

Friction Stir Welding of three dissimilar aluminium alloy used in aeronautics industry

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Abstract. Friction Stir Welding (FSW) is an innovative solid-state joining process. This process was, in first time, develop to join the similar aluminum plates but now the technology can be used to weld a large area of materials similar or dissimilar. Taking these into account FSW process, for dissimilar materials are increasingly required, more than traditional arc welding, in industrial environment. More than that FSW is used in aeronautics industry because of very good result and very good weldability between aluminum alloy used at building of airplanes, where the body of airplane are 20% aluminum alloy and this percent can be increaser in future. In this paper is presented an experimental study which includes welding three dissimilar aluminum alloy, with different properties, used in aeronautics industry, this materials are: AA 2024, AA6061 and AA7075. After welding with different parameters, the welding join and welding process will be analyzed considering process temperature, process vertical force, and roughness of welding seams, visual aspect and microhardness.

1. Introduction

Friction stir welding is a new welding technique invented for aluminum alloy by The Welding Institute - TWI, U.K., in 1991, but before that the principle of solid state welding process have emerged in 1956 in the Soviet Union. In last years this innovative welding process gaining wider industrial applicability like: shipbuilding and offshore, aerospace, aeronautics, automotive, railways, general fabrication, nuclear, military, robotics and computers [1]. Now, this process is developed form materials similar or dissimilar such as: cooper, brass, magnesium, titanium, steel [2], polymeric materials [3] or metal matrix composites (MMCs), such as Al₂O₃, SiC, Si₃N₄ or B₄C [4].

Compared to other welding processes, the FSW has many advantages including the following: edge pieces do not have needed additional preparation, the procedure can be automated and performed in all positions, the welding procedure is perform without consumables, FSW can be used for alloys that cannot be welded with traditional method [5] and is termed “green technology” due to its energy efficiency and environmental friendliness [6]. On the other hand FSW process has several disadvantages such as: a great tool wear, weld speeds are slower, equipment is massive and expensive, friction stir welding for high melting temperature materials have limitations [7].

Considering that FSW process was invented to combine the aluminium alloy, until now the primary research and industrial interest has been to join aluminium alloys. Defect-free welds with good mechanical properties have been made for variety types of aluminium alloy even those previously thought to be impossible to weld, in thicknesses from less than 1 [mm] to more than 35 [mm] [8].



The dissimilar welding of aluminium alloys has attracted more attention, since it offers an insight into many phenomena which were not clear during the friction stir welding of similar aluminium alloys. Many topics like variation of microhardness, material flow, material location, temperature distribution, vertical force distribution, residual stresses, and so forth, across the interface of the abutting materials and their consequent effect on the mechanical properties are of interest to many researchers [9–11].

Since the occurrence of this process, FSW has found great development and importance in the aeronautics industry, in especially for the welding parts of aluminium alloy like: AA2024, AA6061 and AA7075. Until now, this three alloys was weld and mixed together two by two, AA2024 with AA6061 [12], AA2024 with AA7075 [13] and AA6061 with AA7075 [14] with good result, but they have never been welded all three. This paper has purpose to analyse the behaviour of joints these three materials according to input parameters.

2. Experimental procedure

2.1. Base materials

In this experimental procedure was used three different aluminum alloy, welding together, one above the other. All of them are used in aeronautics industry, for construction of different parts of planes, this materials are: AA2024, AA6061 and AA7075.

Plates dimensions for this are 140 [mm] x250 [mm] with thickness equal with 2 [mm]. For all three, the effective chemical composition are listed in Table 1 and effective mechanical characteristics are listed in Table 2.

