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Research Paper

EXPERIMENTAL STUDY OF FRICTION STIR WELDING OF 6061-T6 ALUMINUM PIPE

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Friction Stir Welding (FSW) is a relatively new joining process that has exhibited many advantages over traditional arc welding processes, including greatly reducing distortion and eliminating solidification. The present work aims to determine the feasibility to weld two pieces of aluminum pipe by friction stir welding process and study the effect on the mechanical properties of welding joints. Special welding fixture fixed on conventional milling machine has been conducted to attempt this welding and group of welding parameters. Three tool rotational speeds (500, 630, 800 rpm) with four welding speeds (0.5, 1, 2, 3 mm/sec) for each rotational speed had been used to study the effect of each parameters (tool rotation, weld speed) on mechanical and microstructure properties of welded joints. Mechanical properties of welded joints were investigated using different mechanical tests including non destructive test (visual inspection, X-ray) and destructive test (tensile test, microhardeness and microstructure). Based on the stir welding experiments conducted in this study the results show that aluminum pipe (AA 6061-T6) can be welded by (FSW) process with a maximum welding efficiency (61.7%) in terms of ultimate tensile strength, using 630 (RPM) rotational speed, 1 (mm/sec) traveling speed.

Keywords: Friction Stir Welding, 6061-T6 Al Pipe, Feasibility, Mechanical properties

INTRODUCTION

FSW is a rapidly maturing solid state joining process that offers significant benefits over conventional joining processes. Invented by The Welding Institute (TWI) in 1991, FSW uses a combination of frictional heating and compressive loading to join metal plates that are butted against each other and tightly clamped to the anvil of the machine. Extensive research has been accomplished on developing the friction stir welding process for aluminum alloys, but there are relatively few papers about aluminum pipes welding. Gerçekcioglu *et al.* (2005). Investigated the friction behavior on the worn surface of AA 6063-T6 tubes welded via friction stir welding

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method. In this study, the effective of rotational speed of stirrer on the outer surface of friction stir welding has been investigated.

Dubourg *et al.* (2009), the study shows the preliminary results on Friction Stir Welding (FSW) of 2024-T3 aluminum alloy tubes and the impact of the welding process on weld quality. Welding was performed on tubes with similar thickness. The mechanical properties of the welds were assessed by hardness and tensile measurements on as-welded and heat treated tubes.

This paper will focus on the mechanical properties of the welded joints of AA 6061-T6 tubes after friction stir welding.

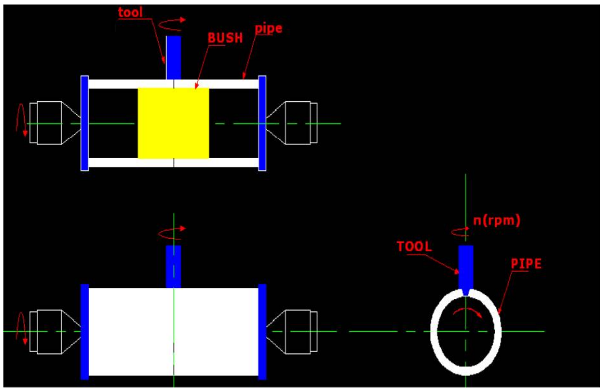
EXPERMINTAL WORK

Due to of the non availability of specialist machine in Iraq for FSW process. A conventional vertical milling machine was used to attempt the welding process as shown in the Figure 1. The machine must has the ability to apply significant pressure on *z* axis direction, wide range of spindle speed, enough space for its working table to holding the welding assembly and rigidly during the welding operation.

Figure 1: Milling Machine

The milling machine used has rotational speed on the head that is suitable to fixing welding tool on it, but it has linear speed on table that is not match with the objective of the study (need circular rotational feed) so that some apparatus were adapted on its working table. Figure 2 shows schematically Friction Stir Welding (FSW) apparatus and equipments.

Figure 2: Illustration of Friction Stir Welding Equipment



A rotating clamping fixture where designed to clamps and hold the two segments of pipe together for butt joint welding.

The clamping fixture consist the following:

- Gear box with a rotating clamp hold the pipe from one side and can be fixed tightly to the working table of the milling machine as shown in Figure 3, the reduction ratio for the gearbox is 40 to 1 rpm.
- Fixing mandrel hold the other side of pipe and tightly forced to the two pieces, preventing them from any horizontal movement during welding process.The mandrel can freely rotate 360 degree with rotational speed of pipe and also can be fixed on the working table of the milling machine as shown in Figure 4.

Figure 3: Rotating Clamp Gearbox

Figure 4: Fixing Mandrel

- To provide the internal pipe support to prevent wall collapse due to the high pressures exerted by the FSW process, an internal, anvil was designed. anvil fixed inside the two pieces of pipes before welding operation by use hydraulic press. Figures 5 and 6 show the anvil, fixing hydraulic press
- An external anvil used to prevent bending of the two pieces of pipe due to the force applied from the tool and tool shoulder during welding operation. Figures 7 and 8 show the external anvil position during welding operation.

