrical tool where the diameter of the shoulder is 20 mm and the pin is threaded M6, (fig. 1). The length of the threaded part of the pin was 4.5 mm. The

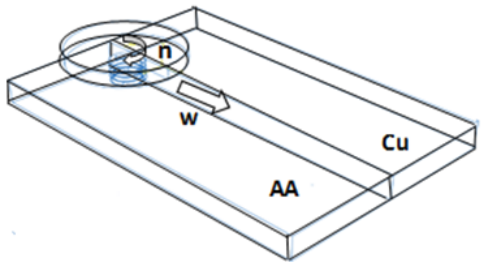

Fig. 1 Schematic illustration of dissimilar FSW

Table 1

THE ALLOY COMPOSITION (IN WEIGHT PERCENT)

Copper alloy (Cu 99)					Aluminum alloy (EN-AW-5754)								
Zn	Al	Si	Mg	Cu	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.1458	0.0326	0.0235	0.008	98.80	0.4	0.4	0.1	0.5	2.6-3.6	0.3	0.2	0.15	Rest

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joining by FSW process of the two samples was performed with the pin of the tool tangential to copper plate (in order to homogenize the heat distribution on the two materials with a different thermal conductivity). The values of the process parameters were the same in both cases: (i) the rotation speed of the pin 1200 rpm (rotation per minute), (ii) feed rate 60 mm / min.

Microstructural analysis was performed by Transmission Electron Microscopy (TEM) using the 5000-SU Hitachi microscope coupled with an EDS spectrometer for the elemental analysis of the joined area. The voltage was 25 kV and the working distance varied between 9-15 mm in Hight Vaccum MODE. The hardness was measured using the Vickers method by the equipment Falcon 500 Innovatest. It has achieved a line of hardness with the step between two fingerprints of 1 mm. To determine the residual stress there was used the method $\sin^2\psi$ with the Rigaku AutoMate II diffractometer, the tensions being determined on the crystallographic direction by normal perpendicular on the section of the test samples.

The stresses were measured along a line of 12 mm, step of 1mm, starting from the Al material, continuing with the mixing zone, and ending with the Cu material (for the butt joined parts). X-ray incident spot size was approximately 1.03 mm in diameter. For data acquisition, X-ray was used with a wavelength of CrK_α. Operational parameters of the X-ray tube were: accelerating voltage of 40 kV, filament current of 40 mA.

Results and discussions

At the surface of the joint there was obtained an Al alloy layer. The nugget area is composed of Al alloy and copper, and its structure is complicated due to the flow of the two materials.

Also, microscopic analysis revealed the existence of groove defects in the joint zone, at its top (below the shoulder of the tool).

In order to analyze the microstructure and mechanical properties, in the central zone of joined plates was taken a sample of about 20 mm thick. It was polished in section and attacked successively with Keller's etchant F.2 (950 mL water H_2O + 25 mL nitric acid HNO_3 + 15 mL hydrochloric acid HCl + 10 mL hydrofluoric acid HF) - to highlight the Al microstructure and with Alcoholic acidified ferric chloride solution E.1 (960 mL industrial meyhylated spirits + 20 mL hydrochloric acid HCl + 50 g iron chloride $FeCl_3$) - to highlight the Cu microstructure.

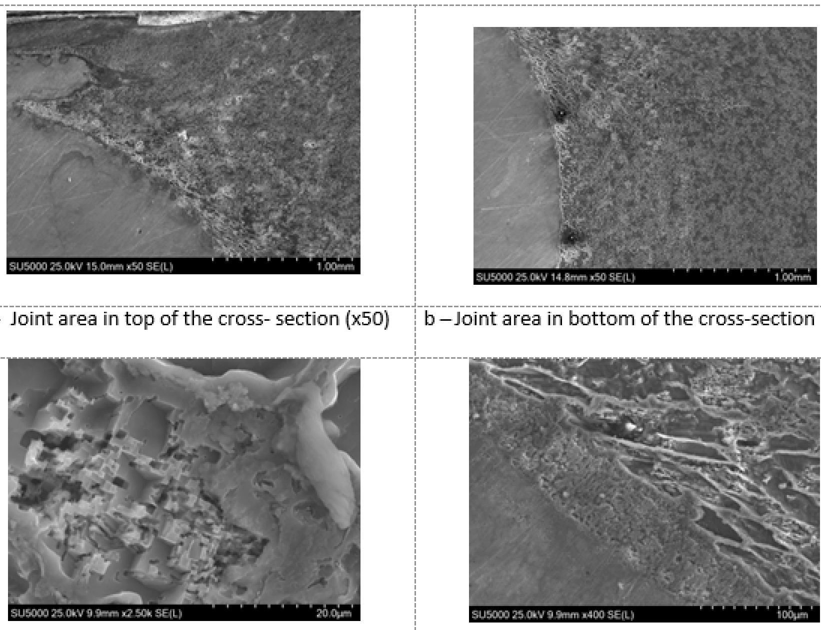
It is noted that the width of the nugget diminishes from the top surface toward the bottom of the joint, from approx. 50-60 μm to 15 μm (tending toward zero value), (fig. 2).