Table 1. Chemical composition of AA2024, AA6061 and AA7075 aluminium alloys

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ti+Zr
AA2024	0.10	0.11	4.40	0.47	1.50	0.01	0.14	0.04	0.05
AA6061	0.74	0.40	0.22	0.14	0.90	0.18	0.09	0.05	-
AA7075	0.05	0.10	1.60	0.05	2.70	0.19	5.80	0.05	0.01

Table 2. Mechanical characteristics for AA2024, AA6061 and AA7075 aluminium alloys

	UTS [MPa]	YS [MPa]	Elongation [%]
AA2024	464 to 466	344 to 348,8	17 to 18
AA6061	317 to 319	286 to 290	10 to 12
AA7075	593 to 594	531 to 532	11 to 12

2.2. Welding process

The dissimilar materials AA2024, AA6061 and AA7075 were joined according lower configuration, presented in Figure 1 and Figure 2. The position of this, in package, for welding are: AA6061 in upper position, AA7075 in meddle position and AA2024 in lower position.

All three plates were fixed with a special device, on the machine table, in welding time. The welding process was performed in three steps: (1) tool was vertically plunged through the upper plate (AA6061), the second plate (AA7075) and partially in third plate (AA2021), (2) the tool travel along the welding seam and joining this plates, (3) at the end, the tool was vertically extraction and on the following this, in materials remains a hole with a diameter equal to the diameter of the pin tool. The width difference, between welding plates, was compensated through three additional plates with dimensions 60x250 [mm] with thickness 2 [mm].

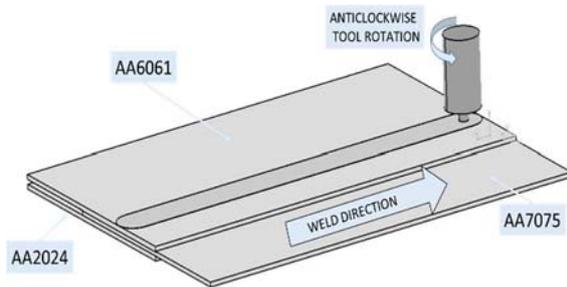


Figure 1. Friction Stir Welding process – isometric view

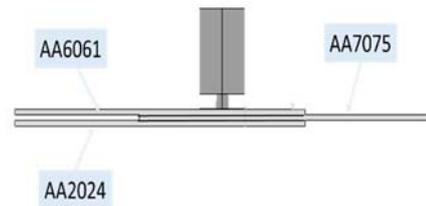


Figure 2. Friction Stir Welding process – front view

The welding tool, used to joint this three aluminium alloy, is a cylindrical tool, with the diameter of the shoulder equal with $\phi 22$ [mm] and the pin with shape threaded M6 and high equal with 5.3 [mm]. The tool material is P20+S (carbide of sintered tungsten), Figure 3. The joining by FSW process of the plates was performed with the anticlockwise tool rotation on the middle of the package upper described. The process performing are showed in Figure 4.



Figure 3. Welding tool

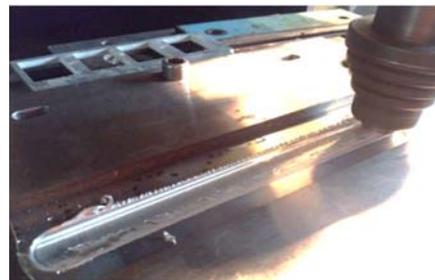


Figure 4. FSW process performing

2.3. Measurement of data during the process

During the friction stir welding process it was measure two output parameters: the temperatures and the vertical force exerted by the welding head. In process time, the temperature was measured using a high-speed and high-sensitivity thermographic infrared camera (FLIR A40M), the used camera have a field of temperature measurement between -40 [$^{\circ}\text{C}$] and $+ 2000$ [$^{\circ}\text{C}$], this is presented in Figure 5. Measurement was made on the welding line, behind the welding tool shoulder, very close by them. The measure dates was extracted using ThermoCAM™ Researcher specialized soft, and look like in Figure 6.