Figure 5: Internal Anvil

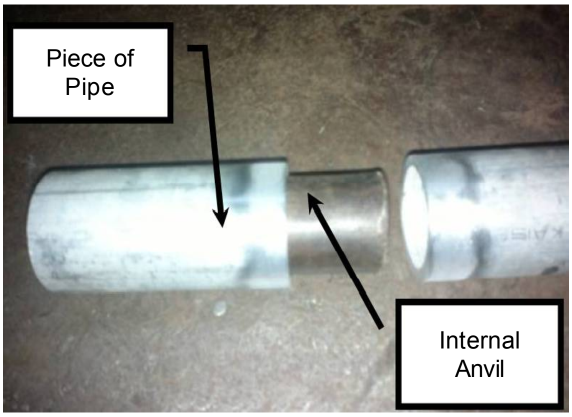


Figure 6: Hydraulic Press

Figure 7: External Anvil

Figure 8: External Anvil Position

- To have the rotational speed for the clamping gearbox, driving gearbox connected to it by means of two gears and chain as shown in the Figure 9.

Figure 9: Driving Gearbox

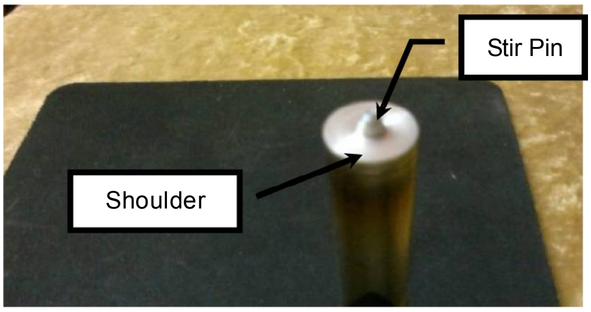
Specification of driving gearbox. Reduction ratio 1500 to 80 rpm.

Motor 380V, 50HZ, 0.75hp.

- To control speed of driving gearbox an inverter AC driver fixed on the driving gear.

High speed steel material was used for welding tool. Figure 10 show the tool geometry which is consist from two main part shoulder and probe. The cylindrical shoulder produces a mixture of frictional heating and forging pressure, most of heat generation related to the tool shoulder while the probe When descended to the part, the rotating pin contacts the surface producing frictional heating which softens a small column of metal.

Figure 10: Welding Tool



Shoulder diameter 20 mm and it fit to the holder of milling machine.

Pin has conical shape start from diameter 5 mm to 3 mm and length of pin is 4.2 mm.

Set of parameters were used as shown in the Table 1.

Table 1: Variable Parameter Used

Rotational Speed (rpm)	Weld Speed (Feed) (mm/sec)
500	0.5
	1
	2
	3
630	0.5
	1
	2
	3
800	0.5
	1
	2
	3

RESULT AND DISCUSSIONS

Visual Inspection Results

Visual inspection was performed on all welded samples were obtained from different welding parameters in order to verify the presence of possible macroscopic external defects, such as surface irregularities, excessive flash, and lack of penetration or surface-open tunnels.

Visual Inspection Prior Welding

After the preparation the two segments of pipes and fixed it on the welding fixture Some features that might be affect the quality of welding should be inspected as following.

- The edges for the two segments that welding occur on it should be good finish ,faced and cleaned surface from oil and dirt to get defect free welded joints.
- Internal anvil securely fixed inside the two segments of pipe without any gap between the welding edges, this gap if it exists effects weld quality and then the welded joint may be has a defect in the welded line.
- Tightly clamped the two segments on the welding fixture preventing the assemble from any movement during welding operation.
- Positioning accurately the external anvil dawn the interface of the two edges on the same axis of welding tool (*z* axis),otherwise bending occurred due to force applied from tool shoulder and probe on the pipe that produce gab dawn the interface of two segments.

Visual Inspection During Welding Process

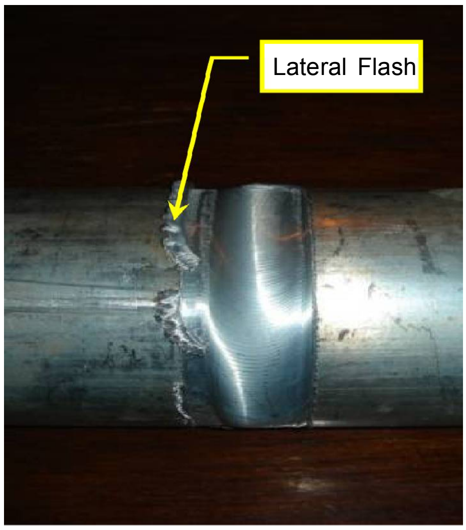
The Second stage on visual inspection was performed during welding process to check:

- Initial starting point is the most important that pin must be come to the interface both pipes. Besides, the bond desired between the both pipes cannot be taken place well. And also, some gaps and cracks can be occurred as shown in Figure 11.