There were investigated several joint areas, shown in figure 3 (cross section).

The images of the nugget, obtained by microscopy are presented in conjunction with EDS analysis. Morphology of the joint area and the concentration of chemical elements in various areas (sites), located as in figure 3, are shown in the following.

In the area at the base of the joint (Site 1), there is no nugget, the two material areas are simply adjacent (fig. 4).

In the area where the width of the joint is very small (Site 2), Cu bulks are moved in the Al zone (there is no plastic deformation, Cu particles are rather broken). Aluminium concentration is 60.55% and Cooper concentration 36.72%, (fig. 5).



a - Joint area in top of the cross- section (x50)
b – Joint area in bottom of the cross-section (x50)
c - BM in Al side; (2.500 ×)
d - Joint area (x50)

Fig. 2 Morphology of the joint area

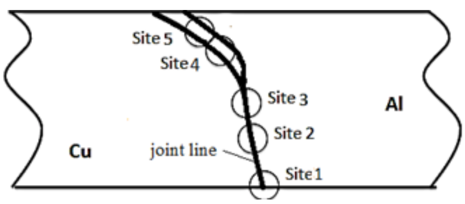


Fig. 3. Position of analyzed areas (cross section)

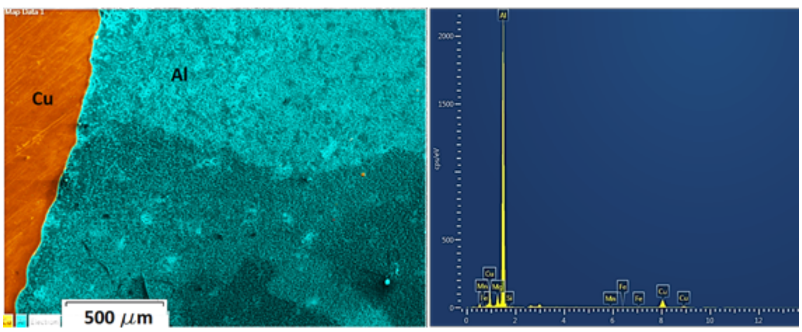


Fig.4. Microstructure and chemical composition at the base of the nugget (Site 1)

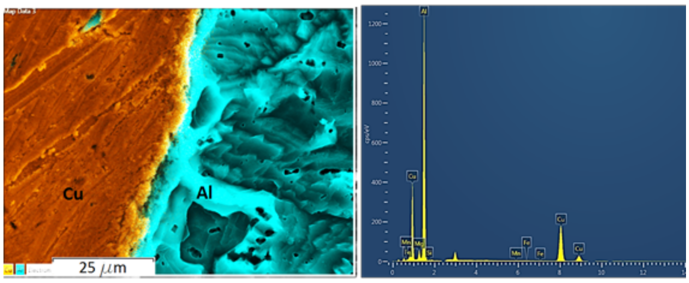


Fig.5. Microstructure and chemical composition at the base of the nugget (Site 2)

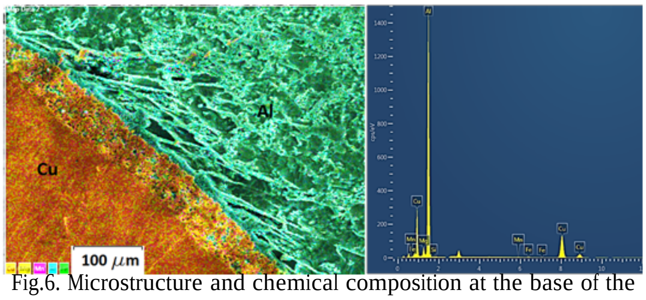


Fig.6. Microstructure and chemical composition at the base of the nugget (Site 4)

