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Research Article

Influence of the Tunnel Defect in Al 6061-T651 welded by FS on the Bending, Tensile, and Stress Concentration Factor

Isam Tareq Abdullah†*

†Middle Technical University – Engineering Technical College- Baghdad, Iraq

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Abstract

Friction Stir Welding (FSW) is a very effective technique mainly to join the Aluminum alloys that faced a difficulty when welding in the classic methods due to the occurrence of defects. Even though FSW has some disadvantages, as heat input plays a very important role in occurrences of these flaws. Heat input during this process is dependent on many factors like FSW parameters, such as (rotational and transverse speeds), tool design (pin geometry, pin and shoulder diameters, etc.) and axial force. Certain variations in welding parameters generate defects in the weld due to improper heat input. In this paper, several efforts were investigated to study the effects of various types of tunneling in friction stir welding (FSW) with different variables i.e. tool rotational speed (1120, 560 and 1400) rpm with welding speed of (50, 16 and 125) mm/min respectively to weld Aluminum 6061-T651 and a tool that has a 6mm diameter pin of 5.8mm height, and 24mm shoulder diameter with concave angle of 2.5^0. The tunnel defect at friction stir welding was examined under these parameters and investigated implementing the bending and tensile tests as well as the determination stress concentration factor via a Finite Element method using (ANSYS software). The important conclusions found for the present study are that the tunneling was observed in at the welded zone, when applying a rotational speed of (1400, 1120) rpm, and Traveling at (125, 50) mm/min. But there were not any defects in samples welded at (560) rpm, the Travel speed of (16) mm/min. Also, the FSW best results were obtained at 560rpm and 16mm/min, according to the outcome of the tensile test which showed that at the above variables the strength increased by (65%). The fracture of the specimens welded by FSW occurred in the heat affected zone (HAZ) on the advancing side. The softest zone in the FSW joints is due to significant coarsening of the precipitates. Most of the FSW weldments produced the U-shape during bending test. The highest Bending force of 3.6 KN was achieved at the mentioned speeds as well.

Keywords: *Friction Stir Welding, Tunnel hole, Bending test, Finite element method, ANSYS, stress concentration factor, Aluminum alloy 6061*

1. Introduction

Friction Stir Welding FSW was invented by (Wayne. T) by T-W-I. Ltd. in 1991. It overcomes many of the problems in traditional joining techniques and can produce welds of high quality, particularly in the case of difficulty to weld materials such as aluminum alloys, magnesium, and copper. It is widely utilized for manufacturing transport structures such as boats, trucks, trains, and aircraft. FSW is now widely implemented because it is energy saving and environmentally friendly process. Although the quality improvement of FSW joints as compared to the fusion techniques, there are some defects that may be increased and that are very important to decrease its variation in the welding process. (Joshi *et al*., 2011) studied the defects in FSW by radiography, conventional ultrasonic and phased array ultrasonic technique and then compared between them. (FU R. D. *et al*., 2012) studied the parameters effect on the FSW (ambient temperature and direction of a friction stir welding).

On the assumption that the weld parameters are the same under different directions, the joints welded using a stir tool rotated in a counterclockwise direction exhibits better formation quality than those welded in a clockwise direction. The formation quality of the joints welded underwater clearly improves compared with that of the joints welded in the air. Excellent weld joints free from defects are obtained in the present range of the FSW parameters for joints welded underwater and the stir tool rotated in the counterclockwise direction. (S. Ravikumar *et al*., 2013) studied the effect of welding parameters on the macro and micro structural characteristics of friction stir welded butt joints of dissimilar aluminum alloy plates between AA7075-T651 and AA6061-T651.The base material AA6061-T651 was placed in advancing side

*Corresponding author's ORCID ID: 0000-0000-0000-0000

(AS) whereas AA7075-T651 placed in retreating side (RS) respectively. The Friction stir welded materials were joined at three different tool rotational speeds 800,900 and 1000 rpm, and three traveling speeds 90, 100 and 110 mm/min, which are the two prime joining parameters in FSW. Three different pin profiles (Taper cylindrical threaded, Taper square threaded and Square) tools were used to consolidate the weld. The better mixing of both materials and good strength were achieved for the process parameters 900rpm, 90mm/min with Taper cylindrical threaded tool. (Sebastian Balos and Leposava Sidjanin, 2013) in this work, an attempt was made to study the effects of various types of tunneling defects in friction stir welding (FSW). Two types of welding tool were used, (one with a threaded and the other with a polygonal pin). To enable the formation of tunneling defects, (the shoulder-to-pin-volume ratio) was larger than (1) for both tools, while the ratio of spindle speed to welding speed (feed rate) was optimized as well. Tunneling defects were tested on (H38) alloys and (EN-AW 5052 H32), having the thicknesses of (8 and 3) mm. It was found that the threaded tool produced a single or double triangular, as well as crack-shaped tunnel.