Figure 11: The Welding Surface Near the Initial Point

- Excessive lateral flash was also observed in most of the welds resulting from the outflow of the plasticized material from underneath of the shoulder due to high plunging tool depth Figure 12.

Figure 12: Lateral Flash in the Joint



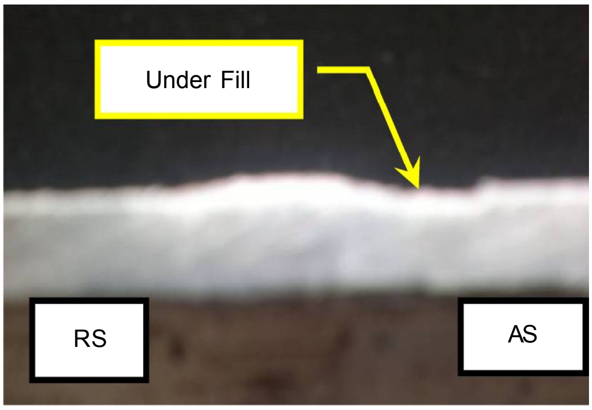
- External surface behavior (rough or smooth) and that depends on welding parameters from rotational speed of tool and welding speed.

Visual Inspection After Welding Process

Final Welding joint inspected in this stage from weld face and root. The visual defects from this inspection are:

- In the weld area Figure 13, the thickness reduction from 5 to 4.8 mm was always observed on advancing side, even for the optimized welding parameters. This defect was named under fill and this formation can be explained considering contact conditions between the welding tool and the pipe.
- Inspection the final weld faces for any defects found due to tool shoulder.
- Tunnel type defect and crack where observed due to inadequate flow of material caused by insufficient heat input when high rotational tool speed (800 rpm) or high traveling speed (2 mm/sec) where used for different welding parameter.

Figure 13: Cross Sections of a Circumferential Weld



Radiography Inspection Results

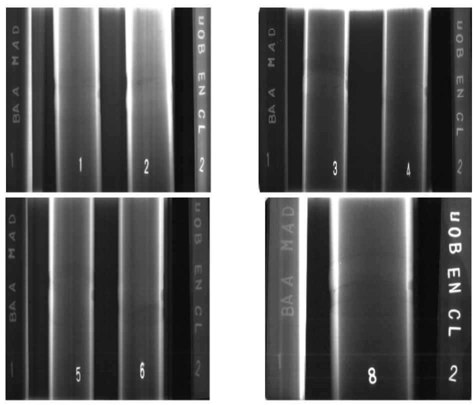
According to radiography inspection results (which conducted using 100 KVA and 5 mA source, Exp. time 36 sec), only two joints had been accepted from the inspector (sample 5, 8 which is represent the experiment, FSW6 and 7) others have internal defect in weld line. The type of defect is evaluated as incomplete fusion (tunnel or worm hole), incomplete cap.

It is believed that these defects are attributable to the combination of the following parameters: insufficient or excessive rotational speed or welding speed combined with too low downward force. In such case the welded parts cannot be correctly stirred and mixed together and a tunnel (also called “worm hole”) is created, running along the entire weld (Adamowski and Szkodo, 2007).

Radiography inspection results did not (as expected) reveal any type of porosity or blow holes or any type of hot cracking because no melting and freezing occurs in welding process due to the solid state nature of (FSW) process.

Figures 14 show samples of radiographic inspection film, which were conducted using the above inspection parameters.

Figure 14: X-Ray Radiographic Image for Selected Sample



Tensile Test Results

Tensile tests were conducted for each welding joint that produced from different welding parameters. The test results compared with the tensile properties of base metal and the welding efficiency (based on ultimate tensile strength) for friction stir welding have been calculated for each experiment.

Table 2 show the tensile tests results and welding efficiency for each welding parameters.

