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Effect of Process Parameters on Metallurgical and Mechanical Properties of Friction Stir Welded Aluminum Alloys

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Abstract

AA65032-T6 aluminum alloy has gathered wide acceptance in the fabrication of light weight structures requiring a high strength-to-weight ratio and good corrosion resistance. Compared to the fusion welding processes that are routinely used for joining structural aluminum alloys, friction stir welding (FSW) process is an emerging solid state joining process in which the material that is being welded does not melt and recast. This process uses a non consumable tool to generate frictional heat in the abutting surfaces. Important process parameters that control the quality of the weld are rotational speed (rpm), welding speed (mm/min), axial force (KN) tool geometry and tool tilt angle. The process parameters that was considered in this study are rotational speed (rpm), welding speed (mm/min) and tool tilt angle. The tool used in this process were tapered square profile tool pin. The present studies aimed to understand that micro structural changes and the associated mechanical properties during the FSW of 65032-T6 aluminum alloy at various parameters. It is observed that, during the friction stir welding process extensive deformation occurs at the nugget zone results fine grained structure, enhances strongly mechanical properties of the joint.

Keywords: FSW, aluminum alloy 65032-T6, Process parameters, Mechanical properties, Microstructure

1. INTRODUCTION

Friction Stir Welding (FSW), a solid state joining method developed and patented by TWI Ltd., Cambridge, UK in 1991 [1], has attracted significant interest from aircraft and car manufacturers for joining high strength aluminum alloy components. Specific examples include the wrought 6000-series Al-Mg-Si (Cu) alloys that are commonly used in aircraft fuselage skin and automotive body panels, mainly due to their ability to be strengthened by artificial aging after forming. FSW has also been used to produce rocket shells, the panel of the cabin of aircrafts with stringers and beams, hollow panels of wagons, and pipes [2].

The basic concept behind FSW is simple: A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of the two parts to be joined and traversed along the line of joint (Figure 1).The FSW tool primarily serves two functions: a) heating the work piece, and b) flowing the material to produce the joint. A detailed list of parameters controlling this joining process is given in [3] as follows:

1) Rotational speed (rpm)
2) Welding speed (mm/s)
3) Axial force (KN)
4) Tool geometry.
    i) Pin length (mm)
    ii) Tool shoulder diameter, D (mm)
    iii) Pin diameter, d (mm)
    iv) Tool tilt angle (°)
    v) D/d ratio of the tool

1.1 Metallurgical Aspects

During friction stir welding, heating is accomplished by friction between the tool and the work piece and plastic deformation of the work piece. The localized heating softens the material around the pin, and a combination of the tool rotation and translation leads to the movement of material from the front of the pin to its backside. As a result of this process a joint is produced in the ‘solid state’,because of various geometrical features of the tool, the material movement around the pin can be complex to study [4]. During the FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in the generation of fine and equiaxed dynamic recrystallized grains [5-8]. Consequently, the fine microstructure in friction stir welds results in good mechanical properties (e.g., the tensile strength for FSW of Al 7039 plates is as high as 311 MPa while the base metal has a tensile strength of 383 MPa [9]).

FSW joints usually consist of four regions, as opposed to primarily three in "normal" welds, different regions as shown in Figure 1. a) unaffected base metal; b) heat affected zone (HAZ); c) thermomechanically affected zone (TMAZ) and d) friction stir processed (FSP) zone (nugget). The formation of these regions is affected by the material flow behavior under the action of the rotating non-consumable tool. The material flow behavior is predominantly influenced by the FSW tool profile, tool dimensions and welding process parameters [8,10].