The polygonal tool produced multiple triangular tunnels (the material flows toward the weld direction) with a complex shape or a crack-type tunnel with a complex shape. The most unfavorable tunnel obtained with the polygonal tool was the crack-shaped one, resulting in the 62 and 46 %) joint yield and ultimate tensile strength efficient. (Sagar *et al*., 2014) investigated the analysis of the mechanical behavior of friction stir welds of AA6061 aluminum alloy plate using different tool pin profiles. This investigation includes four different tool pin profiles (square, triangular, threaded and straight cylindrical) used to weld joints in two process mode (single and sequential double sided). Square tool pin profile has more joint efficiency of 72.2% in double side welded joints as compared to single sided welded specimens. The lower value of tensile strength and percentage of elongation was observed in weldments fabricated by single pass process compared to the ones accomplished by double pass process. The tensile strength is maximum for square tool pin profile as compared to other tool profiles for double pass welded joints. (Inderjeet Singh *et al*., 2014) studied the Friction Stir Welding by combination of alternative parameters i.e. speed of rotational tool 1000, 1200, 1400, 1600 and 1800 rpm and feed rate of 25 mm/min. to weld Aluminum 6063 using a cylindrical left hand threaded tool and 20 mm tool shoulder diameter and 7 mm pin diameter for welding. The effect of tool rotational speed on the mechanical properties was examined. It was observed that excessive heat generation and insufficient flow of plasticized material at higher values of tool spindle speed, leading to the formation of defect that results in the failure of weld joints between (Stir Zone) and (Thermo- mechanically affected Zone). (D. Trimble *et al*., 2015) Macrostructure, microstructure, and micro hardness of friction stir welded AA2024-T3 joints were studied. The influence of tool pin profile on the microstructure and hardness of these joints was examined. Square, triflute, and used cylinder pins with cone shape and results from each weldment are reported. Vickers microhardness tests and grain size measurements were taken from the transverse plane of welded samples. Distinct zones in the macrostructure were evident. The zones were identified by transitions weld samples for the microstructure and hardness. The zones identified across the sample were the unaffected parent metal, the (Heat Affected Zone (HAZ)), the (Thermo-Mechanically Affected Zone (TMAZ)), and the (Nugget Zone (NZ)). Measured hardness values varied through each FSW zone. (P. Podržaj *et al*., 2015) investigated an overview of different types of defects at friction stir welding. An energy supply based, division of defects into three disjoint groups was used. The occurring defects are demonstrated on various materials. (Ramachandran, K. K *et al*., 2015) studied FSW to join 3mm thick Al Alloy AA5052 H32 and HSLA steel IRS M42 in a butt joint configuration. The effect of tool rotational speed and tool tilt angle on the mechanical and metallographic characteristics of the joint was investigated.

The microstructure at the joint interface region was investigated by optical microscopy, scanning electron microscopy, and EDS analysis. (S. M. Bayazida *et al*., 2015) studied the effect of the pin profile on defects of FSW 7075 alloy. Cylindrical, square and triangle geometry shape of pin were used in the process. The Microstructure of the welding zone showed that the tunnel hole produced by triangle pin has smaller dimensions compared to cylindrical pin. (N.A.A. Sathari1 *et al*., 2015) concerning on the influence of the position of material and spindle speed on tensile test for dissimilar welding of the aluminum plate (AA7071 and AA6061) with 2.0 mm thickness by a conventional milling machine. Ten joints were produced by varying spindle speed and by alternating the location of the metal on the advancing and retreating sides. The results shown that the maximum tensile strength of 207 MPa was achieved when AA6061 aluminum alloys were placed on the advancing side at a rotational speed of 1000 rpm with seamless surface appearance and no inner defect across the weld area, while the lowest tensile strength of 160 MPa was obtained when AA6061 was placed on the retreating side with severe tunnel defects across the weld area contributing to crack propagation. Thus, in dissimilar welding, weaker materials should be on the advance side and smooth of the flow of metal formation in the stirred side.