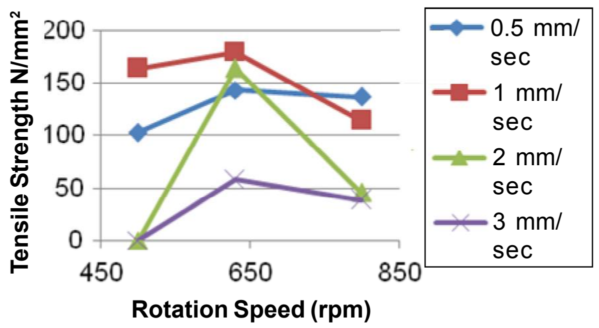
Table 2: Tensile Test Results

FSW Experiments	Rotational Speed (rpm)	Welding Speed (mm/sec)	Tensile Strength (N/mm²)	Joint Efficiency in Terms of Tensile Strength(%)
Base Metal	–	–	290.18	–
FSW 1	500	0.5	102.56	35.30
FSW 2	500	1	163.49	56.34
FSW 3	500	2	FAIL	–
FSW 4	500	3	FAIL	–
FSW 5	630	0.5	142.98	0.49
FSW 6	630	1	179.00	61,7.00
FSW 7	630	2	163.4	56,34.00
FSW 8	630	3	57.60	19,86.00
FSW 9	800	0.5	136.39	47.00
FSW 10	800	1	114.21	39.38
FSW 11	800	2	45.68	15.75
FSW 12	800	3	38.25	13.18

In FSW, the properties of the weld joints are highly dependent on the operational parameters and the materials to be welded. Two of the most important welding parameters are the rotational speed and the welding speed (travel speed).

Figure 15 show the tensile test results for three rotational speed (500, 630, 800 rpm)

Figure 15: Relation Between the Rotational Speed with Tensile Strength of Welded Joints



with different welding speed (0.5, 1, 2, 3 mm/sec) and from above results we see increasing in tensile strength with increase the welding speed from 0.5 to 1 mm/sec but when increasing the welding speed to 2 and 3 mm/s the tensile properties of the joints seriously deteriorate and reach to minimum value 38.25 mpa for welding speed 3 mm/s with 800 rpm, joint efficiency 13.18.

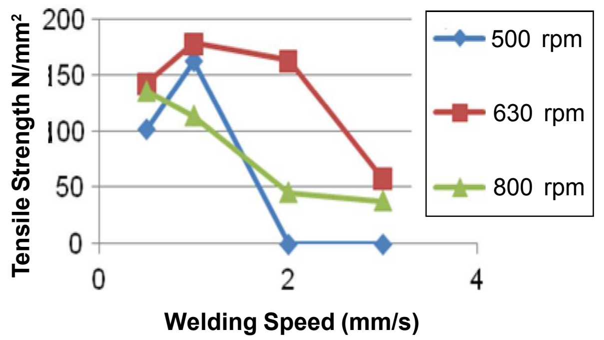
Its seen that decreasing in tensile strength due to inadequate flow of material caused by insufficient heat input.

The faster welding speed leaves less heat to the work piece and thus is generally called "cold weld" (Weis, 2008).

It can be explained that the weld material is unable to accommodate the extensive deformation during welding. This may result in long, tunnel defects running along the weld which may be surface or subsurface. Low temperatures may also limit the forging action of the tool and so reduce the continuity of the bond between the materials from each side of the weld (Kumbhar and Bhanumurthy, 2008).

Figure 16 show the relation between the rotational speed for the stir tool with tensile strength of the welded joint. From the result

Figure 16: Relation Between Welding Speed with Tensile Strength of Welded Joints



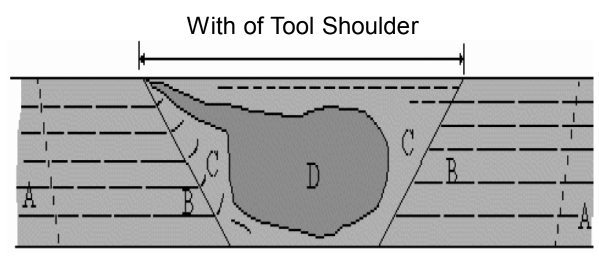
above the tensile strength increase when the rotational speed increase from 500 to 630 rpm and reach maximum value 179 mpa with joint efficiency 61.7%, but increase the welding speed from 630 to 800 rpm decrease the tensile strength of the welding joint and that attribute to increase the heat input to the welding area due to higher tool rotation rates generate higher temperature and softening takes place in the nugget zone because of the dissolution or growth of strengthening precipitates during the welding thermal cycle, thus resulting in the degradation of the mechanical properties of the joints (Liu *et al.*, 2003b).

Microstructure Results

Friction Stir Welding (FSW) process generates large local deformations and heat cycles, which consequently modify the microstructure and mechanical properties of several zones in the joint.

The examination of many friction stir welds in aluminum alloys has revealed that there are four major micro structural zones, as indicated in Figure 17. The microstructure of the weld is complex and highly dependent on the position within the welded zone. The fine

Figure 17: Friction Stir Welding Macrostructure Zones



Note: A – Unaffected Material, B – Heat-Affected Zone (HAZ), C – Thermo-Mechanically Affected Zone (TMAZ), D – Weld Nugget (WN).

Source: Indira et al. (2011)

grains are found in the nugget zone, in contrast to the TMAZ and HAZ zones where coarsened grains are observed (Soundararajan *et al.*, 2006).

