IOP Conference Series: Materials
Science and Engineering

PAPER • OPEN ACCESS

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To cite this article: M Milčić *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **393** 012107

Mechanical behaviour of Al 2024 alloy welded by friction stir welding

M Milčić[1], T Vuherer[2], I Radisavljević[3], D Milčić[1], J Kramberger[2] and B Andjelković[1]

[1]Faculty of Mechanical Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia
[2]University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia
[3]Military Technical Institute, Ratka Resanovića 1, 11000 Beograd, Serbia

E-mail: miodrag.milcic@masfak.ni.ac.rs

Abstract. The paper presents the results of structural and mechanical testing of the alloyed aluminum alloys AA 2024 welded by the FSW process. Using the optimized tool and welding, 6 mm thick plates were connected. In this paper, the influence of rotation speed and welding speed on the macrostructure and cross section micro hardness of FSW welded joints of EN AW-2024 T351 a aluminium alloy is studied. The following welding parameters were used: the rotation speed of the tool did not change and amounted to 750 rpm, and the welding speed was 73, 116,150 mm / min. The compounds were obtained without the presence of errors and with an acceptable flat surface of the compound.

1. Introduction

Aluminum alloys have been widely used in both the automotive and aerospace industries. Both industries are pushing the boundaries of new innovative products, a requirement for greater capacity and, at the same time, a lower weight with robust design. Aluminum alloys are characterized by high load capacity relative to the mass level at a relatively low price. In order to improve aluminum properties, aluminum alloys are used, which are obtained by alloying pure aluminum with the following elements: copper, zinc, magnesium, silicon, manganese and lithium. In aluminum alloys with copper (Series 2), copper is the main alloying element in this family whose mechanical values reach those in structural steel. There are no good anti-corrosive properties and as a rule, they are poorly welded by conventional welding procedures.

Welding is a fabrication process used to join materials, usually metals or thermoplastics, together. During welding, the pieces to be joined (the workpieces) are melted at the joining interface and usually a filler material is added to form a pool of molten material (the weld pool) that solidifies to become a strong joint. Aluminum alloys are the alloys in which aluminum is a predominant metal. For welding of aluminum alloys, fusion welding and solid state welding processes are used. In this work welding of aluminum alloy by MIG, TIG and FSW is done and effect is compared. Thus, Friction Stir Welding - FSW is a very suitable, and increasingly used, for joining high strength aluminium alloys (2xxx, 6xxx, 7xxx and 8xxx series), currently applied to the aerospace, automotive, marine and military industries.

2. Friction stir welding (FSW)

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys [1,3].The principle of obtaining inseparable joints by welding with friction stir welding is shown in the Figure 1.

The tool geometry plays an important role in material flow and in turn decides the traverse rate at which FSW can be carried out. A FSW tool has two basic functions: (i) localized heating, and (ii) material flow. In initial stage of the tool plunge, the heating results primarily from the friction between pin and workpiece. The tool is plunged till the shoulder touches the workpiece. The friction between the shoulder and the workpiece results in the biggest component of heating.