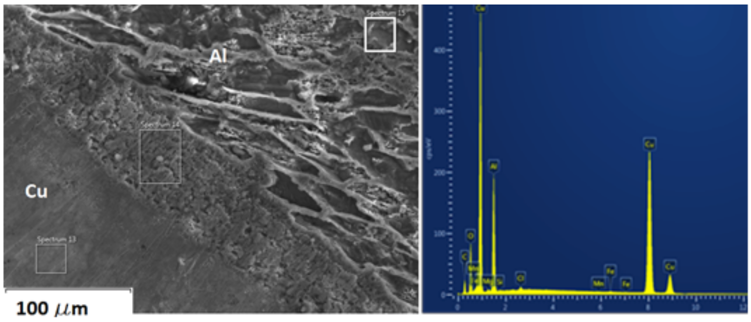


Fig.7. Microstructure and chemical composition at the base of the nugget (Site 5)

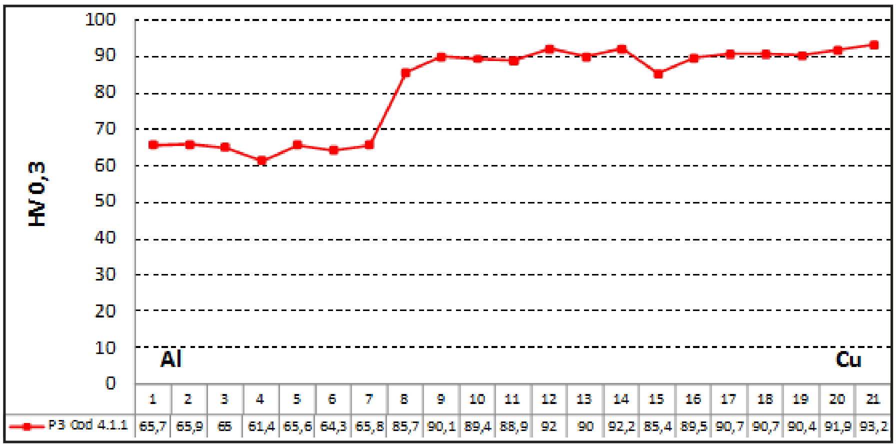


Fig. 8. The profile of microhardness in cross-section

Table 2
RESIDUAL STRESS VALUES

Position of measuring point in **Al**, compared to the joint Al-Cu (mm)	σ (MPa)	$\pm\Delta\sigma$ (MPa)	Position of measuring point in **Cu**, compared to the joint Al-Cu (mm)	σ (MPa)	$\pm\Delta\sigma$ (MPa)
0.0	-80.67	12.10	12	-96.91	16.30
1.0	-83.47	24.20	8.7	-119.84	4.80
2.0	-75.34	26.16	7.7	-118.22	17.10
2.9	-63.42	17.28	6.7	-121.59	11.40
4.0	-64.66	37.78	5.7	-146.84	20.83
4.9	-43.76	9.00	4.6	-128.43	9.14
5.9	-63.22	5.84	3.7	-149.85	16.41
10.1	-17.12	5.53	2.7	-115.40	12.51
			1.6	-132.88	16.75
			0.7	-135.11	21.47
			0.3	-101.21	9.74

In the area where the width of the nugget tends to zero (Site 3), the concentration of the two materials varies so Al = 25.67%; Cu = 51.07%.

At the base of the nugget, Site 4, there are visible fine grains in the nugget zone and plastic deformation of Al grains, (fig. 6).

The concentration of chemical elements in the centre of the nugget (Site 5) is shown in figure 7. Al is present in a proportion of 15.49% and Cu in a proportion of 56.97%. The presence of oxygen and carbon is normal.

There was performed only one line of microhardness, in the cross section of the joined parts, on a parallel direction to the outer surfaces of the joined parts. The load used was of 300 g, step of 1 mm and the measurements were carried out in 21 points. The microhardness values thus obtained are shown in figure 8.

It is noted that in the joint zone there is no increase in microhardness values in relation to microhardness values of the base materials (90 HV0.3 for Copper respectively 65 HV0.3 for Aluminum alloy). The microhardness in the joint area is comparable in value to that of Copper.

Residual stress values determined are shown in table 2 and in figures 9 and 10 are shown the experimental values of the diffraction angles and intensities measured for some

