Analysis of microstructure and mechanical properties of aluminium-copper joints welded by FSW process

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Abstract. The research conducted in this article aimed to check the quality of joining some dissimilar materials Al-Cu by determining the mechanical properties and microstructure analysis. For the experimental measurements there were used tin alloy Al - EN-AW-1050A with a thickness of 2 mm and Cu99 sheet with a thickness of 2 mm, joined by FSW weld overlay. The main welding parameters were: rotating speed of the rotating element 1400 rev/min, speed of the rotating element 50 mm/min. The experimental results were determined on samples specially prepared for metallographic analysis. In order to prepare samples for their characterization, there was designed and built a device that allowed simultaneous positioning and fixing for grinding. The characteristics analyzed in the joint welded samples were mictrostructure, microhardness and residual stresses. The techniques used to determine these characteristics were optical microscopy, electron microscopy with fluorescence radioactive elemental analysis (EDS), Vickers microhardness line - HV0.3 and X-ray diffractometry.

1. Introduction

These is a process for joining in solid-state purely mechanical, which is based on heating by friction and plastic deformation of the material welded, obtained from the interaction of a tool for non consumable welding, which rotates on contact surfaces of the parts to be joined.

The welding tool is moved at the welding speed along the weld line. The material brought in plastic state is transferred to the rear part of the tool, creating a welded joint [1-3].

The maximum temperature reached is about 0.8 parts of the melting temperature. In contrast to conventional friction welding, the FSW process overlaps the effect of heating on the mechanical effect of mixing the welded materials.

The parts to be assembled are positioned without clearance on a base plate and are fixed so as to avoid any relative movement between them during the welding process [4-5]. The welding tool has a specified configuration, being formed of two parts: a cylindrical bulk portion called *shoulder* and the end which actually mixes the joining material called *pin*. After fixing the materials to be joined, the welding tool is driven in a rotation and translation movement to the fixed parts. The pin penetrates the materials until the surface of the materials to be joined comes into contact with the shoulder. As a result of the friction between shoulder and base material, locally, it is released a quantity of heat which has the effect of plasticizing the materials to be joined. At this point, the welding tool, by the equipment, is engaged in a translational movement. As the rotating element is moved in the welding direction, the material in front of the pin, softened due to heating by conduction, is trained in the space behind the welding tool, which is freed by advance of the tool. The rear of the shoulder forges the

deformed material, leaving a smooth nugget. The local deformation process is assimilated to a process of continuous extrusion on the length of joint [6-7].

The research conducted in this article was aimed at obtaining experimental results to determine the physical and mechanical properties and microstructure analysis of the joint obtained by the FSW process for materials Aluminium - Copper. For experimental measurements there were used EN-AW-1050 sheet with thickness of 3 mm and Cu 99 sheet with thickness of 3 mm, joined by FSW butt welding. The main welding parameters applied were: rotating speed of the rotating element 1400 rev / min, speed of the rotating element 50 mm / min and position of pin 90% on Aluminum.

2. Experimental procedure
2.1 FSW process and materials used
It was used the FSW butt process consisting of assembling two parts in contact, fixed by clamp which allows the formation of a linear weld nugget.

Table 1 Chemical composition [%] of material Cu99.

Alloy	Ag	As	Bi	Cu+Ag	Fe	Pb
Min	-	-	-	0.99	-	-
Max	0.15	0.2	0.005	-	0.1	0.03

Table 2 Chemical composition [%] of material EN-AW-1050A.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
1050A	0.5	0.4	0.05	0.01	-	0.01	0.07	0.05	0.03	99.5

