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Friction Stir welding and Friction Stir Processing for 6061-T6 Aluminum Alloy

ABSTRACT

6061-T6 Aluminum Alloy plates were welded by using Friction Stir Welding (FSW) at different rotation and welding speeds. The effects of two factors on Ultimate Tensile Strength (UTS), which include rotation and welding speed at 20 tool tilt angle, were investigated. Ultimate Tensile strength increases with decrease the welding speeds and increases the rotational speeds. The rotation speeds have a higher effect on ultimate tensile strength when compared with the welding speeds. Friction Stir Processing (FSP, Double pass) led to increasing the ultimate tensile strength and elongation at same welding and rotation speeds. FSP lead to improve fatigue life and reduce residual stress.

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Introduction

Friction stir welding (FSW) considered solidstate welding; was discovered in 1991 by The Welding Institute [1]. In Friction stir welding, the work-pieces were firmly clamped onto the worktable to prevent it from moving and vibration. At the start welding the pin rotates at specified rotation speed and then plunges into the line interface between the two plates. The heat generated is a product from the friction between the tool and welded material, and the weld material rising to a relative steady-state temperature and becomes plasticized. The tool is moved along a predefined weld path when plasticized state is reached. The material in the weld zone remove from the pin entering and travelling during the part try to extrude out of the pinhole but is kept in place by shoulder[2]. The generator temperature due to welding operation reached to 70 - 90% from the melting point for the base material and its causes soften in the weld regions and permits moving the tool along the welding line. The welding tool will transfer the material from the advance side to return side, FSW presented in figure (1)[3]. Friction Stir Processing (FSP) consider as a solid - state welding process which firstly utilized in 1999 by Mishra et al [4]. FSP is an emerging surface engineering technology depends on the principles of Friction Stir

Welding. FSP worked on reduce inherent defects in the starting material and locally refines microstructures and also enhance its ductility, formability, fatigue resistance, corrosion resistance, and other properties [5]. Basically, FSP is a local thermo-mechanical metal working process, the change in the properties occurs only in local properties without affecting properties of the remaining structure [6].

The main advantages of FSW over conventional welding methods are the defects like voids and porosity are less from conventional welding, low tensile residual stresses and distortion stresses in the resultant welded region, higher mechanical properties, the environmentally safe process due to the absence of radiation and toxic fumes, FSW is operated in all positions, as there is no weld pool. Disadvantages of FSW are, the work-piece clamping is a very important criterion in the operation, the lower welding speed leads to longer process times, the thickness of weld line will reduce during the welding process due to no filler material, when the tool is withdrawn FSW caused hole left. When used large down forces must use heavy duty clamping to hold the plates together, lower flexible than arc and manual Process[7-11].

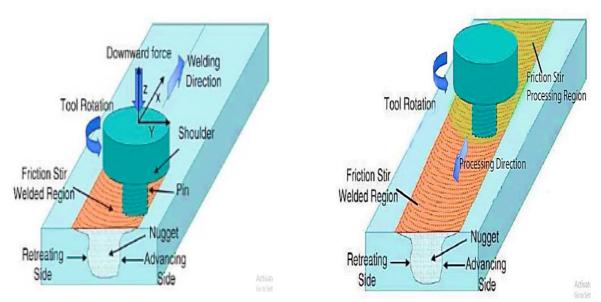


Figure (1,2) Friction stir welding and friction stir processing [12]

II-Friction Stir Welding Zones

- A. Heat affected zone (HAZ): This zone is closer to the weld zone because of the nearness to the heat source, changes in mechanical properties due to changes in microstructural changes. as well as, no plastic deformation[13].
- B. Weld nugget: This zone occurs when the material complete undergoes

The welding zones are dividing into three main zones are presented in figure (3):

- recrystallization, and product fine equiaxed grain structure evolves[13].
- C. Thermo-mechanically affected zone (TMAZ): This zone relative to positions that have undergone deformation, moreover have been influenced by heat. In this region no recrystallization in this region. TMAZ is placed so near to the pin[13].

