

# Friction Stir Welding of three dissimilar aluminium alloy: AA2024, AA6061 and AA7075

A Bosneag<sup>1</sup>, M A Constantin<sup>1</sup>, E Nitu<sup>2</sup> and M Iordache<sup>2</sup>

<sup>1</sup>University Politehnica of Bucharest, Department of Machine Building Technology, Splaiul Independenței Street, No. 313, Romania

<sup>2</sup>University of Pitești, Department of Manufacturing and Industrial Management, Târgul din Vale Street, No.1, Romania

E-mail: ana.bosneag89@yahoo.com

**Abstract.** Friction Stir Welding, named FSW, was invented in 1991 by The Welding Institute - TWI, U.K. and in the first instance was used to weld the aluminium alloy plates. Until now, this process was developed to join a large variation of materials: copper and brass, magnesium and alloys, titanium and alloys, different steel, polymeric materials and composite materials, in similar or dissimilar combination. This paper presents the results of experimental investigation of FSW joints to for three dissimilar aluminium alloys (AA2024, AA6061 and AA7075), in overlapped position, with a thickness 2 mm for everyone. All these three aluminium alloy are use in aeronautics industry, considering that the body of airplane are 20% aluminium alloy. In the experiment study, these three materials were positioned as follows: AA7075 on top, AA2024 in the middle and AA6061 below), and the value of input process parameters, rotation speed and advancing speed, was variate for minimum situation, maximum situation and medium situation and all of this was arranged in an experimental plan with two repetitions to the centre values. The experimental plan contained six experiments. The exit date recorded are: temperature and vertical force achieved in process time, microstructure and macrostructure of welding seams and micro-hardness. These dates will be compared between them and will be identified the influence of welding parameters (advancing speed and rotation speed) on the welding seams properties and the best combination between them for these three aluminium alloys.

## 1. Introduction

Process Friction Stir Welding, shortly FSW, is welding technology invented, in most, for aluminium alloys, in 1991, by The Welding Institute - TWI, from U.K. In first, this process of solid state welding has attested in year 1956 in the Soviet Union. This welding process use a rotating tool to provide frictional heat and mixing, in order to achieve a weld between two or more materials, below their melting point. Since the process work below the melting point of the materials, some defects, from the traditional welding process, are avoided [1]. The benefits of FSW are multiple in the welding process, of these can be listed: FSW does not required joint preparation for plates, the result is a high quality of welding with increased tensile strength, outstanding fatigue and corrosion resistance, is an economical welding method without consumable, with less energy [2].

This process allows the connection of an important number of similar and dissimilar materials witch are difficult or impossible to be welded using other welding procedure [3]. Taking into account



the welding materials, this can be split in three categories: dissimilar alloy having widely different melting point, dissimilar alloy with similar base metals and melting point and different alloy having dissimilar base metals and similar melting point [2].

In Friction Stir Welding the correct melting, without defects, in the welding are dependent of the correct combination between rotation speed, welding speed and tool design [4], in this study the tool shape was the same for all six experiments. The input parameters, rotation speed and welding speed were changed in three situations (minim, maxim and middle) to realise an experimental plan with six combinations.

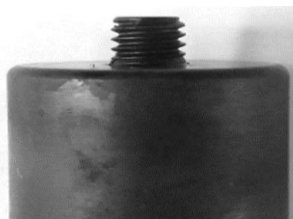
Taking into account the industrial application of this process, until now, the most demanded is automotive industry, followed by aeronautics industry, aerospace industry, railways industry, and others [5].