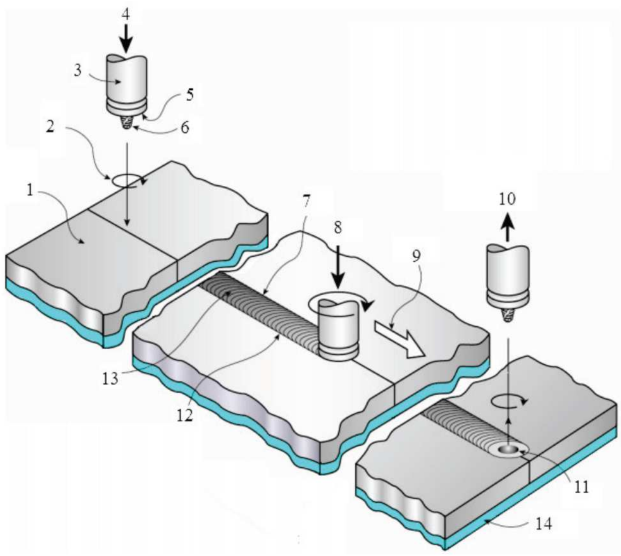

Figure 1. Illustrated scheme of friction stir welding [8] (1 - base metal, 2 - direction of tool rotation, 3 - weld tool, 4 - downward movement of tool, 5 - tool shoulder, 6 – pin, 7 - advancing side of weld, 8 - axial force, 9 - direction of welding, 10 - upward movement of tool, 11 - exit hole, 12 - retreating side of weld, 13 - weld face and 14 - base plate).

Table 1. Key benefits of friction stir welding [3].

Metallurgical benefits	Environmental benefits	Energy benefits
Solid phase process Low distortion of workpiece Good dimensional stability and repeatability No loss of alloying elements Excellent metallurgical properties in the joint area Fine microstructure Absence of cracking Replace multiple parts joined by fasteners	No shielding gas required No surface cleaning required Eliminate grinding wastes Eliminate solvents required for degreasing Consumable materials saving, such as rugs, wire or any other gases	Improved materials use (e.g., joining different thickness) allows reduction in weight Only 2.5% of the energy needed for a laser weld Decreased fuel consumption in light weight aircraft, automotive and ship applications

There have been a number of reports □2-11□ highlighting the microstructural changes due to plastic deformation and frictional heat associated with FSW. Mechanical failure of the welds can take place in the SZ, TMAZ, or HAZ region depending on the amount of energy input which is controlled by the welding parameters such as rotational and travel speed. Since the material flow behavior is predominantly influenced by the material properties such as yield strength, ductility and hardness of the base metal, tool design, and FSW process parameters, the dependence of weld microstructure on process parameters differs in different aluminum alloys for a given tool design.

The main goal of this research is analyse the FSW parmeters on the structural and mechanical properties FSW butt joint of aluminium alloy EN AW 2024-T351.

3. Experimental work

The experiment was aimed to find the influence of input kinematic parameters such as welding speed (v) and tool rotation speed (n) on metallurgical and mechanical characteristics of welded joints. Base material was aluminium alloy EN AW 2024-T351. Chemical composition of experimental plates is provided in Table 2. and mechanical properties in Table 3. [3].

Table 2. Chemical composition of AA 2024-T351.

Chemical composition	Cu	Mg	Mn	Fe	Si	Zn	Ti
wt. %	4,70	1,56	0,65	0,17	0,046	0,11	0,032

Table 3. Mechanical properties of AA 2024-T351.

Yield strength R_{eh} (MPa)	Ultimate tensile strength R_m (MPa)	Elongation A_5 (%)	Hardness HV
370	481	17.9	137

They are experimentally welded plates measuring 500 mm×65 mm×6 mm. The both sides of the welding plates are machined on the grinder at a thickness of 6 mm. When welding under the welding part, the base plate was made of austenitic steel. A milling machine was used for welding. The weld length was approximately 400 mm. Figure 2 shows a machine and figure 3 a tool used for butt joint FSW. Welding was made in accordance with the plan matrix of experiment, with variations in tool rotation speed (n) and welding speed (v), Table 4. Other parameters of welding were maintained constant.

Figure 2. Machine for FSW welding.

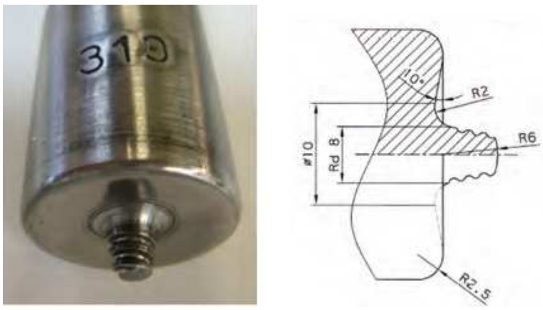

Figure 3. Fabricated FSW tools.