Figure 5. Thermographic infrared camera (FLIR A40M)

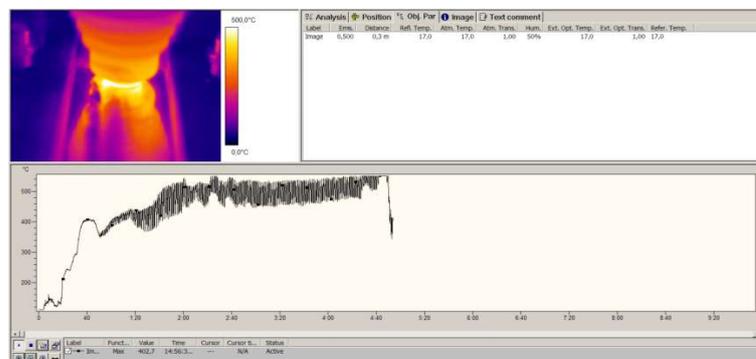


Figure 6. Temperature graphic recording in process time

Interaction between tool and plates generate a reaction force from the material, the most important component of this force for friction stir welding process are vertical force. This vertical force is necessary to accomplish effective welding and it represents the force of penetration of a tool in base material. The vertical force was measure with a mechanical device that has a fixed force transducer, type AM, with range between 0 [kN] and 20 [kN], mounted on main spindle the FSW machine and the information captured are extracted using a special soft. In Figure 7 is represented force traducer type AM mounted on the FSW machine and in Figure 8 is represented graphic with values of force recording in process time.



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



Figure 8. Vertical force graphic recording in process time

After welding process, on the samples, was measured roughness and microhardness. The roughness, was measured with the electronic roughness tester, type MarSurf PS 10, and microhardness was measured with electronic microhardness tester, type Innova Test Falcon 500.

2.4. Experimental plan

In friction stir welding, the input parameters used are: the rotation speed of the welding tool [rpm] and welding speed [mm/min]. In this experiments, the welding speed was keep the same for both attempts and rotation speed of the welding tool was modified in two situation (minimum and maximum) according with lower table.

Table 3. Experimental plan for FSW

Code of experiment	Welding speed [mm/min]	Rotation speed [rpm]
2.1	70	600
2.2	70	1400

3. Results and discussions

3.1. Temperature evolution analysis

Temperature evolution during FSW process for both two experimental situation is presented in Figure 9. In first part of graph, in front of the orange line is represented evolution of temperature in penetration and preheating phase and after orange line is represented evolution of temperature in welding process time on the length of the welding seam.

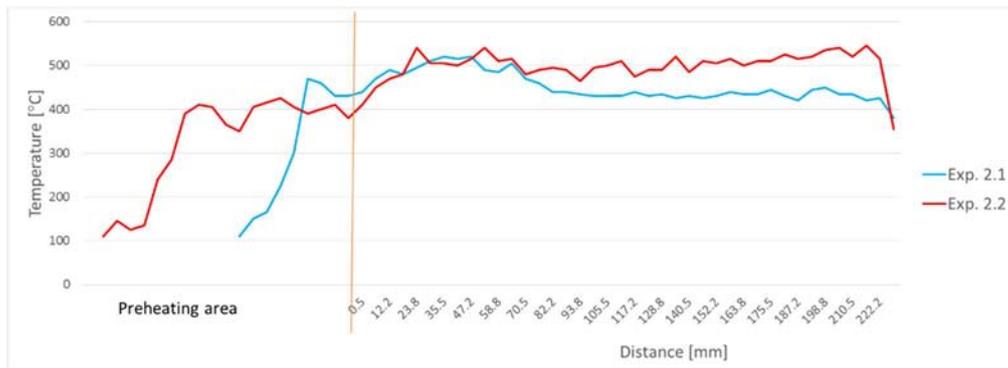


Figure 9. Evolution of temperature for experiments 2.1 and 2.2

The maximum temperature recorded in process time by thermographic infrared camera have very similar for the two experimental cases: for experiment. 2.1 is 520 [°C] and for experiment. 2.2 is 545 [°C], below the melting point. Difference between them being the position of the welding seams, for the experiment 2.1 the maximum temperature are at 35 mm and 50 mm from the start and for experiment 2.2 the maximum temperature are at 25 mm, 55 mm and at 220 mm from the start. The average temperature, in time of process, is bigger with 50°C for experiment 2.2 than experiment 2.1. For one is 450°C and for second is 500°C.