## 2. Experimental procedure

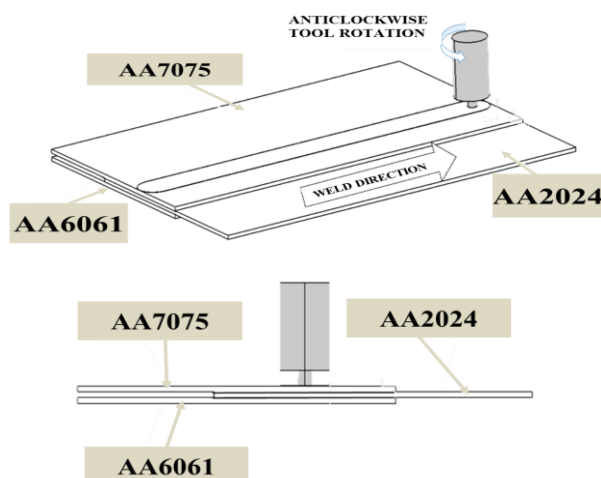
### 2.1. Welding process

In this experimental study, the all six experiments were performed with an identical cylindrical threaded tool. The shape of the pin was threaded M6, the diameter of shoulder pin was  $\phi 22$  mm and the high of the pin was 5.3 mm. The tool material was P20+S named carbide of sintered tungsten. In figure 1 is represented the tool used.

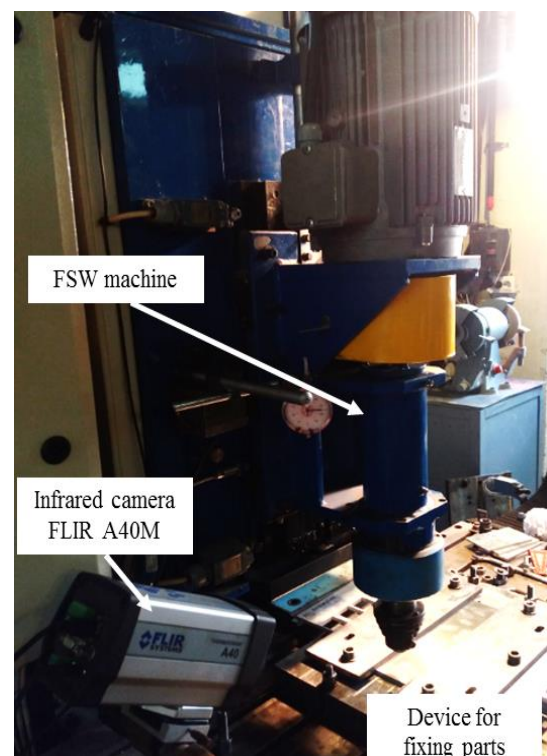
The aluminium alloy plates were cut to the guillotine to size 140 mm x 250 mm, with the large side along the laminating direction, the thickness of plates is 2 [mm]. The joining configuration of plates are presented in figure 2, with AA7075 in upper position, AA2024 in middle position and AA6061 in lower position. As well, in figure 3 is represented the experimental stand used.



**Figure 1.** Welding tool.



**Figure 2.** FSW process: isometric view and front view.



**Figure 3.** Experimental stand.

## 2.2. Base material

The aluminum alloys used for this study are the next: AA2024, AA6061 and AA7075. Effective chemical composition and effective mechanical characteristics of these three alloys, AA2024, AA6061 and AA7075, are presented in table 1 and table 2.

**Table 1.** Effective chemical composition for AA2024, AA6061 and AA7075.

	<b>Si</b>	<b>Fe</b>	<b>Cu</b>	<b>Mn</b>	<b>Mg</b>	<b>Cr</b>	<b>Zn</b>	<b>Ti</b>	<b>Ti+Zr</b>
<b>AA2024</b>	0.10	0.1	4.4	0.47	1.5	0.01	0.14	0.04	0.05
<b>AA6061</b>	0.74	0.4	0.2	0.14	0.9	0.18	0.09	0.05	-
<b>AA7075</b>	0.05	0.1	1.6	0.05	2.7	0.19	5.80	0.05	0.01

**Table 2.** Effective mechanical characteristics for AA2024, AA6061 and AA7075.

	<b>UTS [MPa]</b>	<b>YS [MPa]</b>	<b>Elongation [%]</b>
<b>AA2024</b>	464 to 466	344 to 348	17 to 18
<b>AA6061</b>	317 to 319	286 to 290	10 to 12
<b>AA7075</b>	593 to 594	531 to 532	11 to 12

## 2.3. Experimental plan

For process FSW, the input parameters, in welding process are: welding speed [mm/ min] and rotation speed [rpm]. In the actual paper, the experimental plane contained six experiments with minimum values, maximum values and middle values for both parameters. In table 3 is displayed the experimental plan with all parameters combination used in this study.