Table 4. Friction stir welding parameters.

Sample	Rotation speed n (rpm)	Welding speed v (mm/min)	Ratio n/v (rev/mm)
A – I		73	10,27
B – II	750	116	6,47
C - III		150	5

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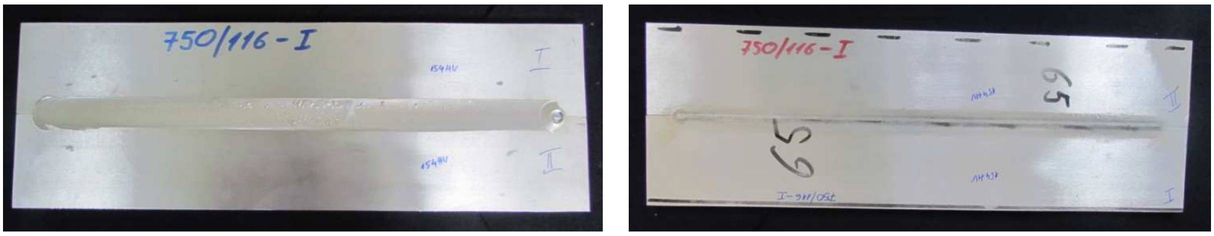

Figure 4. Butt FSW joint.

After the welding process was completed, welds were tested. For that purpose, visual control was performed, on the weld face and root of the seam, as well as the radiographic control of samples. No defects were detected (visually, touch or magnifier). Appearances of upper and bottom butt FSW joint surface are shown in Figure 4.

After the welding process was completed, welds were tested. For that purpose, visual control was performed, on the weld face and root of the seam, as well as the radiographic control of samples. No defects were detected (visually, touch or magnifier).

Specimens are made from FSW welded samples. Figure 5 shows the positions of the FSW welded sample from which the tensile specimens are drawn out, the specimens for impact test with V-notch in different positions of the FSW joint, and the specimens for testing of fracture mechanics parameters – fatigue crack growth rate *da/dN*. A part of the made of tensile specimens and impact test specimens is given in Figure 6. The dimensions of the test tube for tensile test and for impact test are given in Figure 7 and 8.

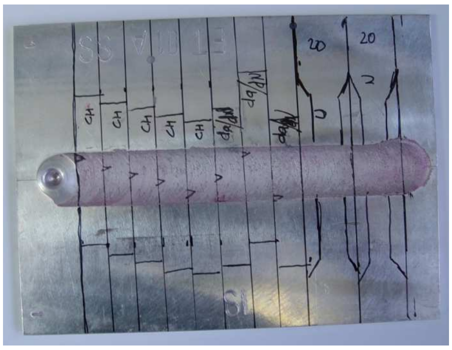

Figure 5. Schematic of specimens locations in FSW welded joint.

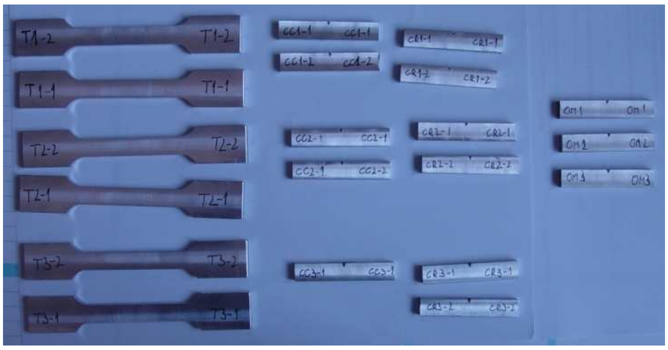

Figure 6. Tensile specimens and impact test specimens.