2.2 Parameters used to obtain the joint
The materials used to obtain the joint were Cu99 and AA 1050, both having a thickness of 3 mm. The joint scheme is of butt type, figure 1, and the type of pin used is with four bevels, having a length of 4 mm. The pin was positioned 90% on Al, and the rotation of the pin was clockwise. The parameters used to obtain the joint were rotation speed 1400 [rev / min] and speed of 50 [mm / min].
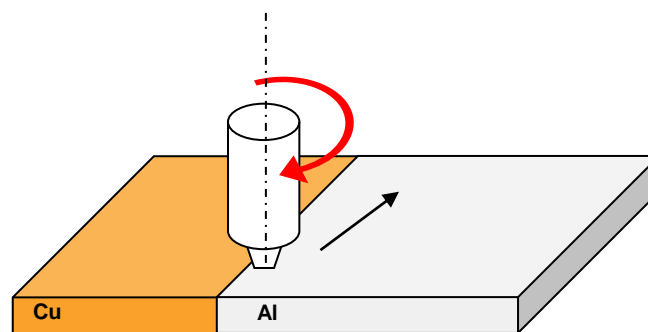

Figure 1. Scheme of the butt joint.

2.3 Methods and means used in the characterization of welded joints
Sample preparation. Analysis of welded joints sought to highlight their main macro and microscopic features, the evolution of microhardness in the joint zone, as well as the state of residual stress relative to the characteristics of the base materials joined.
In order to prepare the samples for their characterization, there was designed and made a positioning and fixing device, figure 2 that allowed simultaneous positioning and fixing them for polish, optical microscopy analysis, microhardness measurement and determination of residual stresses.
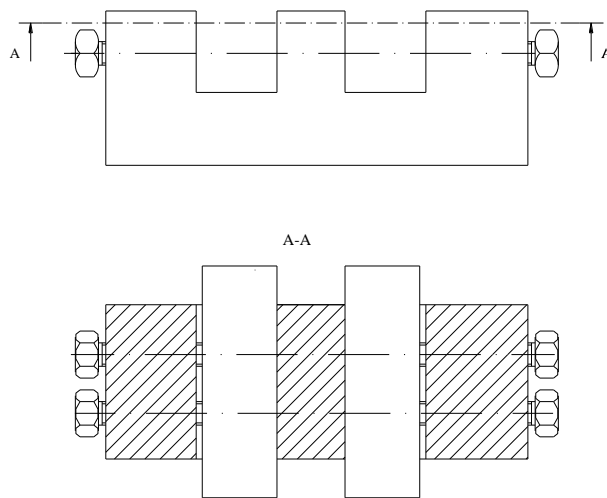
Figure 2. Scheme of the device to prepare and analyze the samples.

The samples were polished smoothly by sanding with grit sandpaper of 320 and 800, grit diamond paste of 5 μm

Analysis of the microstructure. For the analysis of the microstructure there were used optical microscopy techniques (to characterize base materials and joining zone) and electron microscopy by fluorescence radioactive elemental analysis (EDS) for the detailed analysis of the weld zone. In this respect, the samples were attacked as follows:

- solution Keller (F2) - to highlight the microstructure of Al;
- solution (E1) - to highlight the microstructure of Cu

Microhardness measurement. To measure microhardness there was used the Vickers method, which consists in applying to the part to be tested a load F, for a determined period of time (10 seconds) by means of a diamond penetrator having the form of a right pyramid with a square base and the angle between two opposite sides of 136°.There have been various lines of hardness; the step between two fingerprints is of 1 mm.

Determination of residual stresses. The stresses were measured along a line of 12 mm, step of 1 [mm], starting with the Al material, continuing to the mixing zone, and ending with the Cu material (for the parts butt joined). On the part obtained by weld overlay, residual stresses were determined in each of the two materials in directions parallel to the nugget.

X-ray incident spot size was approximately 1.03 [mm] in diameter. For data acquisition, there were used X-rays with wavelength CrK_α. Operational parameters of the X-ray tube were: accelerating stress 40 kV, filament current of 40 mA.