**Table 3.** Experimental plan for FSW aluminum alloys.

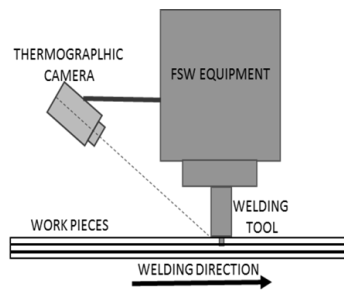
<b>Experiment code</b>	<b>Welding speed [mm/ min]</b>	<b>Rotation speed [rpm]</b>
<b>3.1</b>	70	600
<b>3.2</b>	70	1400
<b>3.3</b>	170	600
<b>3.4</b>	170	1400
<b>3.5</b>	120	1000
<b>3.6</b>	120	1000

## 2.4. Measurement of data in the process time

The output parameters for Friction Stir Welding process, recorded in process time are: temperature in welding seam and vertical force performed by the welding tool. In this experimental study both of these parameters were measured using special equipment.

The temperature, in welding seam, was captured behind of the tool, close by them on the welding line. Temperature was measured using a thermographic infrared camera, of the type FLIR A40M, and measured dates was extracted and recorded using the software ThermoCAM<sup>TM</sup>Researcher. The infrared camera can measure temperatures between -40 °C and + 2000 °C and a accuracy of  $\pm 2$  °C. The scheme with position of camera, the infrared camera and the software are presented in figure 4, figure 5 and figure 6.

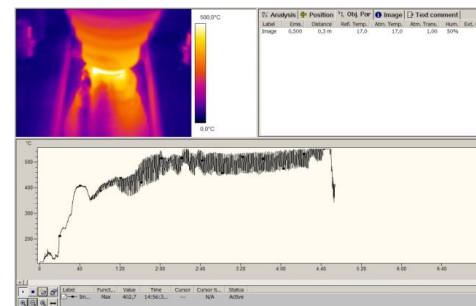
In process FSW, the interplay between welding alloys and tool, generate a reaction force, with vertical force, the most important component. The role of vertical component in welding process is very important, because this component represents the penetration force for the tool in welding materials.



**Figure 4.** Scheme of positioning for thermographic camera.

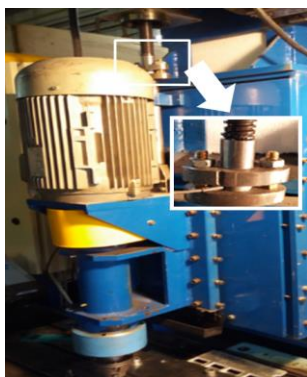


**Figure 5.** Thermographic infrared camera.



**Figure 6.** Temperature graphic recording in process time.

In this experimental study, the vertical component of force was measured with a force traducer, fixed on the device mounted on spindle of welding machine. The force traducer is AM type and have a range between 0 - 20 KN. In lower figures 7 and figure 8 is represented the force traducer and position of this in the welding system and, as well the extracted dates.



