Microstructural and mechanical properties of aluminium alloys joint fabricated by friction stir welding

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Abstract

Nowadays aluminum and its alloys are very common for various applications, particularly in automotive, aerospace, and ship industries. This is because of their low density, high strength and good corrosion performance. However, due to high thermal and electrical conduction, conventional fusion or resistance welding of aluminium alloys encounters many problems and some aluminium alloys are even regarded as non-weldable due to a risk of hot cracking occurrence. The solid state joining method, known as the friction stir welding (FSW) overcomes those problems. FSW is an innovative technique, which has been more popular and successfully implemented in different industry. The most important advantages of this method, which at the same time indicate its environmental friendliness, are: low energy requirement, no generation of toxic fumes and it does not require consumables. Moreover, common defects such as hot cracking, associated with conventional fusion welding process of light weight metals are eliminated in FSW. This is because there is no bulk melting of the material during the FSW process. The paper presents the results of investigation of microstructural and mechanical properties of a friction stir welded joint, which consist of two different aluminium alloys: 6063 and 6082.

Keywords: Friction Stir Welding; FSW; aluminium alloys; mechanical properties; microstructure

1. Introduction

Steel as a constructional material is increasingly replaced by non-ferrous materials, e.g. aluminium alloys, in many industrial applications. Some of these materials have low weight and high strength, which is comparable to that of structural steels. Nevertheless, the process of joining of those materials can be very problematic [1].

Aluminium alloys are difficult to be welded with use of conventional methods, because in this material hot cracking and porosity development occur after welding. The solid state joining method, known as the friction stir welding (FSW) has been used to overcome problems related to fusing welding. Even though the FSW method can be used for various metallic materials like zinc, titanium, magnesium and its alloys, copper and its alloys and also steel, its prevalent industrial area of application is aluminium alloys joining. In this type of welding the temperature does not exceed melting temperature of the materials, thereby heat input and consequently formation of intermetallic phases can be controlled. As a result this improving the mechanical properties. This method of shaping and joining metals allows to acquire highly resistant joints that form parts of manufactured products. In addition, FSW is considered to be a "green" technology due to its energy efficiency [2, 3, 4, 5].

Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state (fusion less) joining technique, and it was initially applied to aluminium alloys. Nowadays, FSW is advanced technology which has been commonly used now mainly in aerospace, automotive, shipbuilding and defense industries with huge research and development investment [1,6].

In the friction-stir welding process, rotation tool has specially designed pin and shoulder, which are inserted into the touching edges of plates or sheets to be joined and after that it traversed along the line of joint. The tool has two main functions, which are: heating of workpiece and movement of material to create the joint. Frictional heat is generated between the tool and the specimen as a result of plastic deformation of workpiece. This heat generated by the plastic deformation softens the material around the pin. As a result it is possible to traverse the tool along the weld line in a plasticized tubular shaft of metal. During FSW process, the material undergoes intense plastic deformation at elevated temperature in the solid state involving dynamic recrystallization of the processed base material. These changes result in formation of fine and equiaxed recrystallized grains. Figure, 1 illustrates the friction stir welding process [1, 6].

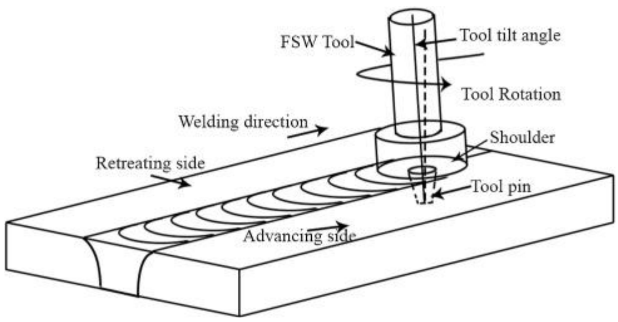

Figure 1. *Schematic arrangement illustrating friction stir welding.*

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1.1. FSW Process of Aluminium Alloys

The significant parameters of FSW process include tool geometry, the tool movement parameters and joint designs. This principal variables affect the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of the material. Furthermore, machine characteristics, workpiece thickness and control mechanisms are also factors, which affect the weld quality [7,8].

Tool geometry is the most significant aspect of process development, because it determines material flow. Whereas the material flow adjusts the traverse rate at which FSW can be conducted. An FSW tool consists of a shoulder and a pin (Fig. 2.). The tool serves two main functions: localized heating and material flow in terms of heating, the relative size of pin and shoulder is important. However the other design features are not critical. The shoulder secures closure for the heated volume of material. Tool design governs uniformity of microstructure, properties and also process loads. Generally, a concave shoulder and threaded cylindrical pins are used [9].