3. Results and discussion

3.1 Microscopy analysis

There were investigated several zones of joint, figure 5, images of the nugget, acquired by EDS technique, as shown in figure 3.
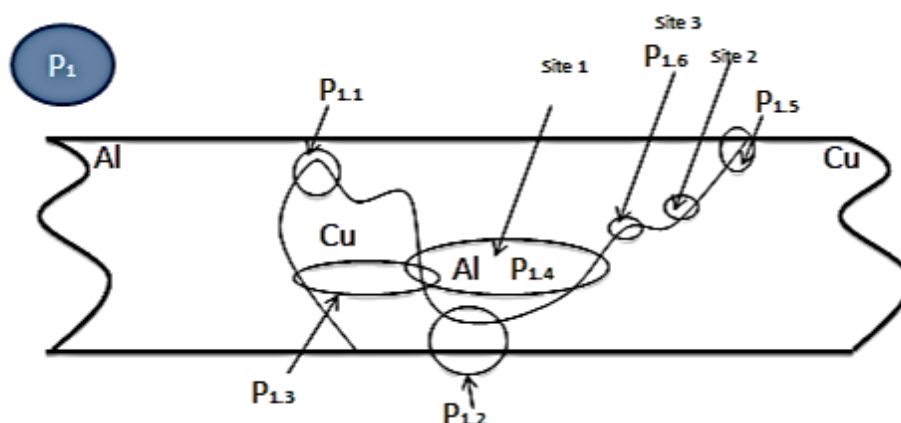

Figure 3. Position of the zones analysed.

$P_{1.1}$

$P_{1.2}$
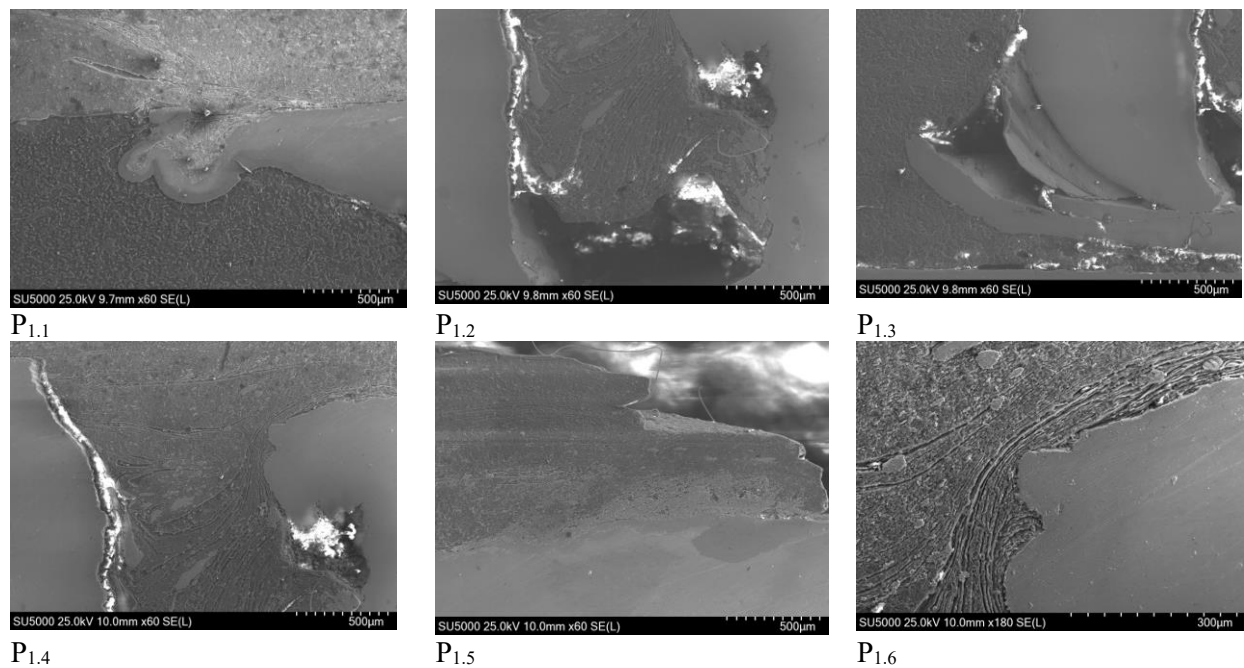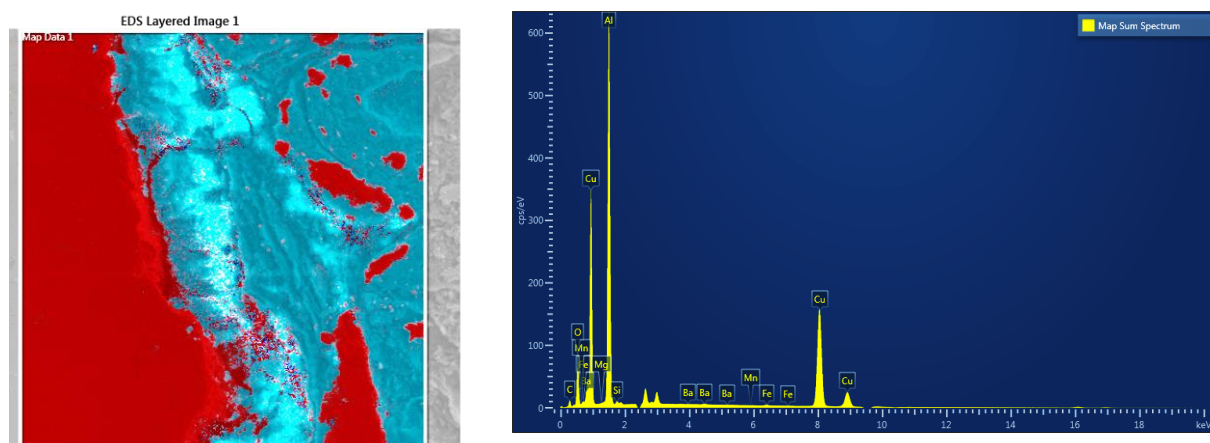
$P_{1.3}$