**Figure 7.** Force traducer type AM fixed on the welding machine.



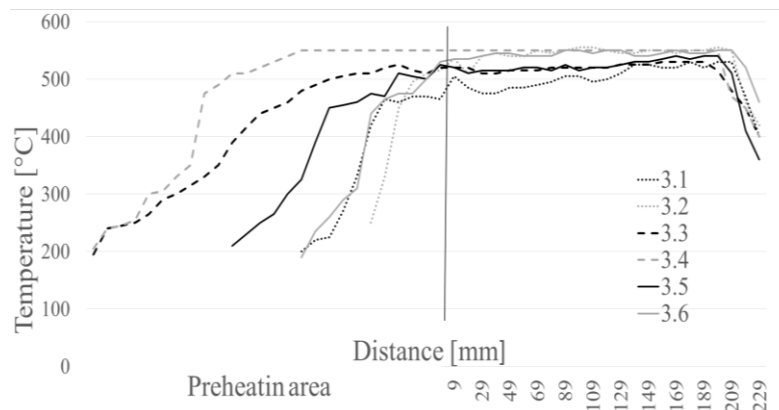
**Figure 8.** Vertical force graphic recording in process time.

### 3. Results and discussions

#### 3.1. Temperature evolution

Temperature evolution during Friction Stir Welding process for current experiments are recorded and presented in lower graph (figure 9). At the beginning of the graph, before the vertical line is represented the temperature evolution in penetration and preheating step and after this line is represented the temperature evolution in process welding time, along on the welding seam.

In upper table corner (table 4) is represented the maximum value for temperature in process time and, as well, the average temperature from process time (without first phase) for all experiments. For all experiments, the maximum value for temperature recorded in time of process, by thermographic camera, have very close, the differences between lower value (530 °C) and upper value (555 °C) is only 25 °C. The maximum recorded temperature is for experiments with maximum rotation speed value, experiment 3.2, and experiment 3.4. As well, the minimum temperature is recordet for experiments with minimum rotation speed value, experiments 3.1 and experiments 3.3.



**Table 4.** Maximum and average temperature during the welding process.

Exp. no.	Max. temp. [°C]	Average temp. [°C]
3.1	530	499
3.2	555	536
3.3	530	511
3.4	555	536
3.5	540	512
3.6	550	535

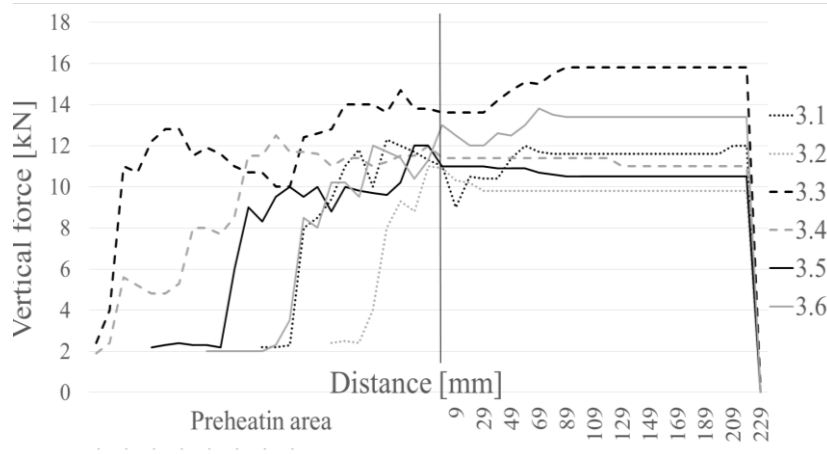
**Figure 9.** Temperature evolution for experiments.

The average have a simmilar evolution, for all six experiments, with maximum temperature, is bigger for experiments with rotation speed bigger and is smaller for experiments with rotation speed smaller. The difference between maximum and minimum average is 37 °C.

The temperature from process time is influenced, in a some extent by rotation speed parameter. When rotation speed is enlarged with 135%, the temperature in process time is enlarged with 5%. The welding speed parameter has not influenced in welding temperature.

### 3.2. Vertical force evolution

Evolution of vertical force during Friction Stir Welding process for this experimentas is presented in the lower graph (figure 10). In the upper place of the graph, before of the vertical line is represented the vertical force evolution in penetration and preheating step and after this line is represented the vertical force evolution in process welding time, along on the welding seam.