The differences between this two experiments show a small influences of rotation speed concerning temperature. Like example for experiment with bigger rotation speed (more than double) the average of temperature in process time was bigger, and, the same, the maxim point of temperature was bigger but, the difference is just by 50 [°C] for average value and 25 [°C] for maximum value.

3.2. Vertical force evolution analysis

Vertical force evolution during FSW process for both two experimental cases is presented in Figure 10. In first part of graph, in front of the orange line is represented evolution of vertical force in penetration and preheating phase and after orange line is represented evolution of vertical force in welding process time on the length of the welding seam.

The maximum vertical force recording in process time, is very different for preheating area, for experiment 2.1, the maximum value is 16 [kN], double versus experiment 2.2, where the maximum vertical force in preheating area is 8 [kN]. This means that for lower value for rotation speed, the vertical force transmitted by the machine is higher.

The vertical force was stabilised after 60 mm from the start, for experiment 2.1, and faster, at 35 mm from the start, for experiment 2.2. Differences exist also at average vertical force in welding time, for first, experiment 2.1, the average force is 8,8 [kN], and for experiment 2,2 the average is 7,2 [kN]. This means that welding machine is much more demanded for experiments with lower level used for rotation speed.

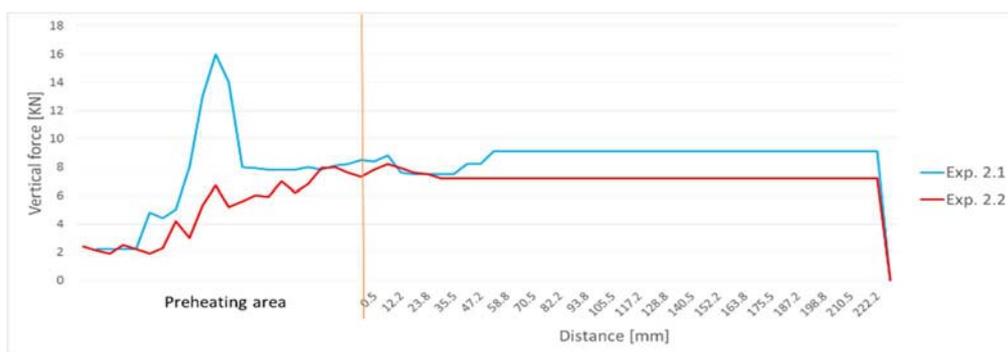


Figure 10. Evolution of vertical force for experiments 2.1 and 2.2

3.3. Roughness evolution analysis

The weld seams exhibit a satisfactory visual aspect, without hole or cracks, in both samples, the difference being due to the presence of burrs on the advancing side for experiment 2.2. Both of them are present in Figure 11 and Figure 12. The causes for this can be the bigger temperature achieved during the process.

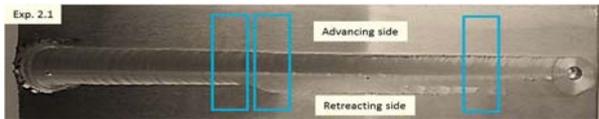


Figure 11. Visual aspect of experiment 2.1



Figure 12. Visual aspect of experiment 2.2

The roughness was measured in three different areas, on a sample located at 90 [mm] to the start point, on a sample located at 110 [mm] to the start point and on a sample located at 200 [mm] to the start point (blue/ red area marked in Figure. 11 and Figure. 12). Three measurements were made on each sample. The average value of the roughness, in all three samples are represented in Figure. 13. In lower graphic is shown a decrease of roughness value from the start welding seams to the end of welding seams. This evolution highlights a stabilization of the process during its realization.