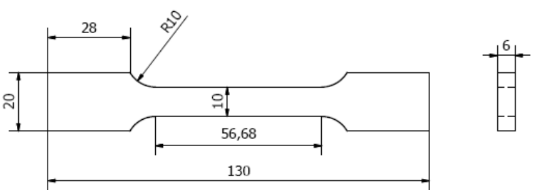

Figure 7. Dimension of tensile specimens.

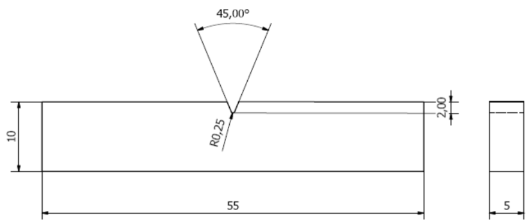

Figure 8. Dimension of sharpy impact test specimens.

4. Results and discussions

Metallographic observation was carried out by optical microscopy (OM) using Leica M205A optical microscope. The specimen for OM was ground, polished and etched using Tucker's (45 ml HCl, 15 ml HNO3, 5 ml HF and 25 ml H2O) reagent. Much care was taken to ensure location-to-location correspondence between the structural observations and hardness measurements. The nugget zone average size measurements were processed using Leica DFC295 camera and LAS software.

Room-temperature tensile tests were carried out at a strain rate of 3.3×10–3 s^{-1} on ASTM E8M transverse tensile specimens (Figure 7). In order to asses the reproducibility, 2 specimens were tested and average value was reported. Bend testing was carried out according to EN 910 with joint centered over the mandrel. The bending specimens were tested using face and root side of the joint in tension. Vickers hardness measurement was conducted perpendicular to the welding direction, at cross section of weld joint, using digitally controlled hardness test machine (HVS-1000) applying 9.807 N force for 15 s. The hardness profiles were obtained along 3 horizontal and 63 vertical directions.

Figure 9 shows hardness distribution across the welded joint at different applied rotation speed (*n*) and welding speed (*v*).

Comparing the hardness distribution for the welding parameter 750/150 and 750/116, it is noted that the hardness of the sample B - II in the stirn region is uniform across the entire height. The hardness measured in all three positions of the weld height in the region between TMAZ and HAZ decreases and is between 110 and 115 HV.

The FSW welded sample C-III shows the hardness difference in the height of the weld: the hardness of the root in the stirn zone is between 110 and 115HV, while the hardness near the face of the weld is between 130 and 135 HV. The hardness measured near the face of the weld in the region between TMAZ and HAZ drops.