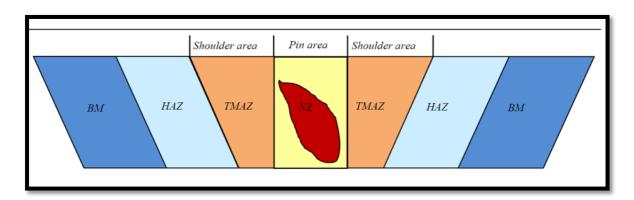


Figure (3): Welding zones for FSW process [14]

III-EXPERIMENTAL WORK

A. Chemical composition

The material which used was aluminum alloy AA6061 with the 4 mm thickness. Aluminum alloy AA 6061, consider one of the most used of heat treatment alloys, It has good feature as

In the current study, using 6061 aluminum alloy with 4mm thickness and length 200 mm and width 100 mm. friction stir welding parameters were (rotation speed, welding Speed and constant tilt angle of the too), it's shown in table (2). A cylindrical tool made of

good toughness and high strength. The chemical composition is explained in the table (1)

B. Welding operation

carbon low steel with dimension explained in figure (4).

Table (1) chemical composition for studies material

Sample	Si%	Fe%	Cu%	Mn%	Mg%	Cr%	Ni%	Zn%	Pb%	Ti%
Standard [15]	0.4- 0.8	0.7 max	0.15- 0.4	0.15 max	0.8- 1.2	0.04- 0.35	0.25 max	0.15 max	0.005	0.07
Plate 6061 t= 4 mm	0.57	0.33 5	0.253	0.097 1	1.151	0.185	0.003 4	0.063	0.004	0.0216

Table (2) welding parameters

parameter	Rotation speed (rpm)	Welding (mm/min)	speed	Welding (mm/min)	speed	Welding (mm/min)	speed
Case 1	630	20		32		45	
Case 2	1000	20		32		45	
Case 3	1600	20		32		45	

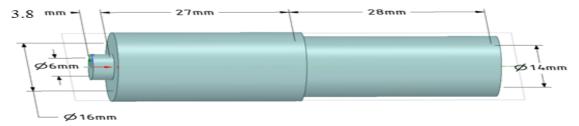


Figure (4): welding tool.

C. Tensile test

The tensile test was carried out in university of technology with production engineering and metallurgy department at room temperature by using computerized (WDW-200E – 200KN) as shown in figure (4) at constant crosshead speed 1mm/min. The tensile test specimen cutting by using water jet CNC machine and perpendicular on welding line, its dimension explain in figure (5).

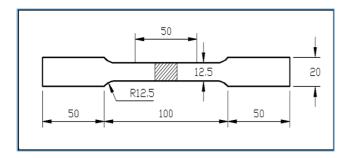


Figure (5): Dimension of tensile test sample [16].

D. Fatigue Test

Fatigue test is done at the mechanical engineering department laboratory in Nahrain University by using fatigue (HI-TE CH)-Rotating device. It is done at a constant stress amplitude cantilever with fully reversed (R=-1), and the specimen dimensions were 60, 10, 4 mm length, width, thickness respectively. Samples were taken from the welded plate with 1600 rpm and 20 mm/min for both single and double

pass as well as the base material. The location of the welding line is near to the fixed point as shown in figure (6).

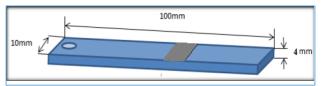


Figure **(6)**: the position of welding line.

E. HARDNESS TEST

The hardness test was performed by digital micro Vickers hardness TH714 shown in figure (4.18) in the mechanical engineering department in Tikrit University. The test is done under applied load (200 g) with a time of 15 sec. The specimens were taken perpendicular on the weld line.

F. X-RAY TEST

The X-Ray diffraction tests were performed in the Ministry of Science and Technology by the (XRD-6000/ SHIMADZU) machine type. The supplied current was (20 mA) and voltage (40KV). The target is Copper with a wavelength (λ =1.5406 A⁰), and the filter is Nickel.

IV-RESULTS

G. Tensile test results

The tensile test results for base material are presented in table (3)

Table (3): Tensile test results for base material.

