Application possibilities of the friction stir welding process to dissimilar aluminum alloys

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1. Introduction

Because the physical and mechanical properties of aluminum alloys, interest for use in the manufacture of products in priority areas is in continuous development.

The aluminium alloys from the 5xxx and 6xxx classes are more frequently used for the fabrication of complex structures or structural elements that need proper corrosion and fatigue resistance. Based on this issue the need to develop new joining methodologies to join these alloys represents a world wide interest.

Welding of the materials with low melting points is realized mostly using the traditional arc welding processes.

The environmental friendly friction stir welding (FSW) process provides a efficient technological alternative to the arc welding procedures.

Friction stir welding process allows the connection of an important number of similar and dissimilar materials, which are difficult or impossible to be welded using other welding procedures [1].

At FSW technique, location of dissimilar materials (left or right) must be correlated with the direction of rotation and displacement of the welding tool. This placement also causes which material is predominantly pushed into the cavity behind the welding tool. Location of the welding tool axis relative to the joint line can also affect the characteristics of the weld [2].

Physical and chemical compatibility of the two welding materials is also important. Materials must provide comparable flow characteristics at temperatures reached during the welding process ($\approx 0.8 \cdot T_{melting}$)[3].

2. Materials

Behaviour of material to FSW is given mainly by its properties, ductility and toughness, tool geometry and welding process parameters FSW [4], [5].

EN AW 1200 aluminium alloy has very good corrosion resistance, high thermal conductivity, good weldability, high resistance. High corrosion resistance is due to formation of surface oxides Al_2O_3 films, compact and adherent. By the anodic oxidation, a coating layer with thickness and high quality is obtained. This makes it usable in construction and civil engineering, but also in the food industry, heat exchangers, etc.

The alloy EN AW 5083 is often used for applications in civil engineering, especially to the bridge construction, because of good corrosion behaviour and the good weldability.

Aluminum alloys from 6xxx series, that containing Si and Mg in proportions leading to the formation of compound Mg_2Si, are heat treatable. Alloying elements of alloy EN AW 6082 gives a good mechanical strength, good behavior in the process of extrusion, high resistance to corrosion and fatigue.

These qualities make the material to be used in railway structures, truck frames, shipbuilding, bridges, bicycles, platforms, hydraulic systems, mining equipment, nuclear industry, etc.

EN AW 7075 (Al-Zn-Mg-Cu) aluminium alloy is recommended for large utilization in aerospace and nuclear fields, through its high mechanical resistance and low weight.

Parts realized using EN AW 7075 are designed following some severe rules about weight and resistance. Developing and improving of welding techniques for this material is the most effective way of meeting the imposed requirements.

Chemical composition for these materials are presented in Table 1, and mechanical characteristics in Table 2.

Table 1. Chemical composition

Material	Chemical composition (%)								
	Al	Mg	Mn	Si	Fe	Zn	Cr	Ti	Cu
EN AW 1200	98.62	-	-	0.78	0.6	-	-	-	-
EN AW 5083	93.41	4.5	0.7	< 0.4	< 0.4	< 0.25	0.15	0.15	< 0.1
EN AW 6082	96.66	1.2	0.62	1.06	0.38	0.01	-	-	0.06
EN AW 7075	89.79	2.5	0.01	0.05	0.2	5.8	0.17	0.08	1.4

Table 2. Mechanical characteristics

Material	Rm (MPa)	$Rp_{0.2}$ (MPa)	A5 (%)	HV
EN AW 1200	107	98	19	37
EN AW 5083	315	228	16	96
EN AW 6082	322	297	11	110
EN AW 7075	540	465	13	160

3. Experimental program

The experimental program was conducted on the specialized FSW welding machine from National Research and Development Institute for Welding and Material Testing - ISIM Timisoara, with the following main technical characteristics:

- adjustable welding speed range: 60-480 mm/min;
- adjustable speed of the welding tool in range: 300-1450 rot/min;
- usable stroke (welding): 1000 mm.