**Table 5.** Maximum vertical force in preheating area and in process time.

Exp. no.	Max. in preheating area [kN]	Max. in process time [kN]
3.1	12	12
3.2	11	10
3.3	15	16
3.4	13	11
3.5	12	11
3.6	13	14

**Figure 10.** Vertical force evolution for experiments.

The maximum recorded value for vertical force in preheating area is 15 kN and the maximum recorded value of vertical force in time of process is 16 [kN], both of them correspond with experiment 3.3. This experiment have the bigger value for welding speed (170 mm/min) and the smaller set value for rotation speed (600rpm).

The minimum value, recorded in preheating area, for vertical force is 11 kN and the minimum value, recorded in process time, for vertical force is 10 kN, for experiment 3.2, this experiment have the smaller value for welding speed (70 mm/min) and the bigger rotation speed parameter (1400 rpm).

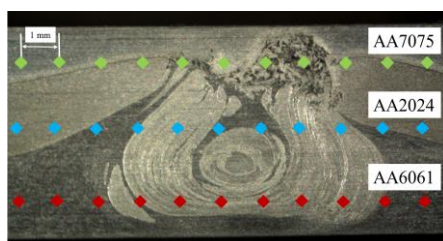


After 19 mm from the start, the vertical force has stabilized, for experiment 3.2, this being the smallest distance from start of the process to stabilization of the process.

All above comparisons demonstrate that combination between welding speed value and rotation speed value is an important criteria for value of vertical force. When welding speed have a smaller value and rotation speed a bigger value, the vertical force will be smaller.

### 3.3 Micro-hardness evolution analysis

The micro-hardness value was measured using electronic micro-hardness, type Innova Test Falcon500, in one area for all experiments. This area is at a distance of 230 [mm] from the welding start. The measurements have been performed perpendicular on the welding tool direction, in three layers of depth. For each material one layer allocated, at distance of 1, 3 and 5 [mm] from the weld surface. The micro-hardness was performed in 11 points at 10 [mm] along the welding centre. The measured points are presented in lower figure 11.



**Figure 11.** The micro- hardness measurements points.

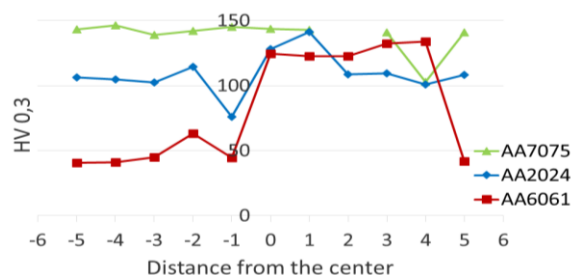
**Table 6.** Average micro-hardness for experiment [HV 0.3].

	3.1	3.2	3.3	3.4	3.5	3.6	Base mat.
AA7075	139	134	144	127	147	141	189
AA2024	109	107	119	105	109	94	141
AA6061	83	72	63	90	87	96	41

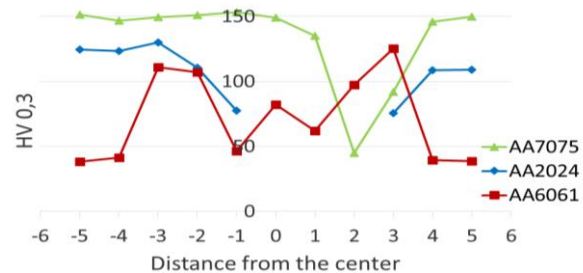
In figures 12-17 is presented the micro-hardness evolution and in table 6 is presented the average of micro-hardness for all experiments and for base aluminium alloy. The values for average micro-hardness are approximately similar, for all six experiments. As well as the value of micro-hardness for welding parts are different from the value of base material, because of mechanical mixture characteristic of the FSW process.