In the present work the Friction Stir Welding by combination of different parameters i.e. tool rotational speed (1120, 560 and 1400) rpm with welding speed (50, 16 and 125) mm/min respectively to weld Aluminum 6061-T651 by a 6mm pin diameter and 5.8mm height and 24mm shoulder diameter with 2.5° cone angle pin diameter was employed for welding. The tunnel defect at friction stir welding was examined under these parameters and investigated its effects on the bending test, tensile test and the stress concentration factor.

2. Experimental Part

A 6mm thick plate of 6061-T651 aluminum alloy is used. The hardening constituent in 6XXX series alloys is magnesium silicide Mg2Si [ASM Vol. 2, Metals Handbook 1990]. Al-Alloy 6061 is one of the most widely used in the 6000 Series. It is also very versatile among the heat treatable alloys [Dieter, G. E.1988]. Chemical composition by Spector device located in (The State Company for Inspection and Engineering Qualification) is shown in Table (1), and it is compared with the standard value according as ASM while Table (2) illustrated the standard mechanical properties of AA6061-T651 aluminum alloy.

Table.1 Chemical composition of 6061- T651 aluminum alloy

AA 6061-T651		
Chemical Composition	Standard Value	Actual
Si	0.4-0.8	0.68
Fe	0-0.07	0.54
Cu	0.15-0.4	0.34
Mn	0-0.15	0.07
Mg	0.8=1.2	0.95
Cr	0.04-0.035	0.3
Al	Bal.	Bal.

Table.2 Mechanical properties of AA 6061-651aluminum alloy

Tensile yield Strength σy (MPa)	UTS σu (MPa)	Elongation EL%	melting point °C
285	317	12.1	582-652

Laser wire cutting was used to specify the geometry of 310 x 100 x 6 mm of aluminum alloy AA6061-T651. Butt joint configuration parallel to the rolling direction was prepared to fabricate friction stir welded joints as shown in Figure (1).

Design of the tool is an effective factor in FSW process due to its function in heat generation, material flow, torque of machine and the weld soundness. These features will govern and determine the acceptance of the weld as well as, the successful application of the process to a wider range of materials and over a wider range of thicknesses depending on the tool geometry. In this work, the tool is designed according to the following specifications:

Figure (2a, b) shows the Friction Stir Welding Tool and schematic plot It was made of High Speed Steel (HSS M35) which has 56 HRC, Pin diameter is 6mm and Height equals 5.8mm. The shoulder diameter is chosen four times the pin diameter (shoulder diameter=24mm) with concave angle of 2.5^0. Friction stir welding tool is in Figure (2a, b). While Table (3) shows the specification of the design's tool.

In this work, a vertical milling machine was employed to carry out all the friction stir welding processes in the Engineering Technical College/Baghdad. The butt joint configuration was obtained by fixing the welding samples into a carbon steel backing plate which was fastened into the milling machine table and was adjusted to have a level surface. During welding, the tool rotation was in clockwise direction with respect to the vertical axis, and the tool was traveling in the rolling direction of the alloy.

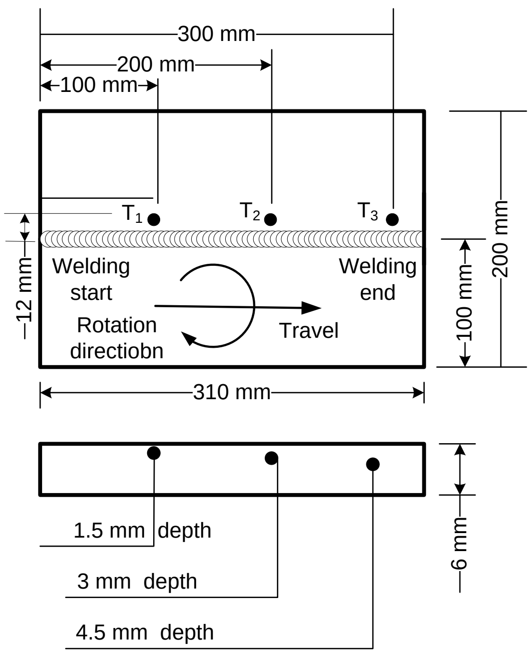


Fig.1 Dimensions of the **AA6061- T651** aluminum alloy square butt joints used for welding processes. Showing the location of temperature measurements