Welding parts were butt positioned and rigidly fixed on a steel backing plate. Welds were made in the direction of plate rolling.

FSW behaviour for following couples of aluminum alloys were analyzed: EN AW 1200-EN AW 6082, EN AW 6082-EN AW 5083, EN AW 7075-EN AW 6082 and EN AW 1200-EN AW 7075 (plates with s_1 = 6mm thickness), respectively EN AW 7075 - EN AW 5083 (plates with s_2 = 5mm thickness).

There have been used two types of welding tools:

- one with threaded cylindrical pin and flat shoulder with Ø = 18 mm diameter (Figure 1)

- one with threaded tapered pin and a shoulder with machined spiral flute, having a diameter of Ø = 18 mm (Figure 2) [6].

Length of the pin was corellated with thickness of the welding plates.

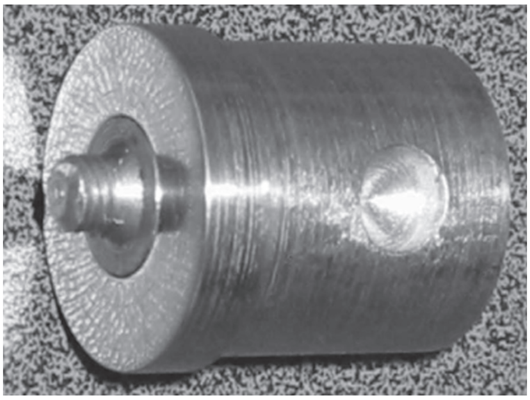

Figure 1. Welding tool with M6 threaded cylindrical pin

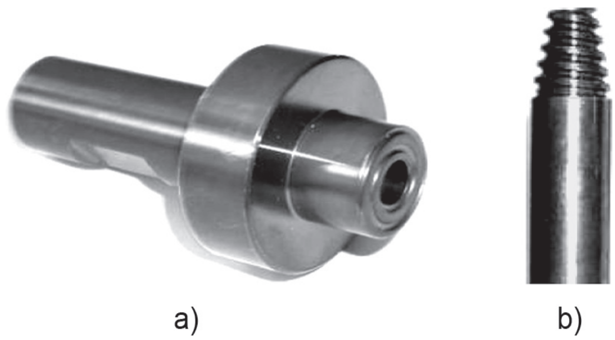

Figure 2. Welding tool: a) tool shoulder with machined spiral flute; b) tapered threaded pin

The welding parameters that have been used are presented in Table 3.

Table 3. Used welding parameters

Nr. Crt.	Materials EN AW	Thickness (mm)	Parameters	
			Rotational speed (rot/min)	Welding speed (mm/min)
I	6082 - 1200	6	800 - 1200	120 - 200
II	6082 - 5083	6	1000 - 1400	120 - 200
III	7075 - 6082	6	800 - 1200	80 - 150
IV	7075 - 5083	5	800 - 1300	80 - 160
V	7075 - 1200	6	1100 - 1300	120 - 150

They conducted experiments with placing materials in the two possible variants, left or right relative to the direction of rotation and advance of the welding tool, as shown in Figure 3.

Also have used different positioning of the axis of symmetry of the welding tool in relation to joint line.

For the evaluation of the FSW welded joints a research program, including metalographic macro and microscopical analysis, hardness measurements, tensile and bending tests, was developed.

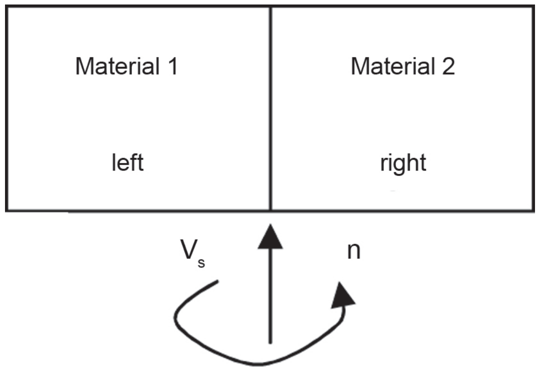

Figure 3. Location diagram of welding materials

Based on the values of temperature measurements made with an infrared thermographic camera, could be achieved the evolution diagram of temperature during FSW welding process. Measurements were made on the joint line at a distance of 1 mm behind the welding tool shoulder.