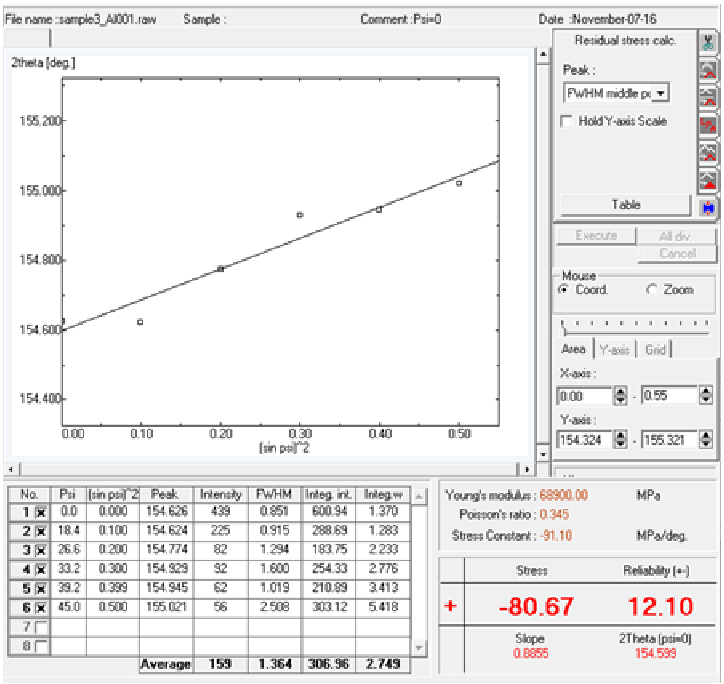


Fig.9. The experimented values of the angles and intensities of diffraction measured in Al, the point located on the joint line

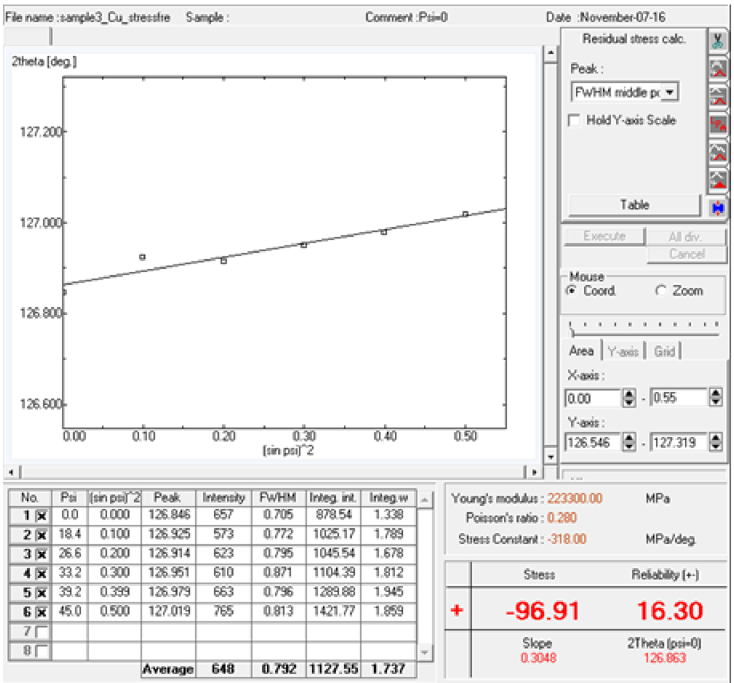


Fig. 10. The experimented values of the angles and intensities of diffraction measured in Cu, the point located at 12 mm from the joint line

points on the measuring line located in the Al material (fig. 9) and Copper (fig. 10).

It is noted that residual stresses of all measurement points are compressive and these tensions, in absolute values, are significantly higher toward the joint area for Al. Cu residual stresses have absolute values higher at 3.5 - 6 mm from the joint line.

Conclusions

FSW is an effective method of joining dissimilar materials Aluminum alloys and Copper, materials impossible to be combined by fusion welding. In addition to the welding parameters, the direction of rotation of the tool and its location in relation to the base materials are important. Material with higher hardness (copper) must be in the advance part and the material with lower hardness (aluminum) on the retreat part to avoid a poor weld quality with surface grooves.

At the joint of two plates of dissimilar materials Al / Cu alloys, with a thickness of 5 mm using a tool with pin screw M6 placed on the board of Al alloy (the rotation speed of the pin 1200 rpm, feed rate 60 mm / min) there was achieved a nugget with a variable thickness, tending toward zero at the base of plates. As the pin is in the Aluminum alloy plate, the nugget is formed in this plate, and Copper is distributed in the nucleus with different forms. Thus, the top of the nugget has the highest concentration of Copper; Cu areas may be observed under irregular shapes. EDS analysis carried out in different parts of the nucleus showed that the variation of the concentration of Cu is in the range of (36.72 ... 56.97) %, and Aluminum alloy in the range of (60.55 ... 15.49) %.

The measurements carried out show that in the joint zone the hardness obtained is comparable to that of copper, and copper hardness is higher than that of Aluminum alloy.

Residual stresses of all measurement points are compressive and these stresses, in absolute terms, are significantly higher toward the joint area for Aluminum.

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