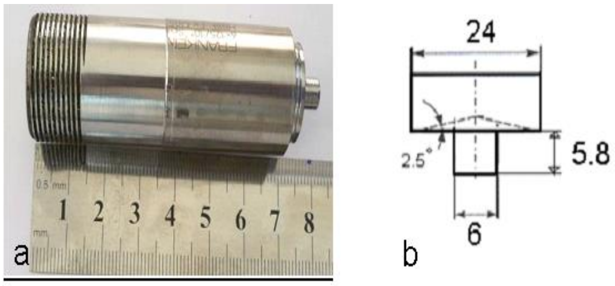


Fig.2 Friction Stir Welding Tool (a) the fabricated tool (b) schematic plot

Table.3 Specification of FSW tool

Shoulder Diameter	24 mm
Pin Diameter	6 mm
Pin Length	5.8 mm
Angle of Concavity	2.5°
HRC	56 HRC

As the friction stir welding process was performed, it requires clamping the pieces with a square butt joint shape. This fixture is also needed to generate an opposite forces to that induced as a result of plunging and moving of welding tool. Clamping system consists of flat metal plate (backing plate) that was made of carbon steel, two clamp steel bar and side screws. The clamping system was connected to the machine table by vertical bolts. The welding parameters used to make the FSW joints are presented in Table (4):

Table.4 FSW parameters for AA6061-T651 aluminum alloy

Rotation speed (rpm)	Travel speed (mm/min)
1120	50
560	16
1400	125

Three-point bending test was carried out to determine the maximum bending force of the welded joints. Face and root bending tests were carried out with the former diameter is equal to 58.1mm (1.5 in.). Testing was performed at room temperature by universal testing machine (united test 100KN) in the (Institute of Technology – Baghdad).

The Fig. 3 displays the specimen dimensions for tensile test. The tensile test was carried out on samples taken in a perpendicular direction to the axis of welding to determine the tensile properties of the welded joints for both welding processes. The shapes and sizes of the transverse tensile specimens according to ASTM (B557M) are shown in figure (3). All tensile tests were carried out at room temperature and constant feed rate (5 mm/min) via universal testing machine (test for 100 KN) in (Institute of Technology – Baghdad). Then the average of three specimens was taken to evaluate the tensile behavior of each welded joint.

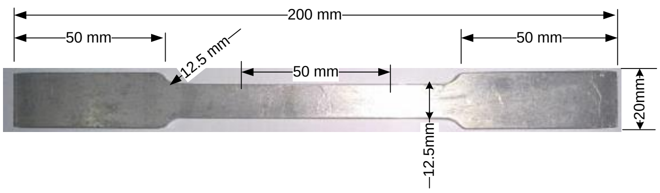


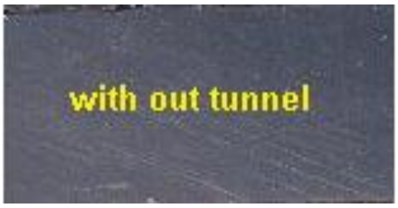
Fig.3 Tensile test specimen

Temperature measurement within the stirred zone is very difficult due to the intense plastic deformation produced by the rotation and translation of the tool [sabah khammass Hussein 2016]. Therefore, the maximum temperatures within the stirred zone during said FSW were recorded by embedding thermocouples in the regions adjacent to the rotating shoulder. The K-type thermos-couples were used to measure the temperature at different depths that were 1.5 mm, 3mm and 4.5 mm within the thickness of welded plate in addition to being at the various distance within the length of the specimen, as illustrated in Figure (1). Also an IR thermometer is used to measure the temperature in addition to the thermocouples, through the work piece.