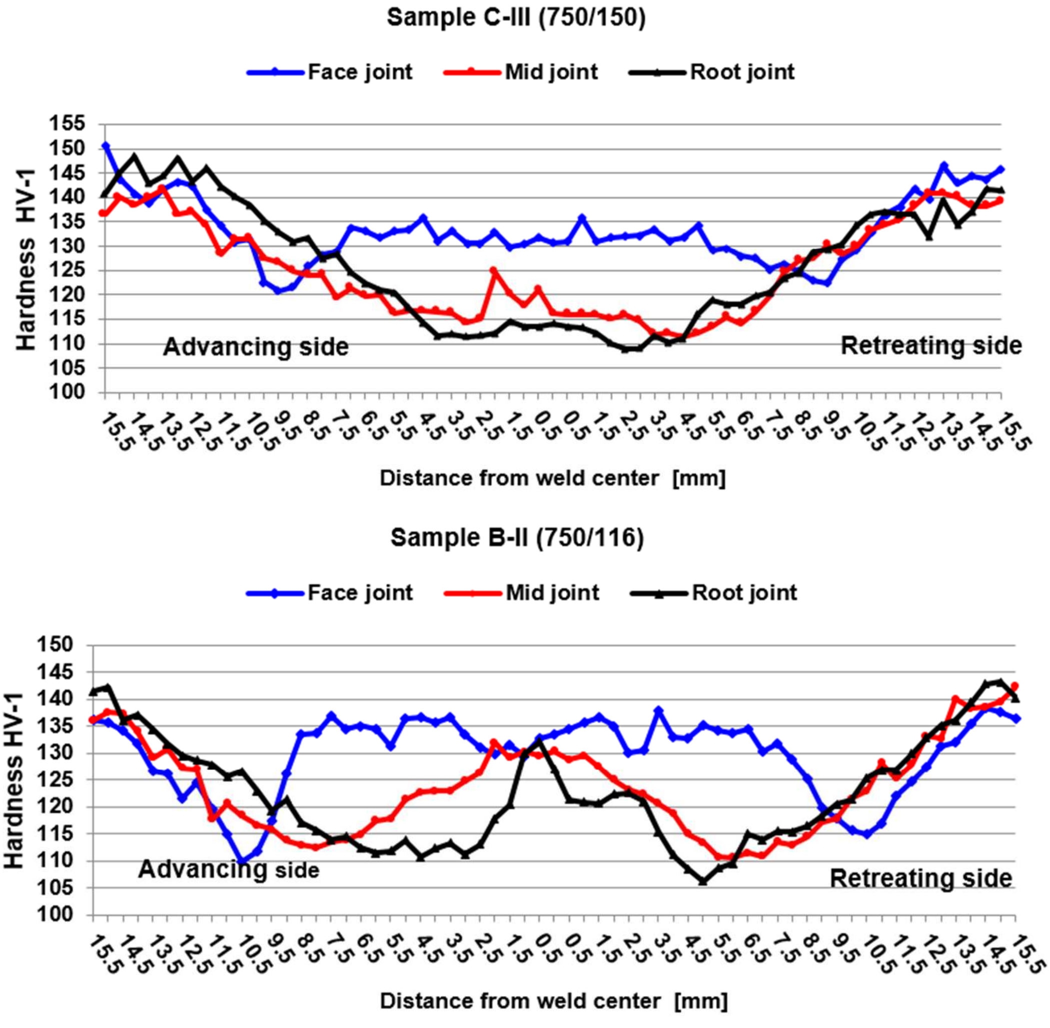

Figure 9. Hardness distribution across the welded joint.

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Tensile testing was performed for all tree FSW joints. The tensile testing results FSW joints are given in Table 5. Among the tree FSW parameters studied, i.e., at 750/73, 750/116 and 750/150 rpm/(mm/min), the average tensile yield strength and ultimate tensile strength.

This variation of tensile strength with rotational speeds for a given traverse speed appears to be linked to the energy of the welds. Joint efficiency as high as 97% of base metal could be achieved at 750/116 rpm/(mm/min). The highest ductility of the welded joint is achieved with the welding parameters 750/116 and is 7,2%. The highest ductility of the welded joint is achieved with the welding parameters 750/116 and is 7%.

The testing of welded joints was also performed on bending, around the face and around the root. The three-point bending test results FSW joints are given in Table 6.The welded FSV joint has poor bending characteristics. Comparing the obtained bending test results, the largest bend angle to the first cracking phenomenon is for welding parameters 750/116 and amounts to 42°.

Table 5. Tensile testing results.

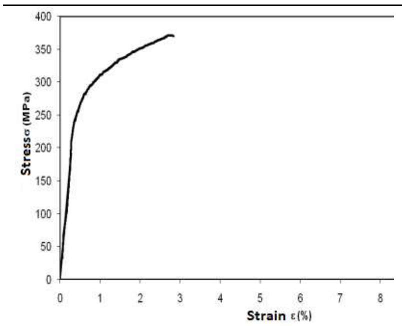
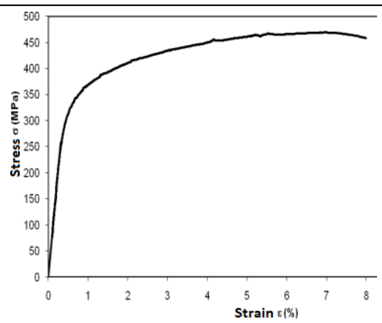
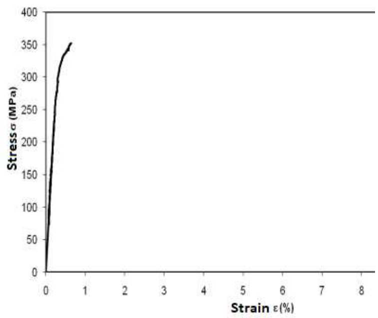
A-I	B-II	C-III
		