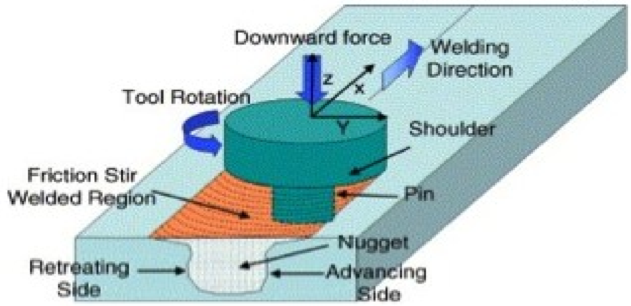

Figure 1. Schematic of the Friction Stir Welding process

Frictional heat and plastic flow during FSW create fine and equiaxed dynamic-recrystallized grains in the stir zone (SZ) and elongated and recovered grains in the thermomechanically affected zone (TMAZ). The heat affected zone (HAZ) is often identified by means of only material hardness changes as there is no difference in grain structure compared to the base metal. This softened HAZ region can be characterized by the dissolution and coarsening of the strengthening precipitates during friction stir welding [11]. As an example, the precipitation sequence during aging of pseudobinary Al–Mg_2Si alloys has been characterized as follows: supersaturated solid solution, needle shaped precipitates (β"), rod shaped precipitates(β"), and β-Mg_2Si [11-13]. It is known that needle shaped precipitates correspond to coherent β" phase, which contributes predominantly to the strength of 6000 series aluminum alloys. During prolonged aging, β" needless are transformed into semi-coherent β" rod shaped precipitates. Coarsened precipitates and the associated loss of coherency lead to a diminished strengthening effect relative to the needle shaped precipitates [14]. FSW tool pins are often featured with threaded forms. A complex pin is designed with thread interruptions such as flats or flutes [15-17]. However, vertical movements of the material during Friction stir weld were presumed to be predominated by helical features in tool pin, tool pin geometries and features are one of the important process control parameters in FSW that influence material flow which in turn affect joint efficiency [18,19].In FSW the welding speed had greater influence on tensile properties than tool rotational speed in FSW of aluminum alloy [20]. The material flow behavior of material 2195 was studied by Reynolds and identified various zones such as heat affected zone, thermo mechanically affected zone and weld nugget zone [21].

The welding parameters are the key art of friction stir welding process. They decide what materials that can be welded by this new technology, and determine the thickness of work piece. From the literature, it is understood that the input welding parameters influence the heat generation and the flow of the plasticized material and eventually affect the microstructure and the mechanical properties of the weld. In the present investigation, the effect of welding parameters such as tool rotational speed (TRS), welding speed (WS) and tool tilt angle (TTA) on mechanical properties and also microstructure of the of friction stir welded aluminum alloy IS:65032-T6 was studied.

2. MATERIAL AND EXPERIMENTAL WORK

The aluminum alloy IS:65032-T6 which is difficult to be joined by conventional fusion welding techniques has been chosen in this investigation, and find its application in aerospace as structural members and storage tanks. The rolled plates of 5 mm thick IS:65032-T6 aluminum alloy, have been cut into the required size 150 mm x 100 mm by power hack saw cutting and milling. The chemical composition of theparent metal and its mechanical properties are given in Table 1. Square butt joint configuration has been prepared to fabricate the FSW joints. The plates were welded in single pass, normal to the rolling direction, by using the Tapered square tool pin profile (Figure 2) of shoulder diameter 16 mm, pin length 4.7 mm and taper angle is 14^0 on a position controlled friction stir welding machine. **Figure 3** shows the weld samples fabricated at various parameters by friction stir welding process.