The thermo-mechanically affected zone (TMAZ) is an area that has been plastically deformed by the friction stir welding tool, and the heat from the process will also have exerted some influence on the material (Soundararajan *et al.*, 2006).

The Heat Affected Zone (HAZ) lies further from the weld center. The material has experienced a thermal cycle, and modifications in mechanical properties and microstructure are noticed. However, no plastic deformation occurs in this zone.

The parent material has not been deformed and may have experienced a thermal cycle from the weld but has not been affected by the heat in terms of microstructure or mechanical properties (Soundararajan *et al.*, 2006).

Figures 18-28 shows the microstructure of nugget zone (WN) for all parameters used in this study, it shows the degree of refining grain size for every type of welded joints.

Figure 18: Base Metal 400X

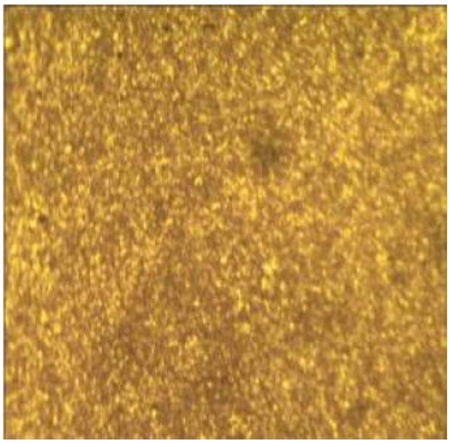


Figure 19: WN FSW1 400X

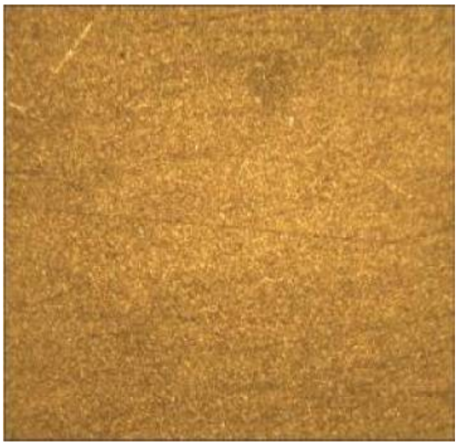


Figure 20: WN FSW2 400X

Figure 21: WN FSW5 400X

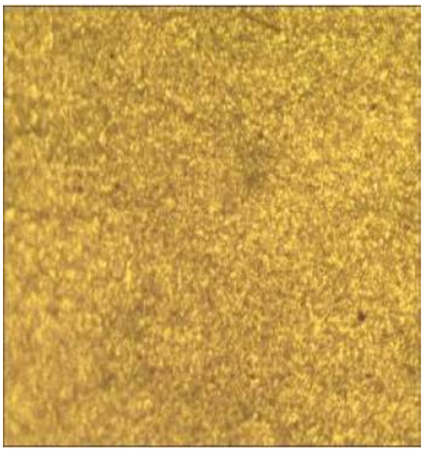


Figure 22: WN FSW6 400X

Figure 23: WN FSW7 400X

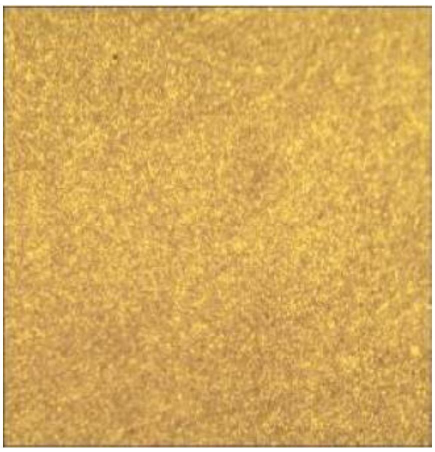


Figure 24: WN FSW8 400X

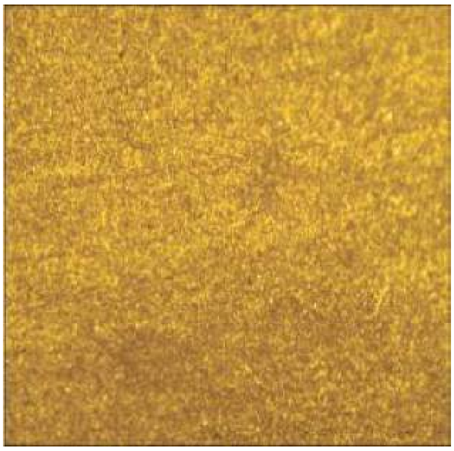


Figure 25: WN FSW9 400X

Figure 26: WN FSW10 400X

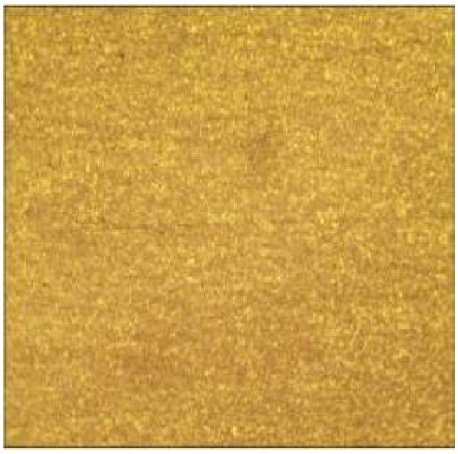


Figure 27: WN FSW11 400X