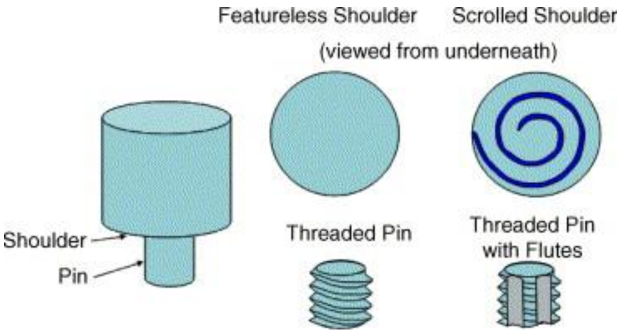


Figure 2. *Schematic of the FSW tool.*

Strength at ambient and working temperatures, superb fracture toughness, wear resistance, thermal and chemical stability at working temperatures, fatigue are properties that are required for any FSW tool material. The materials generally used for FSW of Al alloys are tool steels which have high temperature strength and toughness. The choice depends on the approximate temperature reached during welding of Al alloys. Therefore any tool steel which has tempering temperature higher than 500 °C is a good solution [6, 9].

The next important aspect is combination of compressive and tensile forces, which pose the peak force achieved during tool plunge. This may be a reason of break the tool, especially in concave shoulder tools. The final choice of tool is determined by variables like run length, machinability of material, tool design complexity and economy [7].

In FSW process, two parameters are significant: tool rotation rate and tool traverse speed along the line of joint. The rotation of the tool results in mixing and stirring of the material around the rotating pin and traverse motion of the tool moves the stirred material from the front to the back of the pin and finishes welding process. Higher tool rotation rates result in higher temperature owing to higher friction heating and this makes more severe stirring and mixing of material. Furthermore tool tilt is also an important of FSW process parameter. The appropriate tool tilt of the spindle towards trailing direction guarantees that the shoulder of the tool holds the stirred material and moves material efficiently from front to the back of the pin [10].

Friction stir welding, its characteristics and advantages, have been the subject of view publications over the past years. However, numerous issues associated with the material flow, resulting microstructure and mechanical properties are not fully recognized yet [1].

2. Materials and Methods

The materials used in experiments were 6063 and 6082 aluminium alloys. Chemical compositions of the investigation materials are presented in Table 1.

Table 1. Nominal chemical compositions of 6063 and 6082 aluminium alloys.

Chemical element (wt. %)	AA6063	AA6082
Si	0.20-0.60	0.70-1.30
Fe	max. 0.35	max. 0.50
Cu	max. 0.10	max. 0.10
Mn	max. 0.10	0.4-1,0
Mg	0.45-0.90	0.6-1.2
Cr	max. 0.10	max. 0.25
Zn	max. 0.10	max. 0.20
Ti	max. 0.10	max. 0.10
Al	Balance	Balance

The weld was produced from two abutted plates of 60623 and 6082 aluminium alloys at the rotational speed of 580 rpm and the traverse speed of 80 mm/min. A CNC tool was used to make the one-sided joint, the AA6082 was on the advancing side. A section was then cut in the plane perpendicularly to the welding direction. Subsequently, metallographic analysis was prepared according to the standard preparation technique using grinding and polishing followed by etching with hydrofluoric acid 5% solution to reveal the microstructure using optical microscope.

The tensile properties of the weld were examined across the transverse cross section with the nugget region in the centre of the gauge length of the tensile test sample; the dimensions and geometry of the tensile test specimen are illustrated in Fig. 3

Additionally, microstructural observations were conducted using a Nikon Eclipse ME600 optical microscope with digital image recording and a stereoscopic microscope MOTIC SMZ-168 and also electron microscope (SEM) JSM 5510LV. Microanalysis of chemical composition of selected samples was performed by SEM coupled with energy dispersive spectroscopy (EDS) model IXRF 500.

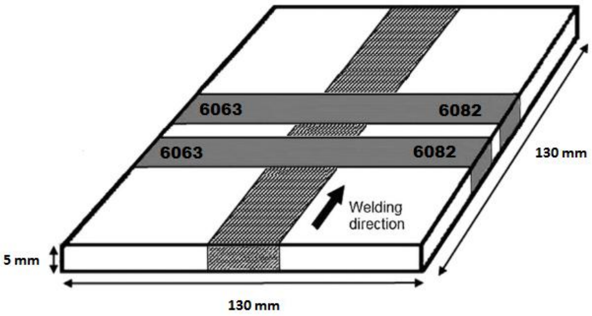


Figure 3. *Dimensions of butt FSW configurations.*

3. Results and discussion

The microstructure of the welded joint is shown in Fig. 4. Moreover this picture presents the typical zones such as: the heat-affected zone (HAZ), a material which is affected by heat but which does not experience significant plastic deformation; the thermomechanically affected zone (TMAZ), where material has been affected by heat and plastic deformation and part of the TMAZ in the centre of the weld will recrystallize to form a fine-grained region, called the nugget (NG). In addition, there is also a through thickness variation within the NG due to the shoulder at the top and variation of the probe diameter from the top to the bottom which affects the temperature distribution through the NG and consequently the effective strain experienced [11, 9].