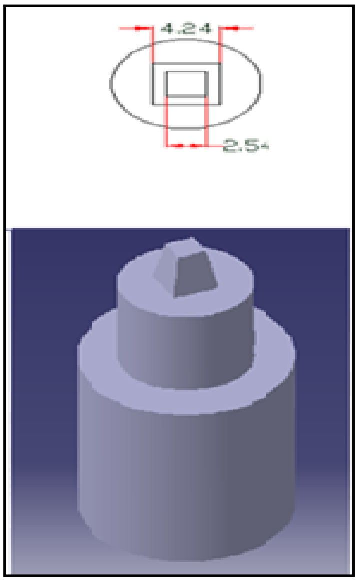

Figure 2. Geometry of a tapered square tool pin profile

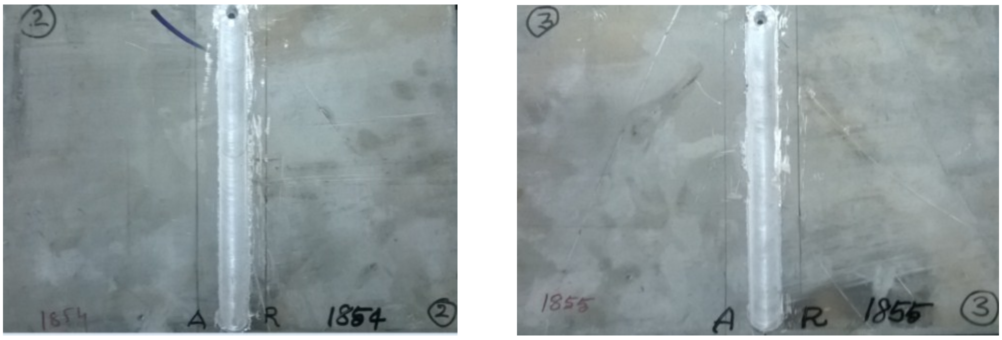

Figure 3. Welded samples of friction stir welding process

Table 1: Chemical composition and mechanical properties of parent metal

Chemical composition (*wt.%*)									Mechanical properties		
Al	Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr	UTS/MPa	%EL	HV
97.1	0.22	0.91	0.54	0.53	0.36	0.24	0.016	0.005	308.5	16.2	120.7

The process parameters used in this work are presented in Table 2. To study the tensile properties the welded joints were sliced as per the standards of American Society for Testing of Materials using wire cut EDM. Tensile test has been carried out in 100KN, electro-mechanical controlled Universal Testing Machine. The specimen is loaded at the rate of 1.5KN/min as per the ASTM specifications, so that tensile specimens undergoes deformation. The specimen finally fails after necking, the 0.2% yield strength, ultimate tensile strength and percentage of elongation have been evaluated.

Microstructure analysis have been carried out using a light optical microscope incorporated image analyzing software (Envision 5.0). The specimens for metallographic examination are cut the required sizes from the joint comprising nugget zone, thermo mechanically affected zone, heat affected zone and base metal regions and polished using different grades of emery papers. Finally polishing has been done using the diamond compound of 1μm particle size in the disc polishing machine. Specimens were etched with killers reagent to reveal the microstructures.

Table 2 : Process parameters and its levels

S. No.	Process parameters	Levels		
		1	2	3
1	A. Spindle speed (rpm)	1000	1300	1600
2	B. Tool tilt angle (°)	0	1	2
3	C. Travel speed (mm/min)	60	80	100

Table 3: Welding parameters used in the experimentatio

Designation	TRS (rpm)	TTA(°)	WS(mm/min)
A1	1000	0	60
A2	1000	1	80
A3	1000	2	100
B1	1300	0	80
B2	1300	1	100
B3	1300	2	60
C1	1600	0	100
C2	1600	1	60
C3	1600	2	80

TRS: Tool rotational speed, TTA: Tool tilt angle, WS: Weld speed

3. RESULTS AND DISCUSSION

3.1 Effect of welding parameters on tensile property of the weld

Figure 4 shows that the variation of tensile properties of the welded joint at different welding speeds and tool rotational speeds. In welding the heat input plays a major role on the mechanical properties of the weldments. From the experimental results, it is found that the tensile strength increase increasing the tool rotational speed. It is also observed that decreasing the tensile strength increasing the parameter WS. In friction stir welding, it is understood that increasing the tool rotational speed at decreased WS for given set of parameters produced the sufficient heat required for the welds. In the present study, since higher rotational speeds(1300 rpm,1600 rpm and 60 mm/min, 80mm/min) were used, FSW produced defect free welds. When a joint is free from defects, the tensile properties of the joint are dependent on the microstructure of the joint. From the tested tensile specimens it is observed that fracture occurred in the HAZ or TMAZ of the weldments.