To see how temperature varies in the two materials during welding, measurements of its were made perpendicular to joint line at different distances from the weld start and have drawn the graphs of variation involved. In this case measurements were made at 50 mm, 200 mm and 350 mm from the weld start. Values were measured perpendicular to the joint line on a total width of 50 mm, symmetrical about the joint line, ± 25 mm.

4. Results. Discussion

The experimental program showed different behavior of the discussed aluminum alloy couples to application of FSW process.

When welding material EN AW 7075 - EN AW 1200, even though we used several combinations of parameters in the range of values given in Table 3, have not obtained good welded joints (even when changing tool welding rotation, which is equivalent to changing the location of plates of two alloys in relation with the tool).

Aspects of samples after FSW is presented in Figure 4.

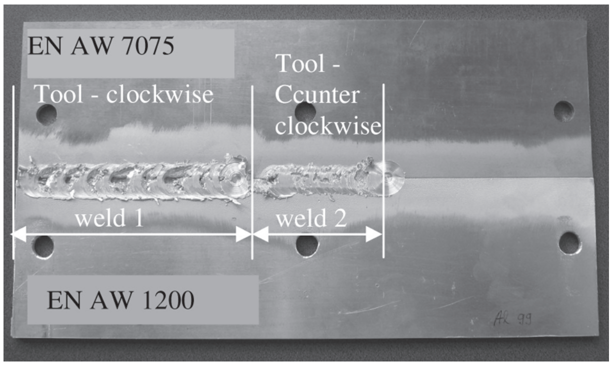

Figure 4. Friction stir weld EN AW 7075-EN AW 1200

Following the evolution of temperature using infrared thermography, it appears that, unlike other couples of materials, the diagram shows high variations during the welding process (Figure 5).

Negative results obtained can be attributed to large differences between the two materials in terms of chemical composition, but also the physical and mechanical properties.

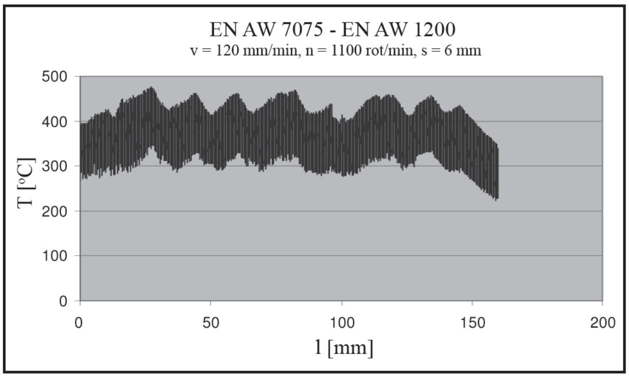

Figure 5. Evolution of temperature during FSW process, EN AW 7075 - EN AW1200

For other couples of materials have obtained welded joints with good characteristics, using the parameters from Table 4 and placement schemes from Figure 6.

Table 4. Used welding parameters

Nr. Crt.	Materials EN AW	Thickness (mm)	Parameters	
			Rotational speed (rot/min)	Welding speed (mm/min)
I	6082 - 1200	6	1200	180
II	6082 - 5083	6	1200	180
III	7075 - 6082	6	1200	110
IV	7075 - 5083	5	1100	100

Samples for macroscopic analysis, hardness, static testing in bending and tensile, from areas to the beginning, middle and end welded, were cut.