Material	Proof strength 0.2% (MPa)	Ultimate strength (MPa)	Modules of elasticity (GPa)	f Elongation max (%)
6061-T6 [15]	255	289	69	12
Plate 4 mm	241	280	68.9	15.43

The figure (7) showed that reduction in ultimate tensile strength for weldment when compared with the base material for all rotation and welding speeds. The weld efficiency is defined as the ultimate tensile strength for welded material to the ultimate tensile test for base material. The ultimate tensile strength for base material was 280 MPa while the higher ultimate tensile strength for weldment was 242 MPa with weld efficiency 86.5 % at 1600 rpm and welding speed 20 mm/min. The lowering tensile strength was 216 MPa with 77.14 % at 630 rpm and welding speed 45 mm/min. The cause of reduction tensile strength for welding return to the different in microstructure between the weld zones and occurs precipitations dissolutions in weld, while the base material contain same microstructure (same grain size) [17]. From figure (8) increasing rotation speed lead to increase in the ultimate tensile strength for all welding speed. The ultimate tensile strength increase from 222.5 MPa to 239 MPa and to 242 MPa at same welding speed (20 mm/min) and also increase the ultimate strength in the same pattern at welding speed (32 and 45) mm/min. The cause of increase strength returns to ultimate increase rotation speed (at same welding speeds) lead to increase the amount of heat transfer during the weld operation and these heat work on increase refines in microstructure in welding [18]. General, the mechanical properties of the aluminum alloy (6061) are dependent on size and distribution precipitations compounds and density of compounds (needleshaped) within the microstructure of these alloy which works on increase its mechanical properties [18], therefore

the decrease in welding efficiency in case 630 rpm and 45mm/min may be due to a random distribution of these components in this alloy. From figure (9) the ultimate strength reduces with increasing welding speed whereby the ultimate strength was 242 at 20 mm/min and at increase the feed rate (welding speed) it reduces to 236 MPa at 32 mm/min after this it also reduces to 231.5 MPa at 45 mm/min. The rotation speeds 630 and 1000 have the same pattern when increase feed rate. The cease for reduction the ultimate tensile strength when increase the feed rate return to the increase feed rate (welding speed) lead to reduction material flow around the welding tool and production non-homogenous distribution for metal [19]. The figure (10) showed that relation between the elongation and feed rate (welding speed) for all welding and rotation weldment speeds and the elongation lower than the base material. The elongation reduction with increasing feed rate (welding speed). The cause of reduction in elongation return to occurrence refining for the microstructure in the weld zone and the grains becomes smoother [18]. In all cases, the fracture occurs in the advance side. In the sample that welded by 630 rpm rotation speed and the welding speed, 45 mm/min the fracture occurs in the region between the TMEZ and SZ because different in the composed between TMEZ and SZ. The **TMEZ** composed of coarse-bent recovered grains while the stir zone composed of fine recrystallized grain and this conform with T. A. Jawad [8] and H.J. Liu[19]. While the others sample the fraction location occurs in the HAZ as shown in figure (11) due to significant coarsening of the precipitated and this conforms with Mishra and Z. Y. Ma[20] and G.R. Babu

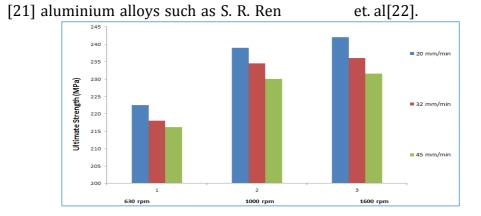
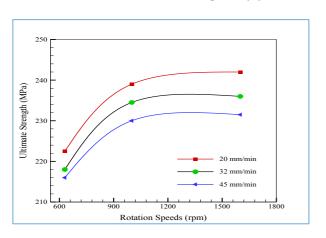


Figure (7): ultimate tensile strength



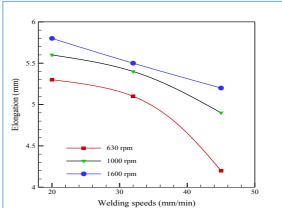
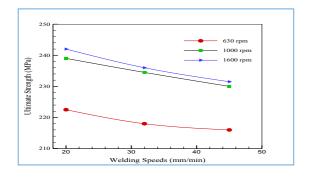


Figure (8): ultimate tensile strength-rotation speeds speeds for weldment.

Figure (9): ultimate tensile strength-welding for weldment.