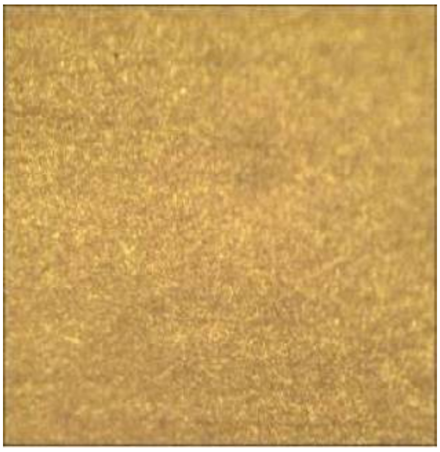
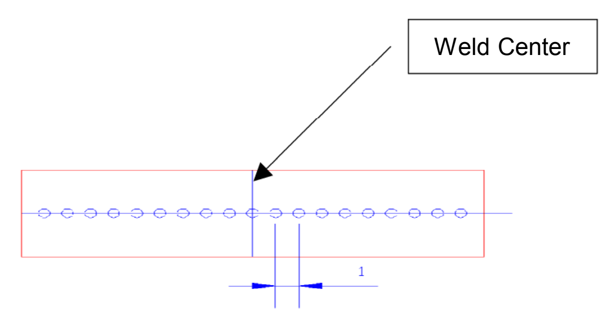


Figure 28: WN FSW12 400X

Micro Hardness Test Results

To examine local variations in the mechanical properties that occur in and around the friction stir weld zone, the hardness of the welding zone was tested. The Vickers hardness profiles across the Weld Nugget (WN), Thermo-Mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ) and partial base material was measured under the load 0.5 kg for 15 sec. along the centerlines of The spacemen and Vickers indentations with a spacing of 1 mm were used as shown in the Figure 29.

Figure 29: Positions of Micro Hardness Test Indentations (1 mm) Spacing



It can be seen from (Figures 30 to 39) that a hardness degradation region, i.e., softened region, has occurred in each joint, thus the tensile properties of the joint are lower than those of the base material. It can believed that FSW creates a softened region around the weld center in a number of precipitation-hardened aluminum alloys [6061-t6]. It was suggested that such a softening is caused by coarsening and dissolution of strengthening precipitates during the thermal cycle of the FSW (Mishra and Ma 2005).

Another observation of the micro hardness results is the hardness on one side of weld center differs from the other side (unsymmetrical weld). This difference can be explained as follows: In the leading side