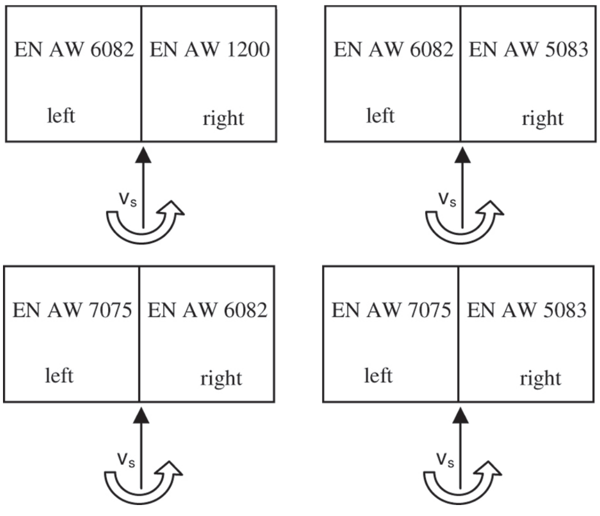

Figure 6. Location of welding materials

Figure 7 shows macroscopical aspects of welded joints for four couples of aluminum alloys.

The macroscopic images shows the characteristic FSW welded joint, without defects/ imperfections, with a well defined nugget. It is obvious for each case the way how the two aluminium alloys have been “mixed”. It is quite clearly observed concentric elliptical rings in the nugget.

Experiments have shown that it is very important to FSW of dissimilar materials, how they are placed in relation to the direction of rotation and advance of the welding tool.

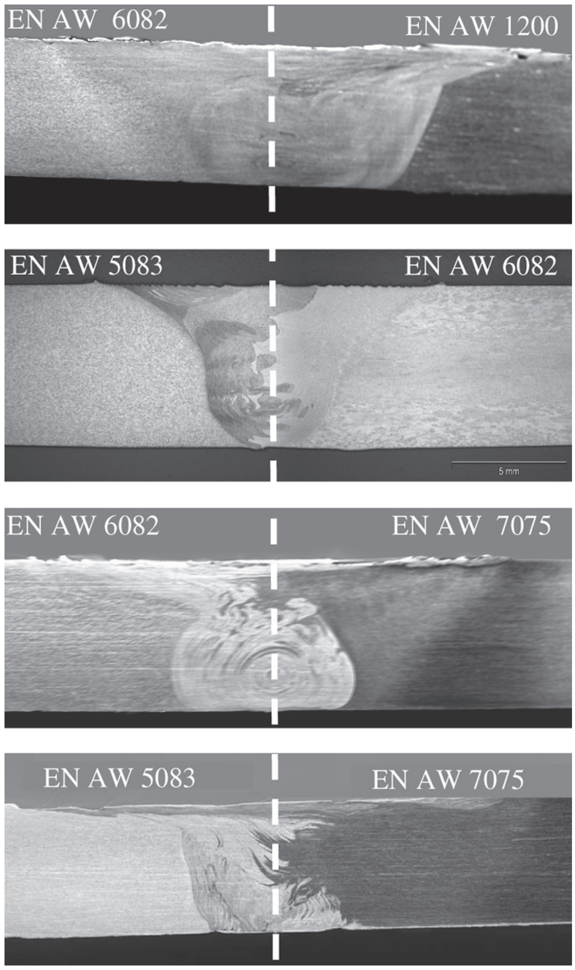

Figure 7. Macroscopical aspects

For example, to the welding of couple EN AW 7075-EN AW 5083, if EN AW 5083 is located on the left and EN AW 7075 the right to the direction of movement of the tool, the direction of rotation and advance as in the Figure 6, a welded joint with defects / imperfections is obtained (Figure 8).