The difference between the values of roughness, for this two experiments, can be explained by rotation speed: for lower rotation speed the roughness is lower and for bigger rotation speed the roughness is bigger.

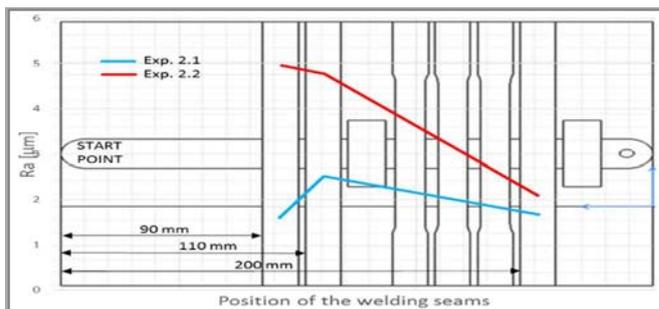


Figure 13. Evolution of roughness for experiments 2.1 and 2.2

3.4. Microhardness evolution analysis

The microhardness was measured in two areas for both experiments, first on a sample located at 140 [mm] to the start of weld and second on a sample located at 230 [mm] to the start of weld. The microhardness (Vickers HV0,3) has been realized perpendicular on the tool movement direction along the welding elements, on three lines of depth, one for each material, at 1 [mm], 3 [mm] and 5 [mm] from the weld surface. On each line, microhardness was measured in 11 points, on 10 [mm] around the welding centre. The sketch with measured points are presented in Figure 14.

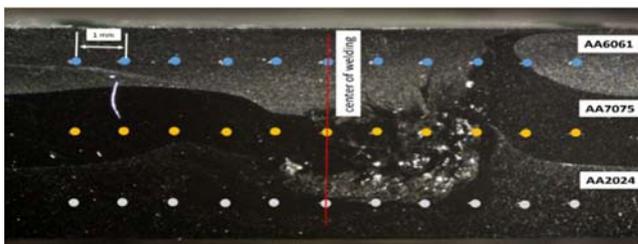


Figure 14. The place of the microhardness measurements points

The evolution of microhardness, for experiments 2.1 and 2.2, in two positions for every one of them are presented in Figure 15, Figure 16, Figure 17 and Figure 18 and average value for microhardness are presented in Table 4. For first experiments, 2.1, from first sample to second sample exist some differences. The value for average microhardness, are different, in middle position the second is bigger

wit 30 [HV0.3] than first. The second difference between them is represented by spread of values, for first, in AA7075 the minimum value of microhardness are spread from the centre with 4 [mm] in advancing side and with 1 [mm] in retracting side, for the second experiment spread are the next, 1 [mm] in advancing side and 1 [mm] in retracting side. This effect can be caused by stabilizing the FSW process.

Table 4. Average microhardness for experiment 2.1 and for experiment 2.2

Average microhardness [HV 0.3]	Experiment 2.1		Experiment 2.2	
	At 140 [mm] to the start	At 230 [mm] to the start	At 140 [mm] to the start	At 230 [mm] to the start
AA6061 upper position	44.7	41.5	58.0	59.4
AA7075 meddle position	91.5	121.2	124.0	131.4
AA2024 lower position	133.6	130.6	127.5	116.1

On the other hand, between experiment 2.1 and experiment 2.2 can be seen big differences. In first, the average of microhardness are bigger on the first two line with approximate 20 [HV 0.3] etch and smaller for lower line with approximate 10 [HV 0.3]. Another difference are between spread of value, for experiment 2.2, all big variations are after centre point on the retracting side between 1 [mm] and 5 [mm] or 0 [mm] and 4 [mm]. Third difference is represented by bigger variation of microhardness value for second experiment, this means a good blending of the three materials in welding process.