$R_{p0,2}$=281,9 MPa R_m=371,00 MPa Z=2,29%	$R_{p0,2}$=330,9 MPa R_m=469,06 MPa Z=7,43%	$R_{p0,2}$=337,6 MPa R_m=352,03 MPa Z=0,33%

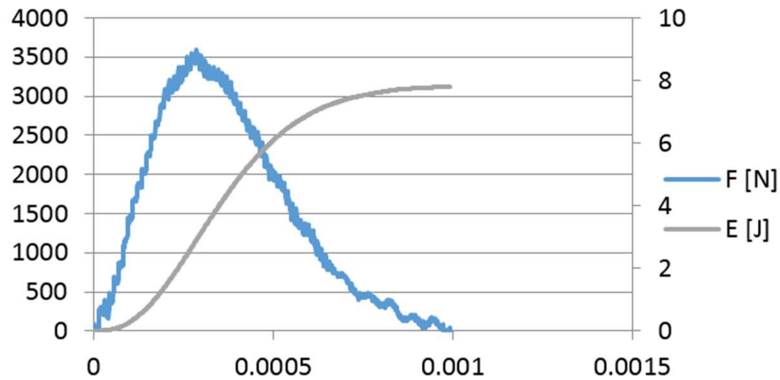
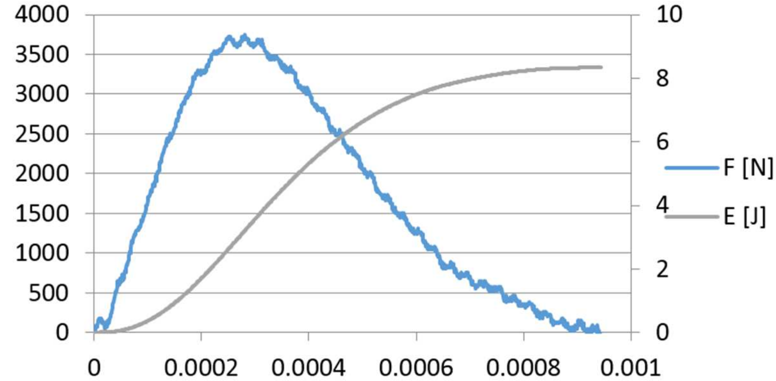
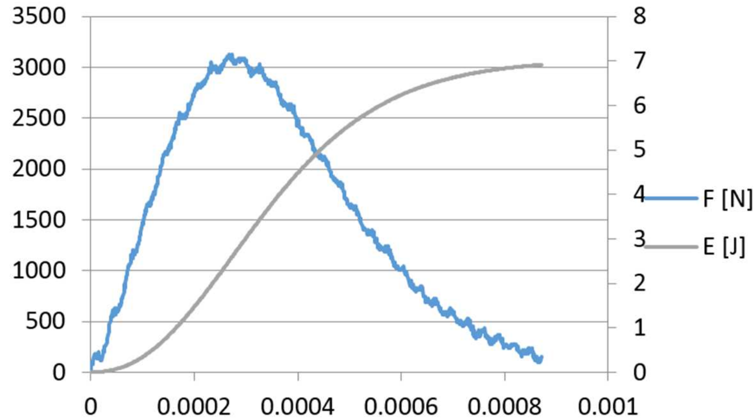
Table 6. Three-point bending test results.