The nearest values of micro-hardness to the base materials is for experiment 3.3, they result from a poor mixing for this experiment. The parameters, for this experiment are: welding speed in bigger value and rotation speed in the smaller value. On the other hand, the most distant value of micro-hardness to the base materials is for experiment 3.4, the both parameters, welding speed and rotation speed are in bigger situation. It can be seen that rotation speed value have an important influence in mechanical mixing in welding process of materials. The best combination for micro-hardness is represented by welding speed and rotation speed in bigger value.

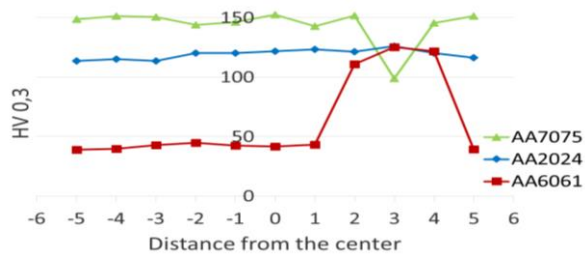
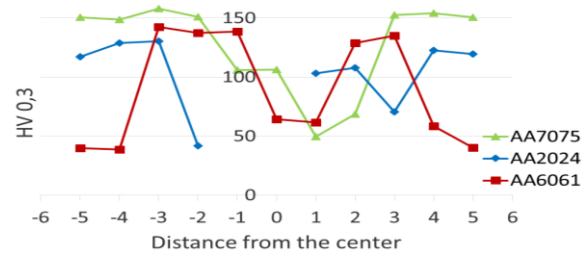
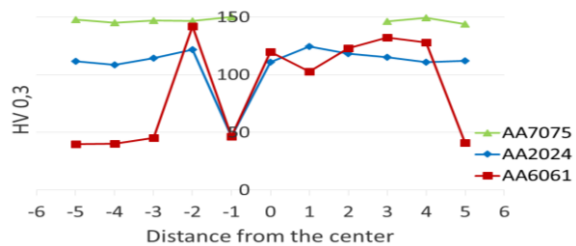
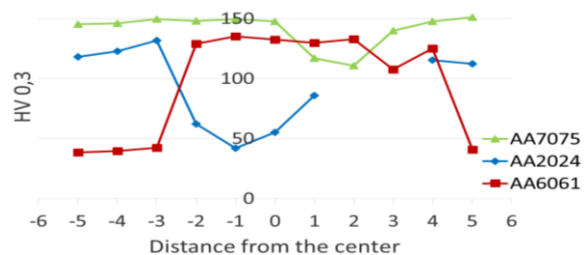
After FSW welding, generally can be mentioned that micro-hardness is in smaller value that base materials.



**Figure 12.** Evolution of micro-hardness for 3.1.



**Figure 13.** Evolution of micro-hardness for 3.2.

**Figure 14.** Evolution of micro-hardness for 3.3.**Figure 15.** Evolution of micro-hardness for 3.4.**Figure 16.** Evolution of micro-hardness for 3.5.**Figure 17.** Evolution of micro-hardness for 3.6.

The second difference between this experiments is represented by the spread of value in upper graphs. The best spread can be observed for experiments 3.4 and 3.2, this experiments have bigger value for rotation speed, the next two experiments with good spread are experiments 3.5 and 3.6 this two have similar parameters and the rotation speed is at middle value. The worst spread can be observed for experiment 3.3 with worst parameter combination.

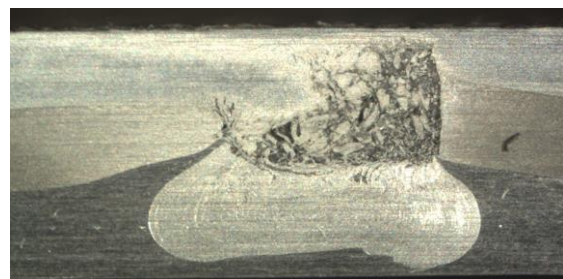
### 3.4. Macrostructure evolution analysis

The macrostructure extracts were made in one position for all six experiments, this are located at 140 [mm] from the welding start. This captures are presented in figure 18-23.