3. Results and Discussion

Figure (4a, b, c) illustrates the welded plate of 6061-T651aluminum alloy in accordance to the designed tool, machine, fixture. etc., parameters and conditions mentioned above. The defects were existing in the friction stir welding FSW, caused by the stir effect of the metals via the processing, inadequate surface preparation, lack of penetration of the pin and non-uniform vertical forging forces along the material thickness.

a: Rotation speed 1120 rpm, Travel speed 50 mm/min



b Rotation speed 560 rpm, Travel speed 16 mm/min

C: Rotation speed 1400 rpm, Travel speed 125 mm/min

Fig.4 Welded plate of AA6061-T651aluminum alloy according to our designed tool, machine, fixture .etc., the parameters and conditions

It can be seen that the tunnel exists in case of (Rotation speeds of 1120 and 1400(rpm), Travel speeds of 50 (mm/min) and 125 (mm/min)) as illustrated in Figure (4a, c) where defects were found in the welded plate while in the case of (Rotation speed = 560 (rpm), Travel speed = 16 (mm/min)) it was free of the tunnel defect as illustrated in Figure (4b) Attributing the parameters of the forming of a tunnel to the excessive heat as in the first case where the metal is plastically deformed by the movement of the tool due to the centrifugal force resulting from the high rotation and the metal being closer to the state of light fluid, so the cooling down is not slow enough for the plastic like metal to close the gap of the rotational speed affected area. Whereas for the second case, despite the circulating speed is not high but the tool is travelling too quick for the plastic metal to fill in the space produced by the tool, before cooling down as the heat is not as much as in the first case, still for the high thermally conductive Aluminum, the temperature drops rapidly.

In this work the stress analysis around the tunnel holes was also performed to observe the stress concentration factor in these zones.

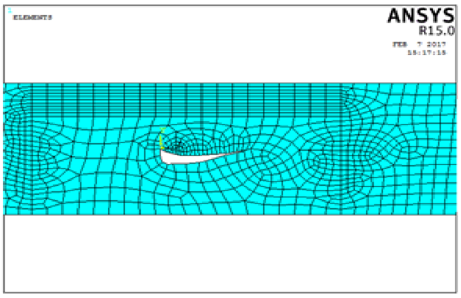
A stress concentration is a location in the object where stress is concentrated. A constant cross sectional area of a tool subjected to a force is stressed distribution as a constant over its area, so a decreasing in area, e.g., caused via a crack, produced in a localized increasing in stress. The maximum stress exists near the crack in the area of the lowest radius of a curvature, where the stress concentration factor is the ratio of the highest stress to a reference stress of the gross cross-section. The welded plates which have the tunnels that were generated under different parameters are examined under static, dynamic and repeated load vis ANSYS software. The ultimate purpose of a finite element analysis is to re-create mathematically the behavior of an actual engineering system. In other words, the analysis must be an accurate mathematical model of a physical prototype. In the broadest sense, the model comprises all the nodes, elements, material properties, real constants, boundary conditions and the other features that were used to represent the physical system. In ANSYS-15 terminology, the method used to generate the model is the solid model. The two dimensional model of a specimen were done with element plane182. Figure (5a, b) shows the specimen model.

Three types of loadings (static, dynamic and repeated) were carried out on the FW welded plate to determine the stress concentration factor.

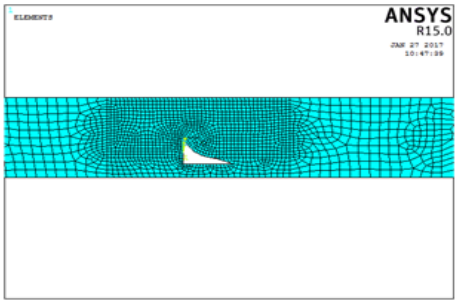
It was seen that cracks within an FS welded plated can produce catastrophic failure when the applied loading causes the stress concentration at the crack tip to reach a critical value (the ratios of the stress concentration factor for the cases were 80% in static condition, 60% in dynamic condition and 57% for repeated loading and the ratios of the stress concentration factor for the cases were 48% in static condition, 76% in dynamic condition and 51% for repeated loading). It is also possible to induce failure as a result of subcritical crack growth causing an increase in crack length and hence in stress concentration, while such crack extension may occur under repeated loading.

The results of face and root bending test are summarized in Figure (6a, b, c). After the welded joints had been obtained each of these joints was subjected to the three-point bending test using universal testing machine that the best bending force values were achieved at (16 mm/min) travel speed for (560rpm) rotational speed as shown in Figure(6b). Figure(6a) and (6c) shown decreasing in bending load with increasing in the travel speed, this is apparently due to the presence of significant tunnel in the stirred zone of this joint, no cracking is observed in bend test of the joints.