Advancing Side Retreating Side

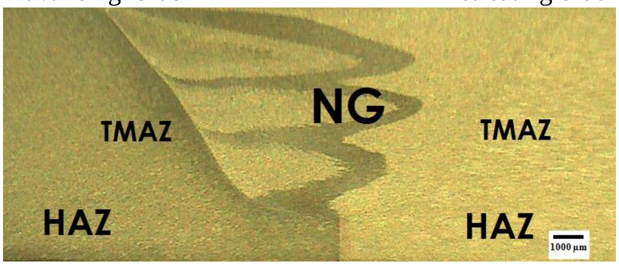


Figure 4. *Cross-section of FSW joint showing distinct zones: HAZ represents the heat-affected zone, TMAZ the thermomechanically affected zone, and NG the stirred (nugget) zone.*

The well-defined differences between microstructures on the retreating and advancing sides are shown in Figure 4 and 5. The clearly visible line (“fusion line”) separating the weld nugget area from the thermomechanically affected zone was revealed. Moreover, the heat affected zones in the joints were wider on the advancing side than on the retreating side. The appearance of a sharp boundary line between TMAZ and the nugget can be explained on the base of thermal/flow model developed by Hamilton et al. [13]. On the advancing side of the model projects that the flow is clockwise through the workpiece thickness with an eddy, or “dead zone”, located in the TMAZ near the weld nugget/TMAZ boundary. Under this flow pattern, a sharp microstructural boundary develops between these regions as the rising flow from the workpiece bottom and the downward flow from the workpiece surface oppose one another with very little cross flow between the currents. On the retreating side, however, the model suggests that there is strong material flow across the weld/nugget TMAZ boundary as material rises from the workpiece bottom and flows downward from the workpiece surface. The boundary between the TMAZ and weld nugget is diffused and gradual [1].

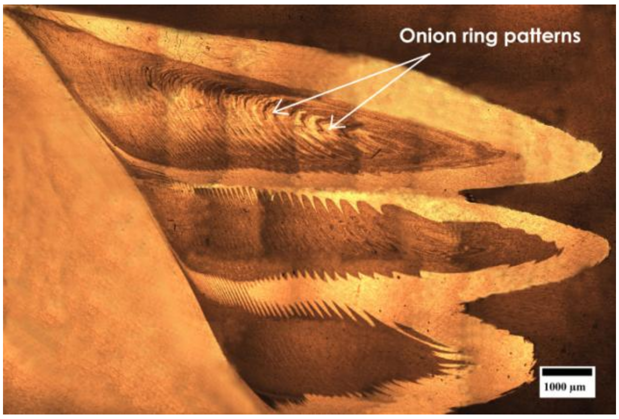


Figure 5. *Characteristic area of FSW single-side joint.*

The quality of weld can be allowed for evaluation based on the microscopic metallographic tests. In the cross section, the examinations didn't reveal any faults. Moreover, the joint was free from voids in the areas on the retreating and advancing sides and also on the surface of the joint. In the investigated cross sections the joints showed full metallic continuity and confirms the proper selection of welding conditions for producing high quality FSW joints [1].

Also, the NG contains periodic onion ring patterns as show in Fig. 5, which suggest that a periodic oscillation in the deformation conditions within the weld may occurred. These microstructural variations can occur depending on the tool rotation rate and traverse speed [9].

The welded joint was tested for mechanical strength and percentage elongation under tensile loading. The tensile specimens were cut perpendicularly to the weld line according to ASTM E8M standard. Tensile tests were conducted at room temperature at a cross-head velocity of 1 mm/s. Figure 6 presents the sample after tensile-strength testing.

Advancing Side Retreating Side

Figure 6. *The sample after investigation of tensile strength.*

The stress strain curve of FSW joints is shown in Fig. 6. From the stress–strain curves, the tensile properties like yield strength, ultimate tensile strength and elongations of the joint were derived and presented in Table 2. The specimen fractured on the advancing side, when the applied load reached 7231.5 N. Moreover, the sample had tensile strength 144.7 MPa and elongation 10.3%.