For all six experiments, the macroscopic examination revealed defects or imperfection in welding seams, such as: tunnels, worm hole, pore or lack of fusion between materials.

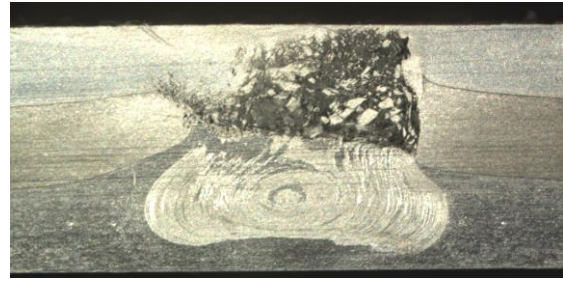
The worst experiments, full of defects, are experiments 3.2 and 3.4. These experiments were performed with bigger value set for rotation speed. The best experiments, with the least defects are experiments 3.1 and 3.3, for this two the rotation speed was at smaller value.

The weld nugget is good defined for 5 experiments, but for experiment 3.3 the mixing was not fully performed, because of parameters set.

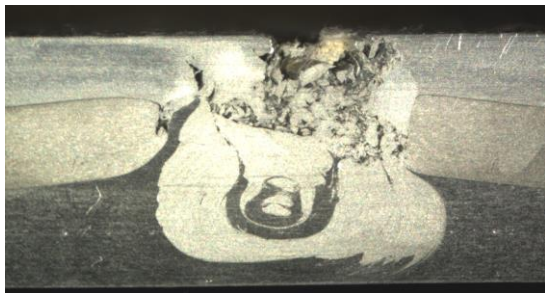
**Figure 18.** Macrostructure for experiments 3.1.**Figure 19.** Macrostructure for experiments 3.2.



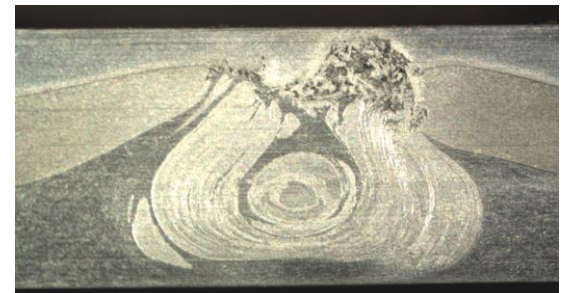
**Figure 20.** Macrostructure for experiments 3.3.



**Figure 21.** Macrostructure for experiments 3.4.



**Figure 22.** Macrostructure for experiments 3.5.



**Figure 23.** Macrostructure for experiments 3.6.

Looking at the macrostructure characteristics for all six sets of parameter, the best aspect is for experiment number 3.1 where the both parameter was sets at minimum value: rotation speed 600 rpm and welding speed 70 mm/min.

#### 4. Conclusions

Based on the researchers results and based on the analysis presented in this paper, the following main conclusions are drawn:

- This paper did not achieve the best result, but is a first step for future researches which involves joining three dissimilar materials.
- In Friction Stir Welding process, the rotation speed value is very important and influences the temperature of the welding process. In these researches, the temperature grows with 5% after rotation speed grows with 135%. The welding speed has not influence in process temperature.
- In this research, was showed that a good combination between higher value of rotation speed and smaller value of welding speed decreases the vertical force.
- In this study, is demonstrated that the micro-hardness value is smaller after Friction Stir Welding for all three materials: AA7075, AA2024 and AA6061.
- The best micro-hardness value was identify when the both welding parameters (welding speed and rotation speed) was in upper limit.
- Macrostructure analysis demonstrate that, until now, for this process have not been identified the correct parameters. All six experiments presented defects in welding seams but, the best macrostructure was identified for the experiment with smaller value for welding speed and smaller value for rotation speed.
- Friction Stir Welding for this three aluminium alloys (AA7075, AA2024, AA6061) used in aeronautics industry is at the beginning of the road, but has a great potential for development.

#### Acknowledgements

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## 5. References

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