$P_{1.4}$

$P_{1.5}$

$P_{1.6}$

Figure 4. Morphology of the joint zone.

Joint microstructure and chemical composition in zones (sites) marked in figure 4 are presented in figures 5. It can be observed the presence of the two base metals of materials used in the joining process, copper and aluminium, as well as the mixing area.

Analysis of figures and spectra presented in these tables highlight the following issues:

- the joining area has an irregular shape (the outline of the joint area is approximately shown in figure 5 and many "gap" type defects have an acceptable quality of the joining process;

- pieces of Copper are ripped and brought to the site of Al and in the zone where should have been the nugget.
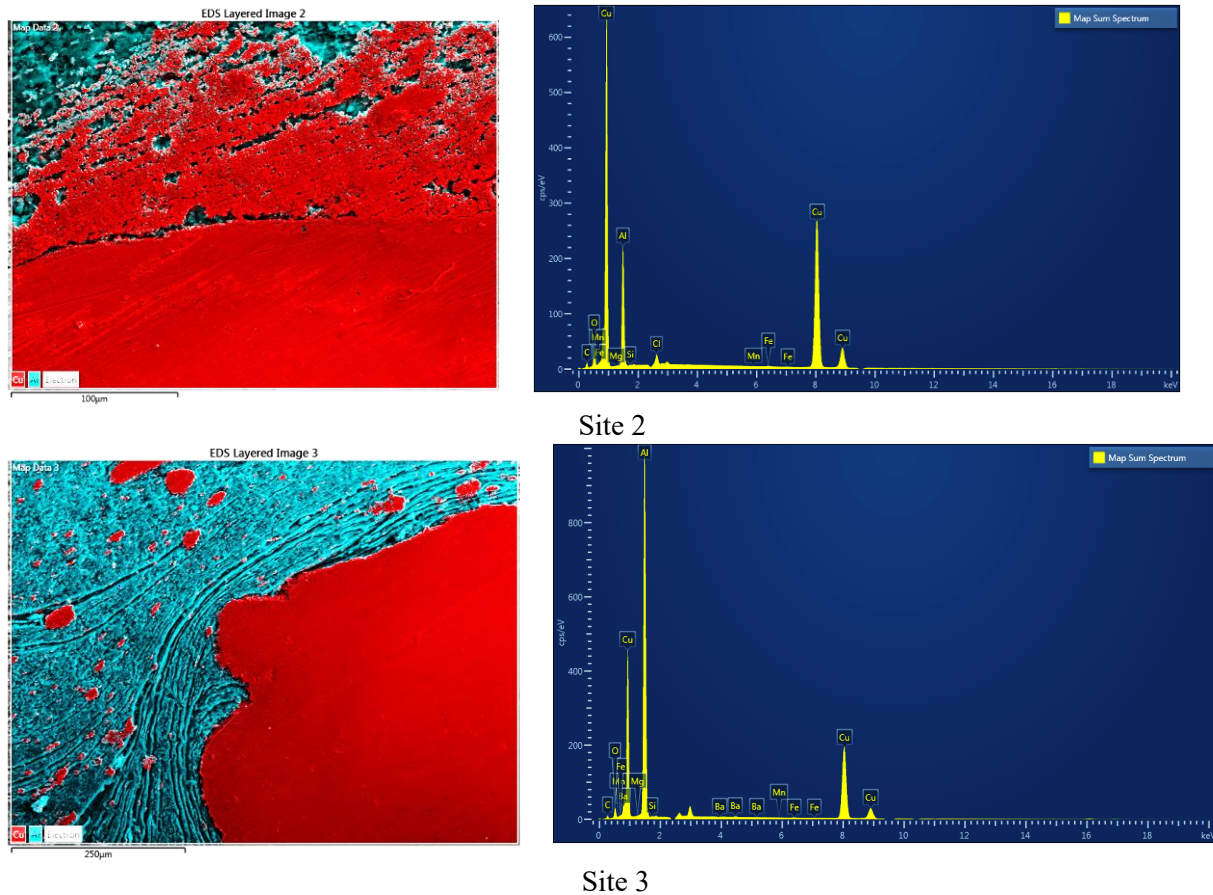

Site 1

Site 2

Site 3

Figure 5. Microstructure and chemical composition.

3.2 Microhardness of the joint

There were made two lines of micro-hardness, in the cross section of the joined parts, figure 6, in the direction parallel to the outer surfaces of the joined parts

Figure 6. Macrographs of microhardness lines for P1.

Each of these lines were placed at about 1 mm from the edges (1 mm or so between them), the load used was 300 g, and the step of 1 mm. The first line has 9 valid values (default values at the measuring points 4 and 7, in the joining zone, due to the existence of gaps in this zone), while the second line has 11 values. The micro-hardness values thus obtained are shown in figure 7.

It is noted that in the joint zone there is an increase of microhardness values in relation to the values of microhardness of the base materials (86 HV0.3 for Cu, respectively, 26 HV0.3 for Al). Thus, the maximum values of microhardness in the joint zone are over 120 HV0.3, which highlight significant

increases of microhardness. These are over more than 50% compared to the "toughest" base material (Cu) and over 360% compared to the "softest" base material (Al).