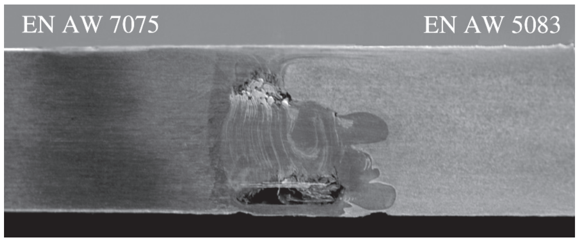

Figure 8. FSW welded joint, with defects

Also must be established and rigorously follow the welding parameters. The importance of this aspect is illustrated, to the same couple of materials, in Figure 9.

The use of welding parameters with different values from the optimum, can result in obtaining of welded joints with defects, although these differences are minimal (in this case ≈ 10%).

Control with penetrant liquids revealed no cracks or surface defects of welded joints.

Analyzing the evolution of the temperature diagram, its uniformity is observed along the full length of the welded joint, after the welding process has stabilized (after approximate 50 - 70 mm from the beginning of the welding process), Figure 10.

After the stabilization process, the average temperature recorded in the joint line area was about 450°C.

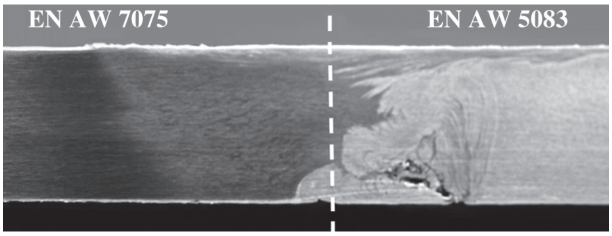

Figure 9. Welded joint EN AW-7075-EN AW 5083

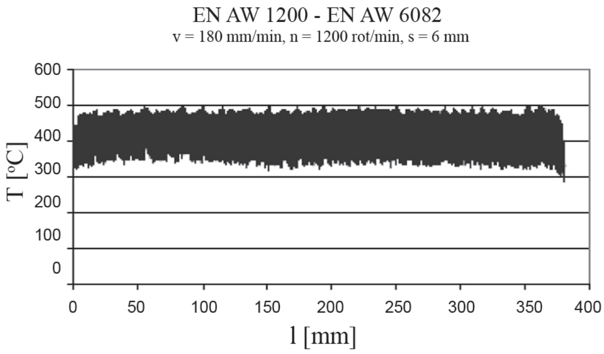

Figure 10. Evolution of temperature during FSW welding process

Comparing the evolution of temperature diagram on a direction perpendicular to the joint line in the three times of measurements (Figure 11) can lay down several conclusions that may have an important role in the evaluation of welded joints and research results generally:

- after 50 mm of welding, process is not yet stabilized and did not reach optimum plasticizing temperature of materials (75 - 80% of melting temperature).

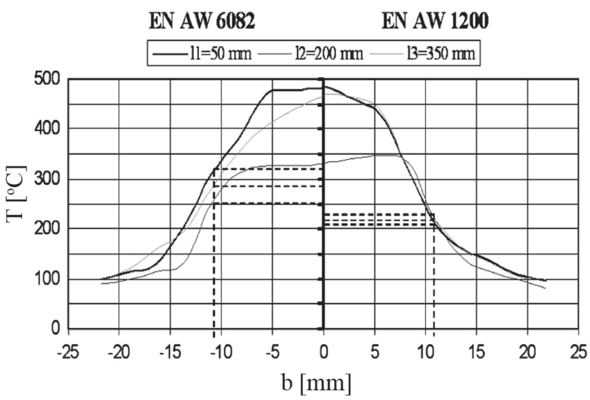

Figure 11. Comparative evolution of temperature

- after the welding process stabilization, the highest temperatures were recorded in the joint line area ≈ 465°C (temperature was ≈ 330°C at 50 mm from the beginning of FSW).

- in interference zone of the welding tool shoulder and welding materials, to ± 11mm from joint line, the following temperatures were recorded: 250 - 300°C (EN AW 6082), respectively ≈ 230°C (EN AW 1200).