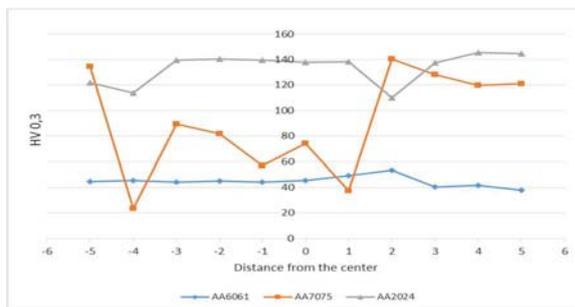


Figure 15. Evolution of microhardness for experiments 2.1 at 140[mm] to the start of weld

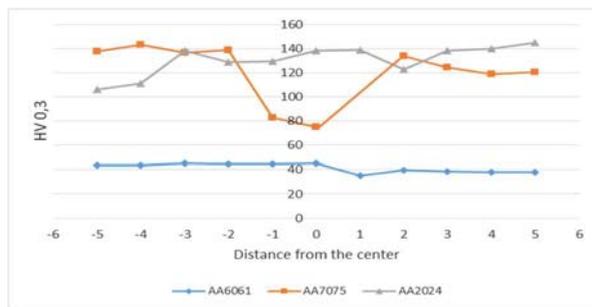


Figure 16. Evolution of microhardness for experiments 2.1 at 230[mm] to the start of weld

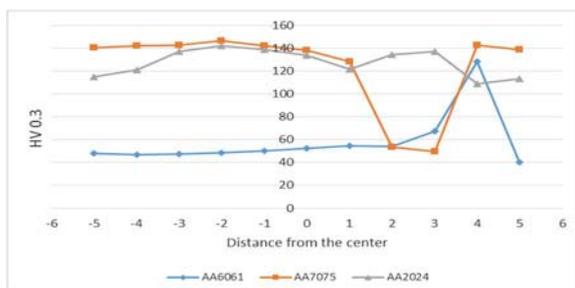


Figure 17. Evolution of microhardness for experiments 2.2 at 140[mm] to the start of weld

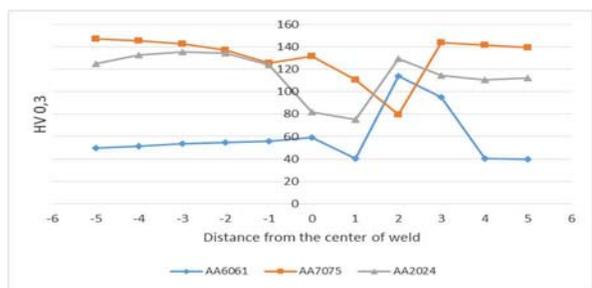


Figure 18. Evolution of microhardness for experiments 2.2 at 230[mm] to the start of weld

4. Conclusions

As a result of the researches carried out and the analysis presented above, the following main conclusions are drawn:

1. Welding of three dissimilar materials, is a new step to the new research topics.
2. In FSW process, the rotation speed is a very important parameter and have a big influence on the temperature of the process. In this study differences of 50 [°C] is given by the doubled value of rotation speed.

3. Vertical force is an important output parameter, when this parameter is bigger means that welding is much more demanded. In this study, was demonstrated that higher value for rotation speed improves (decreases) the vertical force.
4. The value of roughness is smaller when the rotation speed is smaller, and increases with increasing rotation speed. For both experiment the value of roughness decreased with the progress of the welding process, from the beginning of the seams to the end of this.
5. Evolution of microhardness was different for this two experiment. The good results, and the better shuffle of metals was identified in second experiment, where the rotation speed value was bigger.

In the future work this study will be extend to a large set of parameters, other variants to positioning this three materials and to analysis of macrostructure, microstructure, tensile test etc.

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