Tensile tests are done on the specimens of the base metal and the welded metals. Average tensile strength values for base alloy and FSW materials are listed in Table (5) below:



a- Finite element model at Rotation speed 1120 rpm, Travel speed 50 mm/min



b- Finite element model at Rotation speed 1400 rpm, travel speed 125 mm/min

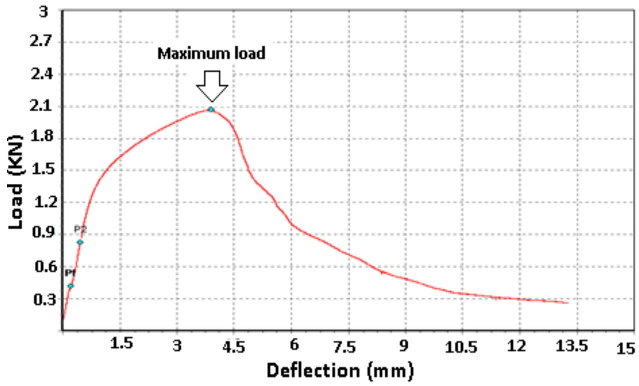
Fig.5 Mesh of the welded plate

Fig. (7a, b, c) shows the type of the fracture in the tensile test was the ductile or high energy fracture, as the specimen material is of high ductility, which would be expected to undergo large plastic deformation prior to and during a rupture process, these types of fracture are more risk failure in welded metals had tunnel defect. Figure (7 a, b, c) represent that the failure of a specimen with tunneling, are fast spreading fracture which is associated with relatively low failure energy (i.e. the input power required to propagated the crack is small with little plastic deformation prior to and during crack extension).

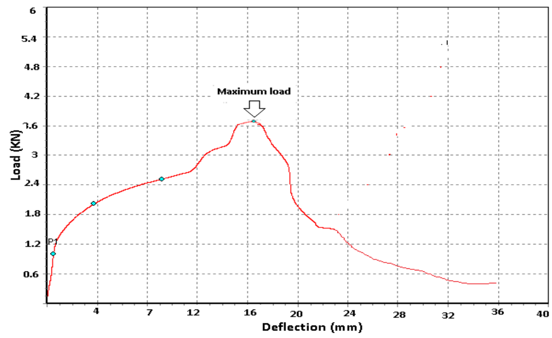
It is worth to note that the bending and tensile tests results were identical in their indications for the best parameters.

FSW results in intense plastic deformation around the rotating tool due to friction between it and work pieces, which subsequently influence the heat increase within and around the stirred zone. Since the temperature distribution in that region, directly causes changes in the Macrostructure of the welds, as well as the mechanical properties of the welds, it is important to obtain information about temperature distribution during FSW. So in this work the temperature is measured along the thickness of the welded plate, three depths are selected (1.5,3 and 4.5) mm.

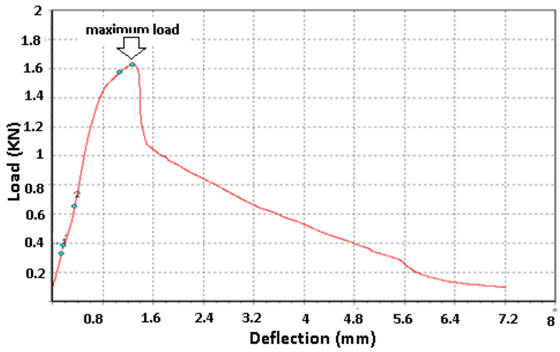
Table (6) shows these temperatures with different parameters.