Figure 30: Microhardness Profile in Welded Joint/FSW1

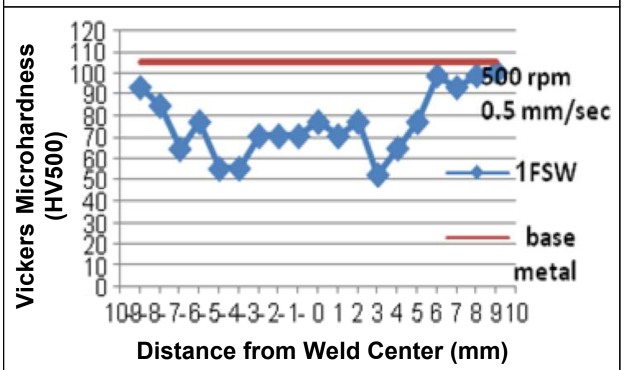


Figure 31: Microhardness Profile in Welded Joint/FSW2

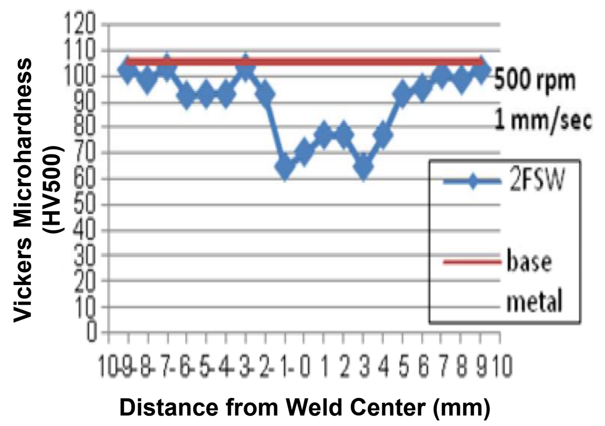


Figure 32: Microhardness Profile in Welded Joint/FSW5

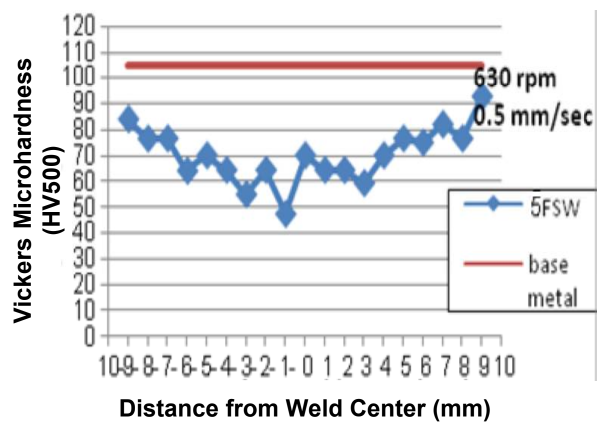


Figure 33: Microhardness Profile in Welded Joint/FSW6

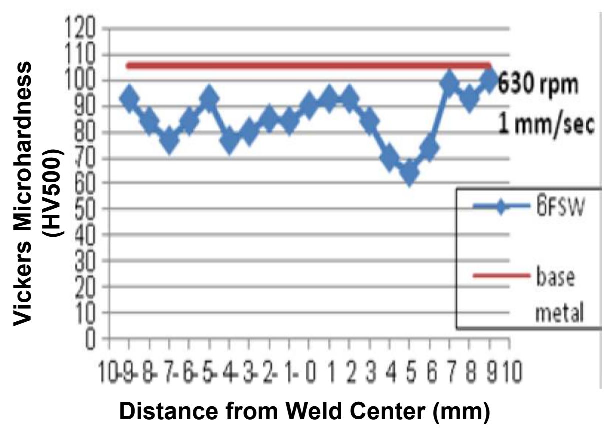


Figure 34: Microhardness Profile in Welded Joint/FSW7

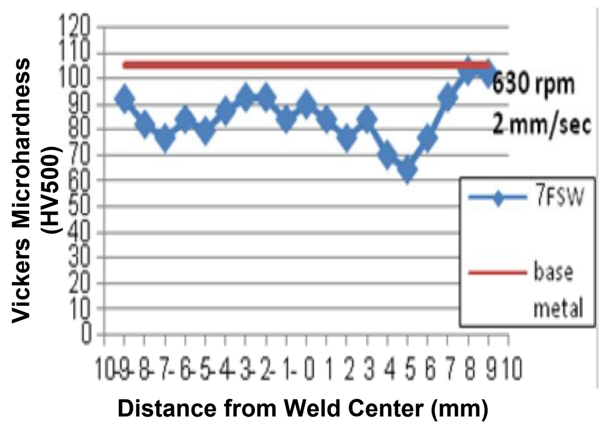


Figure 35: Microhardness Profile in Welded Joint/FSW8

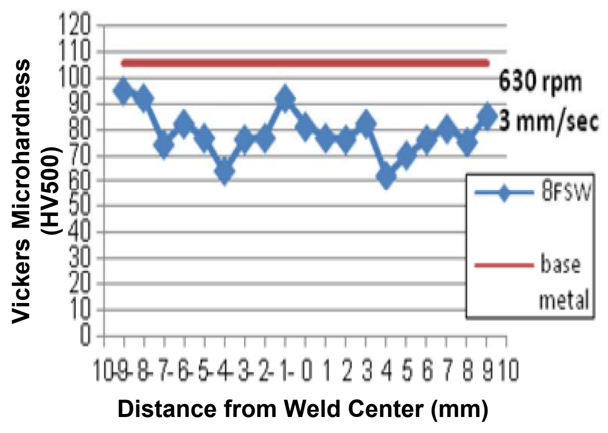


Figure 36: Microhardness Profile in Welded Joint/FSW9

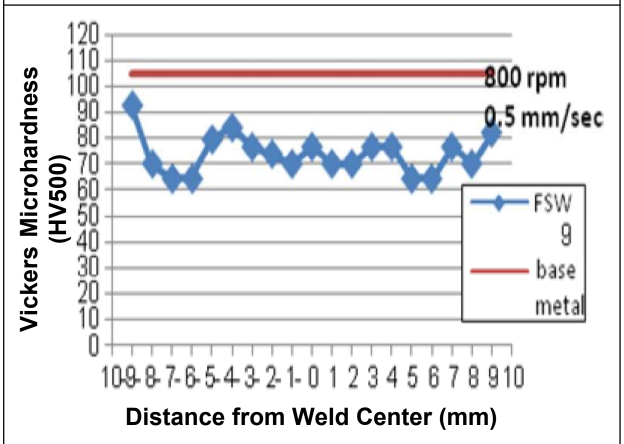


Figure 37: Microhardness Profile in Welded Joint/FSW10

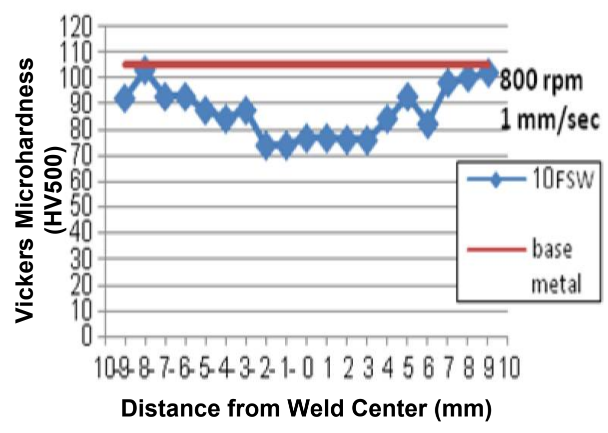


Figure 38: Microhardness Profile in Welded Joint/FSW11

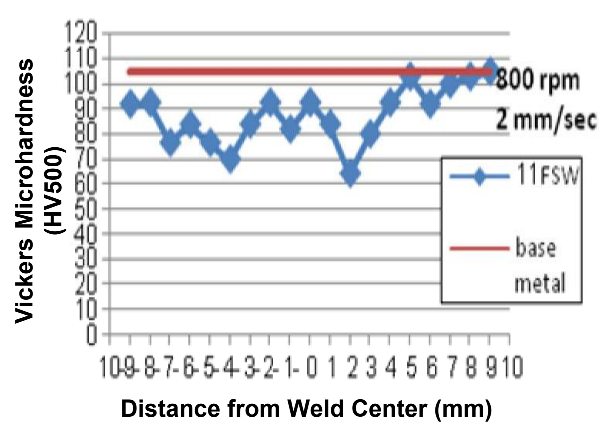
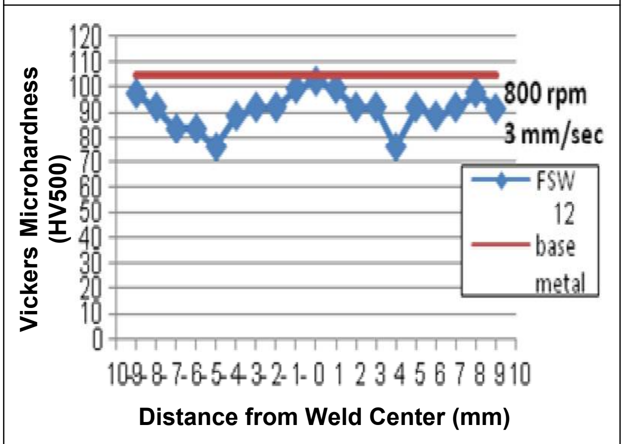


Figure 39: Microhardness Profile in Welded Joint/FSW12



(advancing side) for the rotating tool where the rotational velocity vector and the forward motion vector are in the same direction and due to this there is higher heating on one side of the weld center and hence lower hardens.

Microhardenss profiles below show, there are two low-hardness zones on both sides of the weld center and they correspond to the two HAZs in the joint (Liu *et al.*, 2003a).