By correlating hardness with the mechanical properties and mechanical strength it can be concluded that tensile strength of the joint zone is greater than the tensile strength of any of the materials joined.
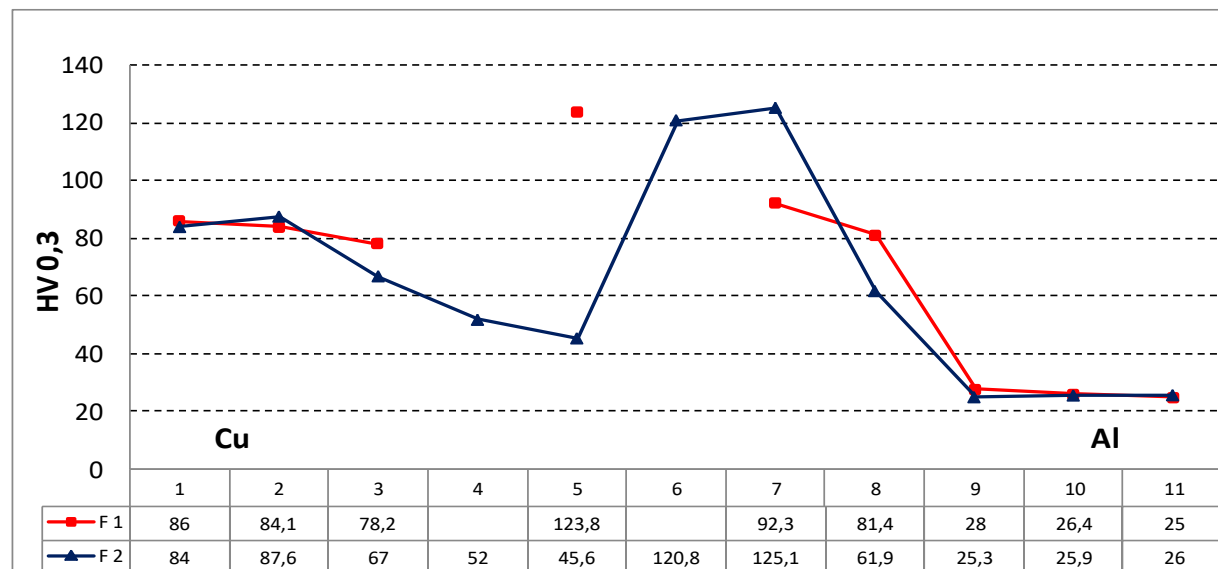

	1	2	3	4	5	6	7	8	9	10	11
F 1	86	84,1	78,2		123,8		92,3	81,4	28	26,4	25
F 2	84	87,6	67	52	45,6	120,8	125,1	61,9	25,3	25,9	26

Figure 7. Values of microhardness for P1.

3.3 Residual stress

The values of residual stress determined are shown in table 3; table 4 and 5 show the experienced values of angles and diffraction intensities measured for some points on the measuring line located in Aluminium material (figure 4) and Copper material (figure 5).

It is noted that:

- residual stresses from all measuring points are compressive;

- these stresses, in absolute terms, are significantly higher in the joint zone.

The presence of compressive stresses with a significantly higher value in the joint zone also confirms the plastic deformation in the joint zone.

Table 3. Residual stress values for sample 1.

Position of measuring point in **Al**, compared to junction Al-Cu (mm)	σ (MPa)	$\pm\Delta\sigma$ (MPa)	Position of measuring point in **Cu**, compared to junction Al-Cu (mm)	σ (MPa)	$\pm\Delta\sigma$ (MPa)
28	-35.50	6.70	0.1	-122.45	13.47
4.5	-31.26	4.97	0.6	-138.61	35.84
4.1	-32.66	8.61	1.1	-121.81	20.02
3.6	-13.33	6.11	2.6	-41.23	12.23
3.3	-35.86	8.07	3.1	-54.45	22.02
2.0	-67.79	14.90	3.5	-77.94	19.84
1.6	-49.57	14.29	20	-97.15	9.25
1.1	-53.90	20.12			
0.7	-169.54	61.70			

Table 4. Values experienced of angles and diffraction intensities measured in Al, at
the position 4.5 mm from the joint line.