According to the literature data, the tensile strength for alloys AA6063 and 6082 are 145–186 MPa and 270-310 MPa, respectively. The results show that the higher tensile strength have the FSW joint as a compared to the based material used on the advancing side (AA6063). It should be emphasized that, although FSW proceeds in the solid state and does not need filler metal, an elevated temperature enhances the material flow around the probe. This also triggers changes in mechanical properties of the materials being welded [1].

Table 2. *Mechanical properties of welded sample.*

R_m [MPa]	$R_{e\ 0.2}$ [MPa]	F_m [N]	A [%]
144.7	100.5	7231.5	10.3

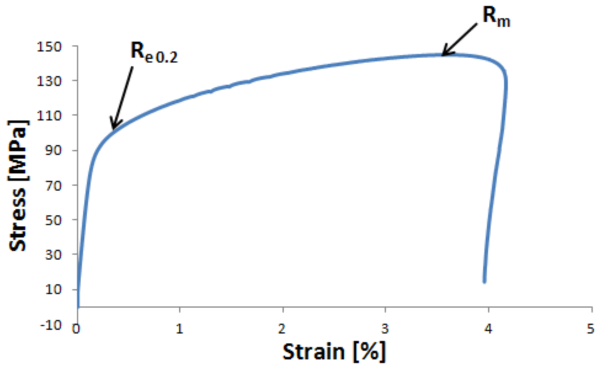


Figure 7. *The stress-strain curves for welded joint.*

Flow serrations are observed on the stress – strain curves from tensile testing of the FSW joint at stress in the range of 120.9 – 132.3 MPa (Fig. 8). Such flow serrations points at dynamic strain aging (DSA) process take place during deformation of the joint. DSA refers to the attractive interaction between the diffusing solute atoms (i.e. Mg atoms in the studied alloy) and mobile dislocations during plastic deformation [12].

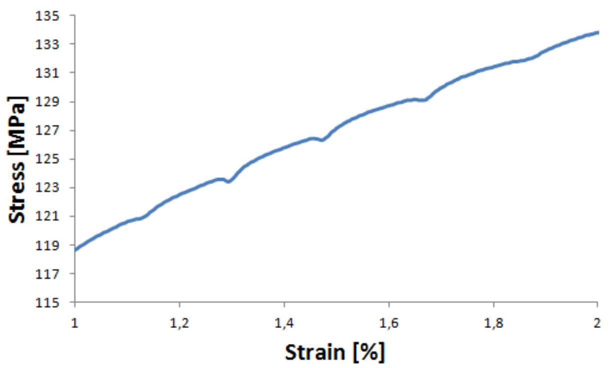


Figure 8. *Fragments of the curve for the FSW sample tested with visible flow serrations.*

Fig. 9, 10 shows representative microstructures of the tested sample. The advancing side and the retreating side of the weld seam both appear to be smooth without visible defects. Uniform striations that derived from periodic deposition of material are formed on the surface of the weld seam. The dense and uniform striations indicate that material flow is stable and regular during the welding process in this welding condition. Such interlocked structure was reported to be beneficial to the strength of weld interface.

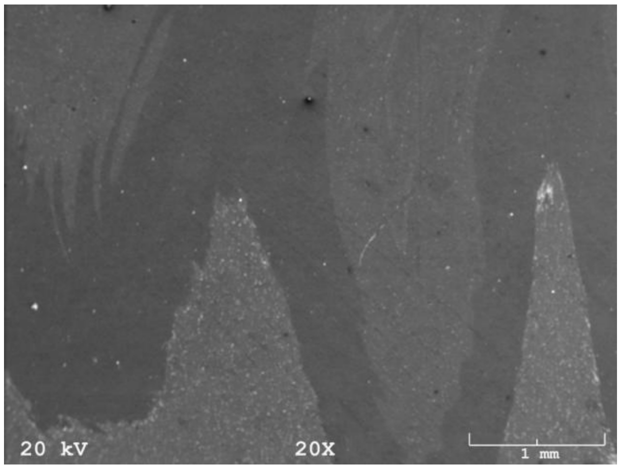


Figure 9. *Profile of precipitated phases in the joint in the stirred zone.*

The bond between the weld seam and the base material is tight and no visible defect is formed on the advancing side and retreating side.

Fig. 10 shows the morphology and distribution of the second-phase precipitates in area of a FSW joint. This photo shows a small number of precipitates in the base material in a shape of roundness or eclipse.