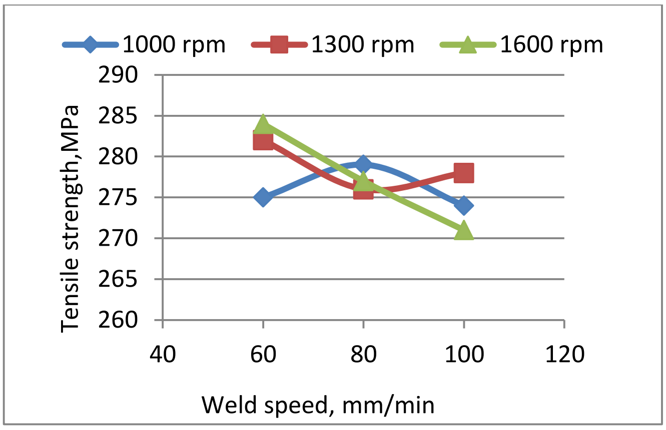

Figure 4. Effect of process parameters on tensile strength

3.2 Effect of welding parameters on elongation of the weld

Figure 5 shows the percentage of elongation along traverse direction obtained from the tensile test plotted against the weld speed. The test plates welded with a tool rotation of 1600 rpm and weld speed of 60 mm/min (high heat input) showed the highest elongation. While the plates welded with tool rotation speed of 1000 rpm and 100 mm/min (low heat input) gave less elongation. It is understood that the heat input has strongly influenced the percentage of elongation. From the experimental results, it is found that increasing the tool rotational speed will increase the percentage of elongation.

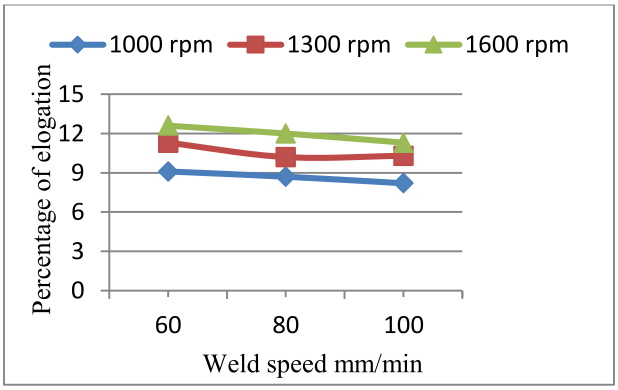

Figure 5. Effect of process parameters on percentage of elongation.

Effect of welding parameters on hardness of the weld

Vicker's hardness testing machine (make: Matzusawa, Japan; Model MMT-X7) has been employed for measuring the hardness across the joint 0.5kg load. The measurements were made at weld nugget zone. Figure 6 shows the variation of hardness, (HV value) for the various tool rotational speed and weld speed. It was observed that the hardness decreases with increase in heat input. For instance, the tool rotational speed of 1600 rpm at 60 mm/min weld, the hardness value is low due to maximum heat input. For the same tool rotational speed the weld hardness value is high at 100mm/min because of lower heat input.

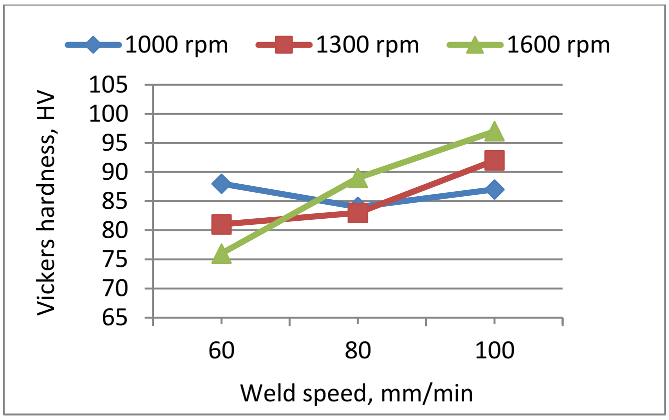

Figure 6. Effect of process parameters on the hardness

3.3 Characterization of weld zones

Figure 7 and 8 shows the macrograph and microstructures of weld joint. The microstructures in the cross-section of a FSW joint can be divided into several zones like weld nugget, TMAZ and HAZ. In the centre lies the nugget, which has a fine grain size and contains onion ring structure. The fine grain structure in the nugget could be due to recrystallisation process during welding. In the TMAZ, the combination of high stress and large strains causes deformation of grain structure (coarse grain structure) but no recrystallisation takes place. Beyond is the HAZ, which is effected by the heat but not by deformation.