The evaluation of the joints has been realized also through the comparison of the mechanical strength, static tensile tests of base material (R_{mBM}) and welded joints (R_{mWJ}). The testing conditions and the static tensile tests results are presented in Table 5.

Table 5. The testing conditions and the static tensile tests results

Equipment for tensile test: MU 100KN ZD 10/90			
Testing conditions: Temperature 16°C, Humidity 42%			
Materials EN AW	R_m (N/mm^2)	R_{mWJ}/ R_{mMB}	Failure position
6082 - 1200	85.3	$R_{mWJ}/R_{mEN\ AW\ 1200} \approx 0.8$	HAZ $_{EN\ AW\ 1200}$ + BM
6082 - 5083	251	$R_{mWJ}/R_{mEN\ AW\ 5083} = 0.8$	HAZ + weld
7075 - 6082	208	$R_{mWJ}/R_{mEN\ AW\ 6082} = 0.68$	HAZ $_{EN\ AW\ 6082}$ + BM
7075 - 5083	195.1	$R_{mWJ}/R_{mEN\ AW\ 5083} = 0.87$	HAZ $_{EN\ AW\ 5083}$ + BM

The static bending tests demonstrated that the samples without defects, the welded joint presented the maximum deformation grade (α = 180°) for both FBB and RBB tests.

The tests results of the welded joints indicate a good behavior, for the optimal welding parameters, considering also the most sever bending test, meaning the bending test with the weld root on the side of maximum deformation.

In determining the degree of deformation for FSW of dissimilar materials EN AW 7075 and EN AW 6082, there was a special phenomenon compared with other dissimilar joints made: samples behaved better than trying to the maximum bending (with extensive root RBB, α = 180°), compared to the testing with extensive surface FBB, where α = 25°.

The experimental program showed that the welding parameters, tool characteristics and how dissimilar materials are placed in relation to the direction of rotation and advance of the tool is critical to achieving flawless joints.

The modification of the welding speed or of the rotational speed may have an important effect to the material flow in the stirred zone. The material mixing grade increases with the increasing of the rotational speed and with the reducing of the welding speed. From this point of view the rotational speed has a more significant influence than the welding speed.

On the other hand for a given combination of welding parameters, wrong location of welding materials can influence the degree of mixing materials.

Reducing of the mixture grade affects the defects formation (voids or tunnell deffects) in the welded joints.

Analyzing the results and taking into account the wide use grade of these aluminium alloys, the difficulties that appear by using classical welding procedures and the necessary precautions in these cases, the possibilities offered by the FSW welding procedure are favorable and may offer the base for future industrial applications.

5. Conclusions

• Al is a light metal, strong and durable. Through of these three basic properties, Al is the preferred metal for applications in priority areas.

• FSW welding process allows easy processing of similar and dissimilar aluminum alloys, is environmentally friendly and has many advantages in terms of economic efficiency.

• The FSW experimental program was developed for following dissimilar couples of aluminum alloys: EN AW 6082 - EN AW 1200. EN AW 7075 - EN AW 6082, EN AW 7075 - EN AW 5083, EN AW 6082 - EN AW 5083 and EN AW 7075 - EN AW 1200.

• Good and very good results to friction stir welding of these dissimilar alloys were obtained from all couples approached, except EN AW-7075 EN AW 1200. In this case, due to very high differences in chemical compositions (EN AW 7075 contains approx. 6% Zn) and mechanical and physical properties, were not provided the metallurgical conditions at microstructural level, which are necessary for the formation of characteristic friction stir welded joints.

• FSW process can be applied with good results to welding of dissimilar aluminum alloys if specific conditions are met:

- use of optimum welding parameters;
- use a welding tool with geometric and dimensional characteristics as presented;
- correct positioning of the welding material according to the direction of travel and rotation of the welding tool.

• Friction stir welding of dissimilar aluminum alloys which are very large differences in terms of chemical composition, but also the physical and mechanical properties, are difficult or impossible to weld.

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