No.	Psi	(sin psi)^2	Peak angle	Intensity	FWHM	Integ. int.	Integ.w
1 ☒	0.0	0.000	156.591	323	0.773	331.48	1.026
2 ☒	18.4	0.100	156.597	609	0.769	626.16	1.028
3 ☒	26.6	0.200	156.653	308	0.752	390.78	1.267
4 ☒	33.2	0.300	156.708	201	0.812	243.64	1.212
5 ☒	39.2	0.399	156.737	164	0.865	239.27	1.456
6 ☒	45.0	0.500	156.736	171	0.880	219.20	1.285
7 ☐							
8 ☐							
			Average	296	0.809	341.75	1.212

Young's modulus : 68900.00 MPa
Poisson's ratio : 0.345
Stress Constant : -91.10 MPa/deg.

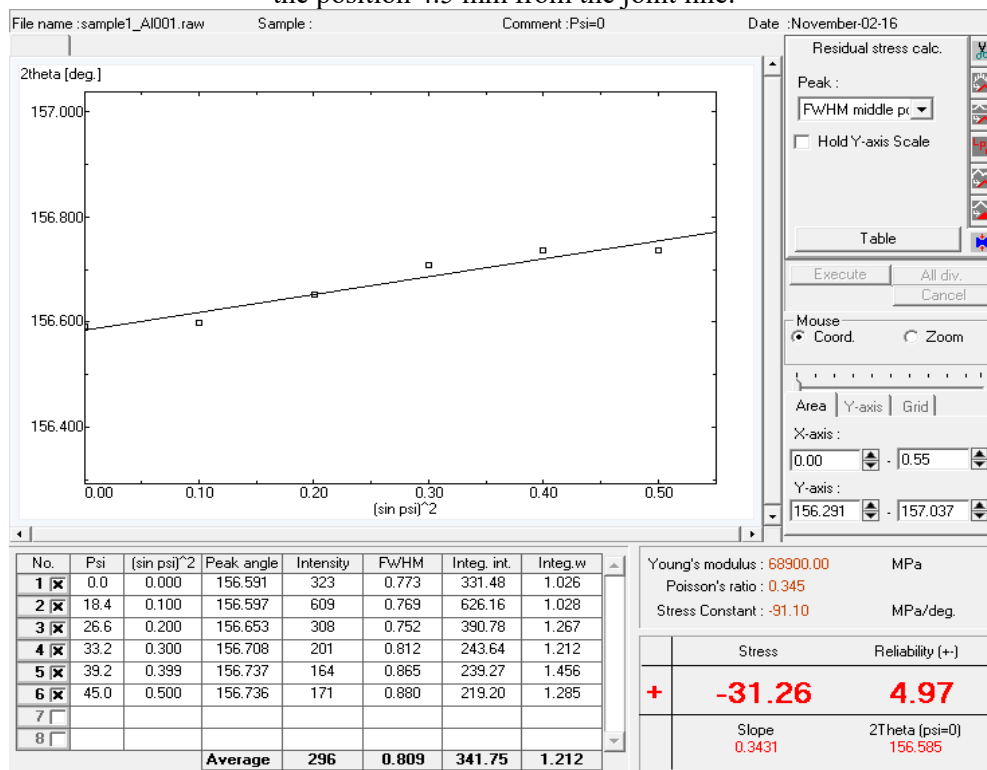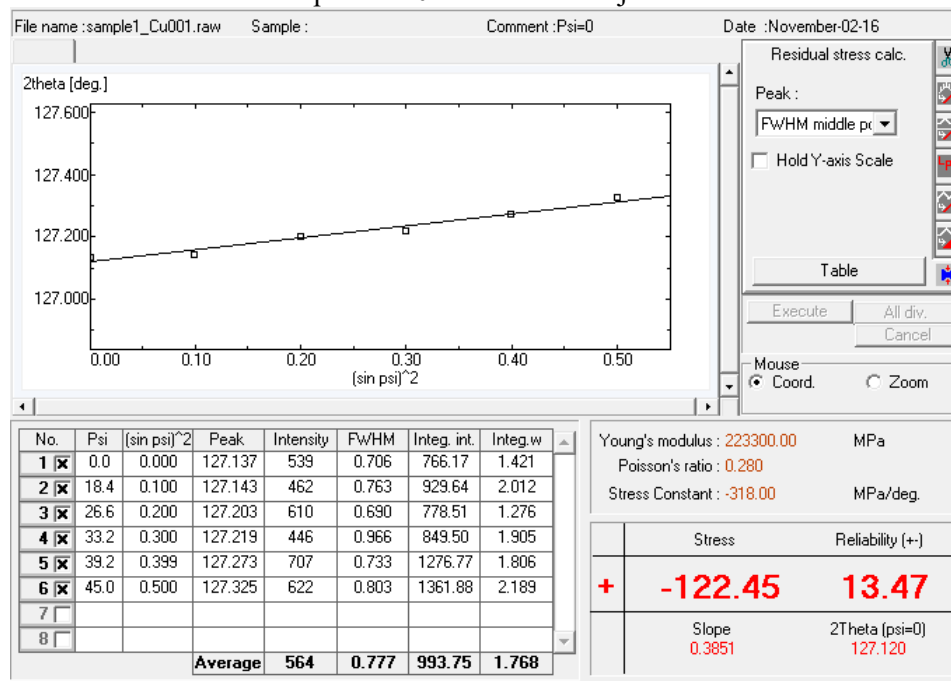| Stress	Reliability (+-)
+ **-31.26**	**4.97**
Slope 0.3431	2Theta (psi=0) 156.585