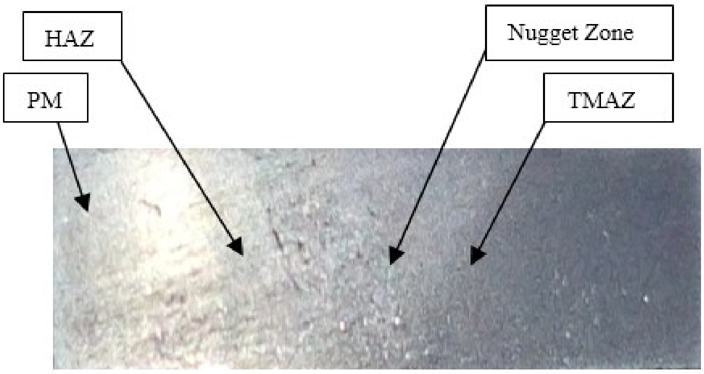

Figure 7. Macrograph of the welded sample

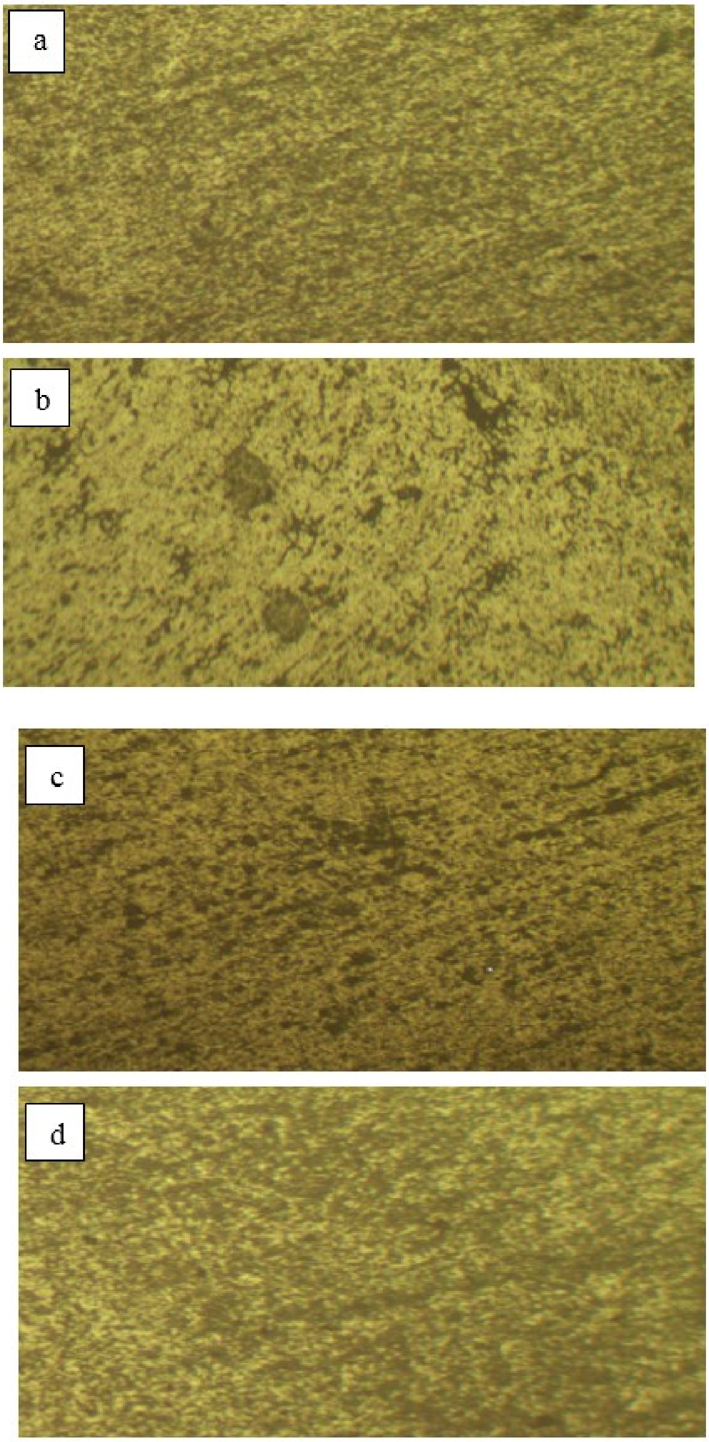

Figure 8. Microstructures of (a) Nugget zone (b)TMAZ (c) HAZ (d) Parent metal

Hardness profile along the traverse direction as shown in figure 9.The characterization of weld zones was done, indirectly by measuring the hardness along the traverse direction of the weld. The unaffected base material was harder (~116HV), and decrease in hardness towards the weld was found. A minimum hardness zone (~74HV), was detected at approximately 6-9 mm from the weld centre on both sides of the weld. The hardness of the weld material was practically constant 3mm distance from centerline of the weld (~86HV).

From the plotted microhardness it was inferred that the retreating side of the weld (near by the tool pin) had lower hardness compared to the advancing side (right side in Figure 9). The advancing side had high hardness due to strain developed by the rotating tool in the weldments.

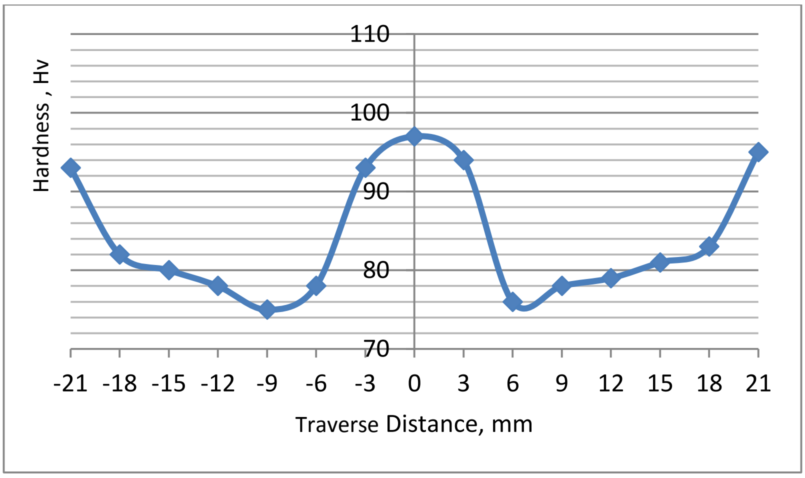

Figure 9. Hardness profile along the traverse direction

CONCLUSIONS

The sample was characterized by means of tensile strength, hardness and elongation. From the investigation it is found that an increase in tool rotational speed and decrease in weld speed increases the tensile strength. Increase in tensile strength causes sufficient heat produce by the rotating tool pin.

It is found that the amount of heat input plays a major role on the elongation properties of the weld samples. Increased heat input results in higher percentage of elongation of the friction stir welded samples. The test plates welded with a tool rotational speed of 1600 rpm and weld speed of 60 mm/min showed the maximum elongation while the sample welded with 1000 rpm and 100 mm/min yielded minimum elongation.

Among the three zones(TMAZ,HAZ and NZ) the sample welded, with tool rotational speed of 1600 rpm and weld speed of 100 mm/min given a highest hardness 97HV. For the same parameters the lowest hardness was 76 HV nearer to the TMAZ.

Extensive micro structural study gives better understanding of the grain structures and their influence on mechanical properties.

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