Considerable softening was observed in the weld zone. However, the hardness in the weld nuggt and the thermal-mechanically affected zones is higher than that in the heat-affected zone. This difference is attributable to the dynamic recrystallization that took place within the weld zone as a result of the friction heat and mechanical work . In the heat-affected zone, the hardness increases with increasing distance from the weld center and approaches that of the base metal at 12-15 mm from the weld center (Wang *et al.*, 2000).

Another indication from microhardenss results that increase with increasing welding speed for the same rotational speed for all welding parameter and it can be attribute to the low heat input when increasing welding speed during welding operation and that resulted in less material softening and it's the same observation seen in the paper (Huijie *et al.*, 2003).

CONCLUSION

According to results of the present study of (FSW) process on selected Al-alloy, several conclusions can be written regarding alloy weldability, mechanical and microstructural.

- Aluminum alloy (6061-T6) are weldable using different (FSW) parameters giving different welding efficiencies.
- The maximum weld strength obtained in this study was (179 MPa) of (61.7%) weld efficiency is recorded and this result had been obtained with welding parameters (rotational speed 630 rpm,1 mm/sec welding speed and 0.2 mm plunging depth).
- FSW defects as indicated on non destructive tests are related to the welding parameters, defect free weld of FSW obtained by using optimum welding parameter.
- Fine grain size microstructure obtained on weld nugget of all FSW joints.
- Microhardness drop was observed in the weld region of FSW joints and an increase in values of microhardeness when increasing welding speed.

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