a- Rotation speed 1120 rpm travel speed 50 mm/min

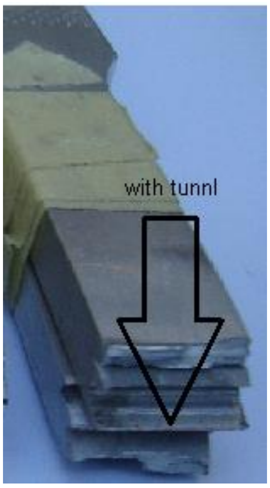


b- Rotation speed 560 rpm, travel speed 16 mm/min

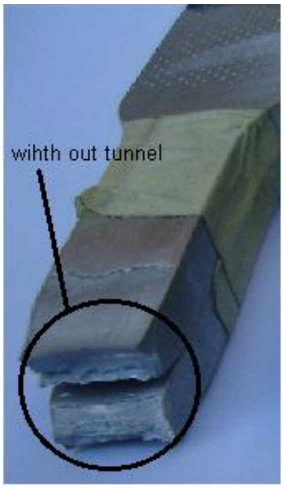


c- Rotation speed 1400 rpm, travel speed 125 mm/min

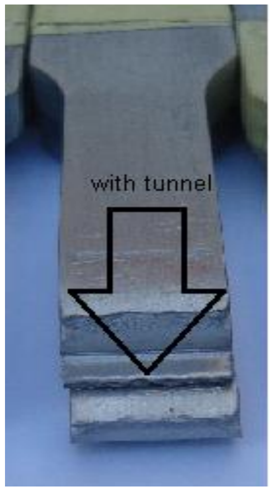
Fig.6 Bending test results for AA6061-T651 aluminum alloy FSW



a- Rotation speed 1400 rpm, travel speed 125 mm/min.



b- Rotation speed 560 rpm, travel speed 16 mm/min.



c- Rotation speed 1120 rpm, travel speed 50 mm/min.

Fig.7 Fracture points of tensile specimen

Table.5 Tensile test results for 6061-T651 aluminum alloy FSW

Rotational Speed (rpm)	Travel speed (mm/min)	Average UTS (MPa)				
1400	125	119	148	167	140	176
560	16	138	173	165	150	176
1120	50	114	152	163	138	163

Table.6 Temperature distribution across the depth of FSW

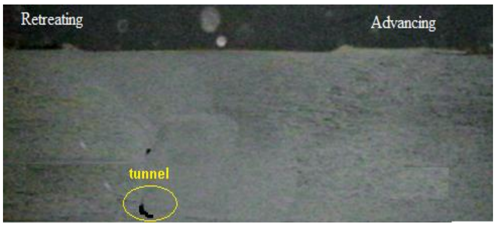
Rotational Speed (rpm)	Travel speed (mm/min)	Depth 1.5mm	Depth 3mm	Depth 4.5mm
1400	125	289 °C	235 °C	322 °C
560	16	196 °C	189 °C	265 °C
1120	50	415 °C	426 °C	442 °C

Also, in this work the temperature in the location of mixed aluminum material is measured using Laser thermometer.

Fig. (8a, b, c) shows the Macrograph of FSW. Optical macroscopic examination was carried out on joints welded at 16 mm/min travel speed and rotation speed of 560 rpm as shown in figure (8b), which revealed that no porosity or other defects (such as tunnel) exist in the stirred zones of most joints produced, then the same examination was repeated on joints welded at (1400 and 1120) rpm and different travel speeds 125 and 50 mm/min as shown in figure (8a) and (8c). From figure (8) it can be seen that the welding profile becomes more uniform with the decreasing in rotational speed at constant travel speed.

a- Rotation speed 1400 rpm, travel speed 125 mm/min

b- Rotation speed 560 (rpm), Travel speed 16 mm/min.



c- Rotation speed 1120 rpm, travel speed 50 mm/min.
Fig. 8 Macrograph of FSW

Conclusions

The joints made-up using different speed of (1400, 560, 1120) rpm, Travel speed of (125, 16, 50) mm/min. The following important conclusions were made for the present study.

1) Tunnel defects were observed in joint zone, at speed of (1400, 1120) rpm, and Travel speed of (125, 50) mm/min. but not any flaws in samples welded at a speed of (560) rpm, and Travel speed of (16) mm/min.
2) FSW best conditions for a 6-mm thick plate of aluminum alloy AA6061- T651 are Rotational Speed 560rpm and 16mm/min Travel speed, according to the results of Tensile test which showed that using the mentioned parameters give the best strength with an increase of (65%) more than those of FS welded samples.
3) The fracture of the welded specimens existed in the heat affected zone (HAZ) on the advancing side. The softest zone in the welded metal is due to significant coarsening of the precipitates.
4) Most of the FS weldments give the U-shape during bending test. The highest force of 3.6 KN achieved when the 560 rpm rotation speed and 16 mm/min travel speed.
5) The change of the Rotation and Travel speeds lead to change in the heat input to the workpiece, material flows in the shoulder flow zone is significantly affected by the tool shoulder inclination that gives enough time, to flow from the zone under the shoulder to accumulate around the pin.
6) To avoid tunnel, the relation between tool circulation and traverse velocities should be well taken care of to control the thermal energy, which is the most important factor in this flaw to occur.

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