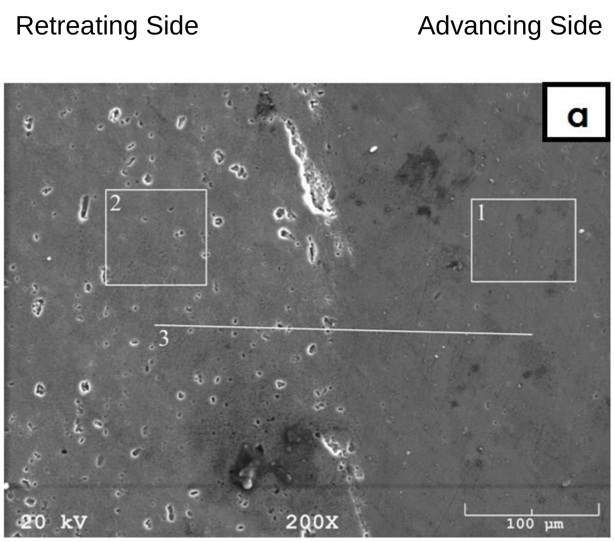
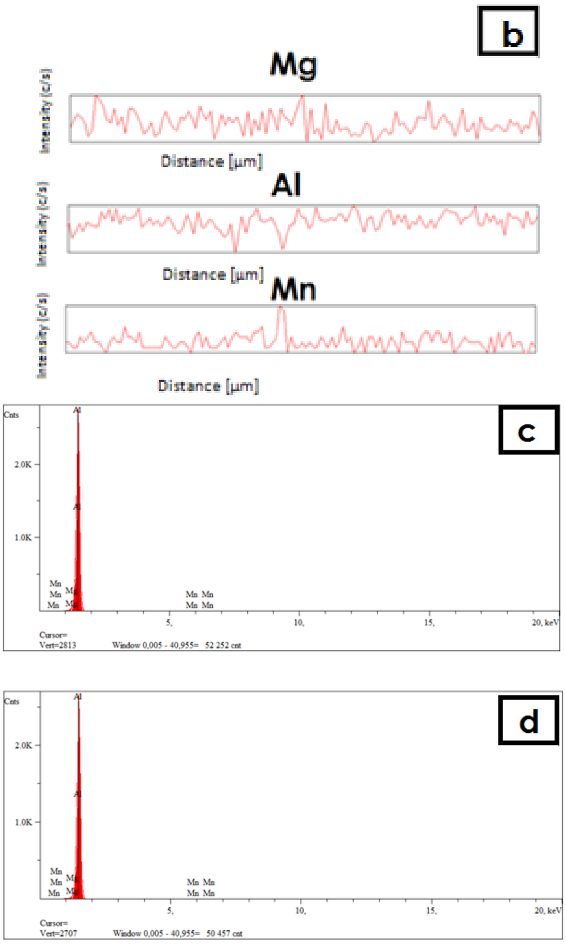


Figure 10. *(a) EDS line and area scans of weld showing Mg, Al and Mn elements scattered in the stir zone, (b) Elements distribution along marked region, (c, d) Elements distribution in area number 1 and 2, respectively.*



In the first area contents of Mn, Mg, Al achieved 0.2, 5.5, 94.3 (wt. %), respectively. Whereas in the second area contents of Mn, Mg, Al amount to 0.4, 5.7, 93.9 (wt. %), respectively. According to linear and areas EDS analysis, Mg and Cu contents in specimen were higher on the retreating side compared to the advancing side. It is evident that on the advancing side AA6063 alloy was used, which is characterized less contents of these elements, than AA6082.

4. Conclusion

In this investigation, an attempt has been made to study the microstructural and mechanical properties of a friction stir welded joint, which consist of two different aluminium alloys: 6063 and 6082. The following conclusions can be made from this study:

● Aluminium alloys 6063 and 6082 are easily weldable by means of FSW. The tests proved that this material has high quality butt joints free from defects or imperfections.

● FSW joint fabricated using tool rotation speed of 580 rpm exhibited maximum tensile strength of 144.7 MPa. Maximum percentage elongation is observed to be 10.3% and the failure load was obtained for sample at 7231.5 N.

● The specimen failure took place in 6063 aluminium alloy on the advancing side. The welded sample has higher tensile strength than the base material (AA6063). This phenomenon showing the advantage of employing FSW for manufacturing materials consist of two different aluminium alloys.

● Results prove the high quality of the weld in this study.

● Flow serrations are observed on the stress – strain curves from tensile testing of the FSW joint. Such flow serrations points at dynamic strain aging (DSA) process take place during deformation of the joint.

● According to linear and areas EDS analysis, Mg and Cu contents in specimen were higher on the retreating side compared to the advancing side. This phenomenon correlates with chemical compositions in used materials.

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