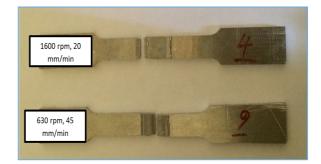


Figure (10): Elongation-welding speeds for weldment

Figure (11): fracture position for weldment

Minitab results

H. Optimum case

In this work, the FSW parameters include rotation speed (630, 1000, 1600) rpm, welding speed of (20, 32, 45) mm/min, and the tilt angle is constant at (2°) with the vertical axis. The suitable orthogonal array (L3) was chosen.

Selection the L3 array for three parameters and their three levels as shown in figure (12) in the design of the experiments (DOE) for welded the similar aluminum alloys (6061-T6) to find the optimum welding parameter.

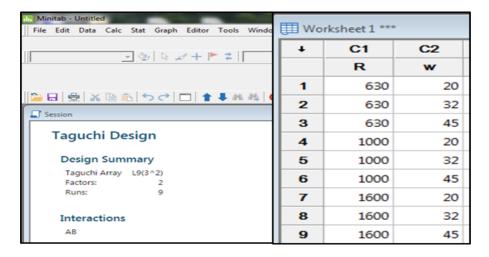


Figure (12): S/N ratio and ultimate to m

The figure (13) explains the optimization case for weldment by depending on S/N ratio and ultimate strength to mean. The best rotation speed was 1600 rpm and best welding speed was 20mm/min due to increase the rotation speed and decrease the welding speed achieved good stir metallic in welding zone and gives better strength for material joint.

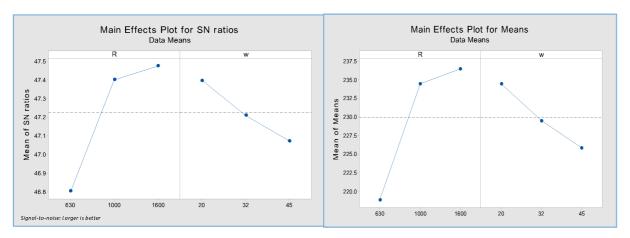


Figure (13) S/N ratio and ultimate to mean

I. ANOVA ANALYSIS

By using an analysis of variance (ANOVA) the percentage contribution of each factor was found. The rotation speeds have a higher effect on tensile strength 83.31% and the welding is lower 16.5%.

J. TENSILE RESULTS FOR DOUBLE PASS

The tensile test results were presented in table (5.4). The ultimate tensile strength for optimum case (single pass)

K. Fatigue results

Figure (14) explained the S-N curve for base material, single pass (optimum case), and double passes (FSP). Nine stress levels were taken to present the S-N curve for base material. When a decrease in the stress level the number of cycles increase and reached to infinite life (106) when applied stress 118 MPa. The fracture location in base material occurs in the region very near to the fixed region because the stress in the region is very large when compared with other regions. Figure (14) also explained S-N curve single pass (optimum case), Usually, the material that welded by FSW has lower ductility and strength from base material due to the softening in nuggets zone which product from the deterioration of precipitates. But the material that welded by FSW has better fatigue strength when compared with the same material that welded

was 242 MPa and elongation was 5.8 mm, but when used FSP (double pass) the ultimate tensile strength increase to 251 MPa to give weld efficiency 89% from ultimate tensile strength to base material while elongation increased to 9.8 mm. The FSP (double pass) lead to enhance mechanical properties and modification of microstructure. These results conform to Kadhim K. Resan, et al [23].

by traditional fusion welding [24]. The reducing in fatigue strength may be caused by the grain refinement in the nugget zone, in addition, the change in micro-hardness during the weldment. This means that there will be a significant change in the residual stresses, which play an important role in the life of the weldment. In FSW all of the fracture locations occurs in the weld zone because the region is less thickness and weaker. The FSP (double pass) work on the higher enhancement of fatigue life and mechanical properties due to the reduction of residual stresses in weldment [25]. The fracture failure for double pass location at low-level stress occurs without weld zones but at high-level stress, the fracture occurs inside the weld zone as shown in figure (15).