Table 5. Values experienced of angles and diffraction intensities measured in Cu,
at the position 0.1 mm from the joint line.

No.	Psi	(sin psi)^2	Peak	Intensity	FWHM	Integ. int.	Integ.w
1 ☒	0.0	0.000	127.137	539	0.706	766.17	1.421
2 ☒	18.4	0.100	127.143	462	0.763	929.64	2.012
3 ☒	26.6	0.200	127.203	610	0.690	778.51	1.276
4 ☒	33.2	0.300	127.219	446	0.966	849.50	1.905
5 ☒	39.2	0.399	127.273	707	0.733	1276.77	1.806
6 ☒	45.0	0.500	127.325	622	0.803	1361.88	2.189
7 ☐							
8 ☐							
			Average	564	0.777	993.75	1.768

Young's modulus : 223300.00 MPa
Poisson's ratio : 0.280
Stress Constant : -318.00 MPa/deg.

Stress	Reliability (+-)
+ **-122.45**	**13.47**
Slope 0.3851	2Theta (psi=0) 127.120

4. Conclusions

Analysis of figures and spectra presented in these tables highlights the following issues:

- joining zone has an irregular shape (the outline of the joint zone is approximately shown in figure 5) and many "gap" type defects;

- pieces of Copper are ripped and brought to the site of Aluminium and in the zone where should have been the nugget.

The analysis of hardness reveals that in the joint zone there is an increase of microhardness values in relation to the values of microhardness of the base materials (86 HV0.3 for Cu, respectively, 26 HV0.3 for Al). Thus, the maximum values of microhardness in the joint zone are over 120 HV0.3, which highlight significant increases of microhardness. These are over more than 50% compared to the "toughest" base material (Copper) and over 360% compared to the "softest" base material (Aluminium).

By correlating hardness with the mechanical properties and mechanical strength it can be concluded that tensile strength of the joint zone is greater than the tensile strength of any of the materials joined.

By analyzing the residual stresses in the joint zone and in its neighbourhood it is noted that:

- residual stresses from all measuring points are compressive;
- these stresses, in absolute terms, are significantly higher in the joint zone.

5. Acknowledgements

6. References

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