A-I	B-II	C-III
		
	Bending angle	
□24°	□42°	□26°

To evaluate the impact behaviour of the friction stir weldments, the Charpy impact test notched specimens (CVN) are machined. Specimen size are 10 □ 6 □ 55 mm with 45° V-notch of 2 mm depth and 0.25 mm root radius. These are subsized non-standard specimens whose dimensions are dictated by the thickness of the plate. Notches are machined at the rear side of the welding direction, precisely along the welding line of weldments.

Charpy impact tests are carried out at room temperature using instrumented impact pendulum. The pendulum is equipped with load cells positioned on a striker edge. The measuring device is connected to high-speed data acquisition with response time in terms of mili-seconds. The instrumented system enabled to collect instantaneous load and time data from pendulum during the “fracture opening time”.

Table 7. Charpy impact tests results.

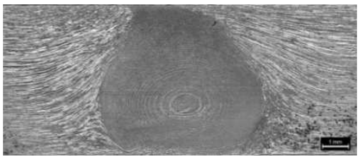
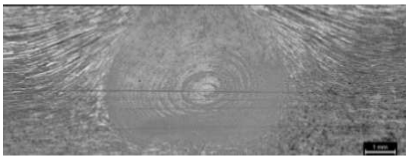
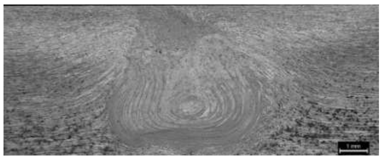
	750/73 E=7.8 J e=19.5 J/cm^2 Ei=2.88 J Ep=4.91 J
	750/116 E=8.34 J e=20.85 J/cm2 Ei=3.19 J Ep=5.15 J
	750/116 E=8.34 J e=20.85 J/cm2 Ei=3.19 J Ep=5.15 J

The Charpy impact tests results FSW joints are given in Table 7.The best characteristics of impact toughness have a welded pattern with welding parameters 750/116 and a impact energy of 8.34 J and a impact toughness of 20.85 J / cm^2.

Typical cross section of the welded joints under different parameters is shown in Table 8. The formation of different zones in FSW such as stir zone (SZ), TMAZ, and HAZ are quite evident from the macrostructures. Depending on processing parameter, different shapes of SZ have been observed.

All samples were welded at the same rotational speed of the 750 rpm tool. The welding speed was changed to 73, 116 and 150 mm / min. At the lowest welding speed, the energy input was the largest, or vice versa at the highest welding speed, the energy input was the smallest. And in one and the other situation in the lower zone of TMAZ appears microvoid. A significantly higher amount of microvoids

Table 8. Macrostructure of cross section of friction stir welded joint.

A-I	B-II	C-III
		

is in the highest welding speed situation. With high heat input, that is, at a low welding speed, intensive mixing of the material and movement of the material towards the upper surface occurs. At high speed welding, it is contrary to the previous insufficient mixing of the material, which also leads to a greater production of the microvoid in the lower zone TMAZ.

5. Conclusions

On the basis of examinations performed, given results of the experiment and their comparison, the following conclusions can be provided:

- Relation between the number of revolutions of tools n velocity of welding v directly influences the value of the fracture toughness and energy which is required for initiation and propagation of the crack;
- The asymmetry of the welded joint and changes in metallurgical transformations occurring around the pin and under the shoulder of the tool during its combined moving, influence the value of impact strength in various areas of the welded joint;
- Profile of distribution and allocation of micro hardness depends on the level of temperature and plastic deformation which is highest under the tool shoulder and around the pin;
- This investigation points out that weld joint B-II (welded by 750/116 rpm/(mm/min)) achieves better properties and microstructure than weld joint A-I and C-III (welded by 750/73 and 750/150 rpm/(mm/min)).

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