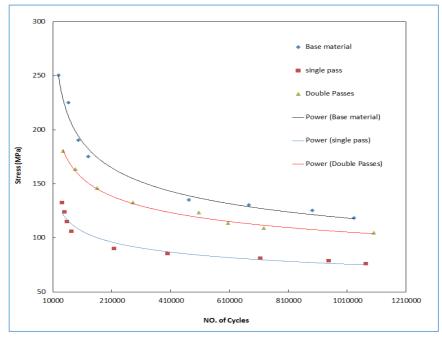


Figure (14): S-N curve for base material, single and double pass.



Figure (15): fracture location for base material and double pass

L. X-RAY RESULTS

From figure (16) that the residual stress for single pass (optimum case (single pass) of FSW) was 726 MPa and it higher than ultimate tensile strength of base material 280 MPa and the maximum tensile residual stress for double pass was 294 and it also higher than ultimate tensile strength for base material 280 MPa. But

the double pass led to reduce residual stress to 59 % due to the double pass work on return distribution residual stress in both two sides advance side and return side. These reductions explain increase the tensile strength, hardness and improve fatigue life for a double pass (FSP).

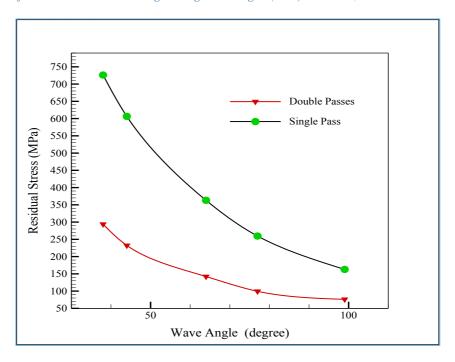


Figure (16) residual stress for a single and double pass

E. HARDNESS RESULTS

The hardness for base material was 99.98 HV. While the minimum hardness for FSW was 50HV in HAZ, and the hardness for SZ was 50.6 HV and this conforms to T. Khaled [3]. This difference in weld zone hardness due to the amount of heat generated which caused softening of HAZ, TMAZ, and NZ due to dissolution and coarsening of the strengthening precipitates during the welding operation [8]. After the double pass with rotational speed (1600 rpm) and welding speed 20 mm/min.

The minimum hardness was in 54.5 HV in HAZ with reduction of about 46.5% from the base material and in SZ were 79.9 HV with the reduction of about 20% from the base material as shown in figure (17). The hardness improved in a double pass in SZ this return to the effect of the recrystallization and the more fineness of the grains. As well as the microhardness is improved in most zones this is due to the second pass worked on reduction residual stresses and homogeneous it on both sides [25].

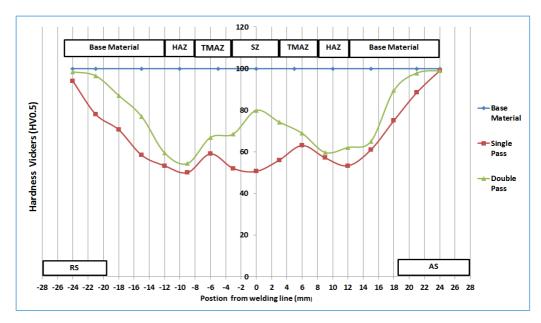


Figure (17): Vickers hardness for BM, single pass and double pass.

IV-CONCLUSION

The previous work concluded that: The optimum case was at rotation speed 1600 rpm and welding speed 20 mm/min gives 86.3 % of welding efficient. Elongation and ultimate strength increase with increasing rotation speed and decrease welding speed. In tensile strength, most failure occurs in advance side in HAZ, but case one (630 rpm and 45 mm/min) the fracture occurs in the region between TMEZ and SZ. Double pass leads to increase the ultimate strength, proof strength, modules of elasticity, hardness, elongation and reduction residual stresses for the same welding and rotation speed. Friction stir processing (double pass) is suitable to improve the fatigue strength

for element whereby the reduction in fatigue strength for the single pass was 31% while for the double pass was 10% only. The rotation speed has a higher effect on ultimate tensile strength was 83.31% while welding speed was 16.5%. Using double pass (FSP) lead to a reduction the residual stresses to 59% when compared with the optimum case whereby was residual stress in optimum case 726 MPa and for a double pass (FSP) was 294 MPa at same rotation and welding speeds. The Vickers hardness at the single pass in stir zone was 50.6 HV0.5 while at the double pass was 79.9 HV0.5.

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