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Research Paper

ANALYSIS AND DESIGN OF FRICTION STIR WELDING

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Friction Stir Welding (FSW) is a materials joining process with great potential as joint quality is exceptionally high and the process is very repeatable. These geometries are used extensively in aerospace vehicles, in nautical vessels, and in pressure vessels. In this work, friction stir welding is applied to the joining of two pipes, thin-walled, thickness variable hollow hemispheres. The aim of this work 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 drilling machine has been conducted to attempt this welding and group of welding parameters. The tool rotational speeds 485, 710, 910, 1120 and 1400 rpm with a traverse speed 4mm/min were applied. The Mechanical properties of welded joints were investigated using different mechanical tests including non destructive test (visual inspection) and destructive test (tensile test, hardness and microstructure). Based on the stir welding experiments conducted in this study the results show that aluminum pipe (6061) can be welded by (FSW) process with a maximum welding efficiency (78.7%) in terms of ultimate tensile strength, using 1400 (RPM) rotational speed, 4 (mm/min) traveling speed.

Keywords: FSW, Al alloys, Mechanical properties, Microstructure

INTRODUCTION

Friction stir processing is an emerging surface–engineering technology based on the principles of Friction Stir Welding (FSW). Friction stir welding is a relatively new joining process, invented at The Welding Institute (Cambridge, UK) in 1991 and developed initially for aluminum alloys. Since then FSW has rapidly evolved and has opened up a variety of research channels. It is a solid-state joining technique that is energy efficient, environment friendly, and versatile.

Friction Welding (FW), is a joining process which has been in development for more than 100 years. This form of joining is most suited to material which is in rod or pipe form. It

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involves rotating or oscillating one rod whilst keeping the other stationary. The two are brought together and friction results. This in turn causes heat. Once sufficient heat has been generated the two rods are pushed together with a force which forges the two rod sections together. The excess extruded material from the circumference of the join can then be removed leaving a welded section (Dalder *et al.*, 2008).

In FSW the heat is generated by a non-consumable tool which is rotated at high speed, plunged into and traversed through the material creating a join at the rear of the tool. The forging force in this case is the downwards force exerted by the spindle. The friction stir welding process is a simple one by its nature. It uses simple technology to produce state-of-the-art joins in previously difficult to weld or un-weldable materials (Buffa *et al.*, 2007). A simple breakdown of the processing steps result in: Material positioning, tool plunge, tooling traverse and pull out/run off, these stages will be described in detail below.

The advantage of hydroforming of FSW tubes is the tailoring of the starting materials that can vary in thickness and/or composition to optimize weight or performance. This tailoring is typically carried out in stamping by welding sheets of different thickness together. The blank is then stretch formed and drawn, resulting in a part with optimized weight (Davies *et al.*, 2005; Ambrogio *et al.*, 2006; Grant *et al.*, 2006; and Buffa *et al.*, 2007). Recently, more, attempts have been made to weld dissimilar aluminum alloys, which ultimately could provide flexibility in design as well as optimize strength, weight, and corrosion resistance (Kou and Le, 1984; Lammlein *et al.*, 2010; Longhurst *et al.*, 2010a and 2010b; and Schneider, 2011). To date, no work has been reported on the welding of tailor welded tubes for hydroforming.

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 (Zeng *et al.*, 2006).

In this study will focus on the mechanical properties and microstructure of the welded joints of 6061 tubes after friction stir welding.

EXPERIMENTAL SETUP AND PROCEDURES

Materials

The material used in this study (6061 Al alloy), was received from Misr Aluminum Company. Tables 1 and 2 show the chemical composition, mechanical and physical properties of 6061 Al alloy.

Tool Design

The tool must be designed to generate sufficient heat, through means of rotational

Table 1: Chemical Composition (wt %) of 6061 Al

Weight %	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other Each	Other Total
6061	Bal	0.40-0.80	0.70 max	0.15-0.40	0.15 max	0.80-1.20	0.04-0.35	0.25 max	0.15 max	0.05	0.15 max

Table 2: Mechanical Properties of 6061 Al/Composite

Description	σ_{u1} Mpa	E1%	VHD
6061	248.82	8%	86

surface contact, to create a plasticised region beneath the tool. It was realized early on in the development of FSW that the tool's design is critical in producing sound welds (Xiao *et al.*, 2003). A basic and conventional design for a FSW tool is shown in Figure 1. This cylindrical probe design will be compared to other more complex and still emerging tool variants. FSW tools follow the same basic trends in terms of their shapes and geometries. They are generally comprised of three generic features: 1) A shoulder section; 2) A probe (also known as a pin); and 3) Any external features on the probe. The shoulder is designed as a relatively large, when compared to the probe, profiled surface. Although the probe makes the initial contact with the pre-welded material the shoulder has a larger contact area and produces more friction.

Figure 1: Photo-of Stir Probe Design

The diameter of the shoulder will determine the amount of contact area applied to the weld material's surface. A shoulder diameter which is too small could result in insufficient heat being applied to the process through an inadequate contact area between tool and material to be joined and therefore a failed weld or broken tooling. To generate sufficient heat during the process the shoulder diameter should be a minimum of 50% larger than the root diameter of the probe with contact areas up to three times larger deemed to be satisfactory. The diameter of the tooling determines the width of the plasticized region beneath the shoulder and the width of the Thermo-Mechanically Affected Zone (TMAZ). The distinct semi-circular trail indentation left in the wake of the tool is evidence of the deformation caused by the shoulder rotation and its width is related to the shoulder diameter (Neugebauer and Stoll, 2004).

Tool Material

The tool must be made from a material which can withstand the process and offer enough frictional heat generation. When selecting a material from which to manufacture the FSW tool the material to be welded must be considered. The tool material must be sufficiently stronger and more wear resistant than the material to be welded and must also have a higher melting temperature. A tool made from a material which is too soft will wear down to an unusable state very quickly due to the constant abrasive contact involved in the process. Tools currently used for industrial applications are capable of completing over 1000 m of FSW without the need to change tool (Thomas *et al.*, 2001). Aluminum can be joined using a tool made from silver steel, however if the weld material was to be steel, the tool would have to be more temperature resistant, for example tungsten with a ceramic coating. This means the selection of an FSW tool material must be based on the weld material properties. Another type of tool material under investigation is ceramic tools. A ceramic tool is more resistant to abrasion and so will not wear as much. This tool would also be able to generate the temperatures required to join steels. Ceramic although tough is a more brittle substance than metal and so the traversing of the tool would be its biggest challen.

Friction Stir Welding Process

Two tubes to be welded were butted up against each other and clamped down using the fixture. Rotational velocity and translational velocity of the tool are set in the adapted drilling machine Figure 2. The tool is then rotated and then slowly plunged into a work piece along the interface of the sheets. The tool creates frictional heat in the work piece until the material becomes plasticized. Heat generated by the mechanical mixing process and the adiabatic heat within the material cause the stirred materials to soften without reaching their melting point. This is a major advantage of friction stir welding. Once the material becomes plasticized the tool traverses along a weld line to bond the two materials together Plasticized material is deformed around the tool and is forged into place by the substantial downward axial force of the tool shoulder. Material then consolidates into the weld joint at the trailing edge of the tool leaving a solid phase bond between the two pieces (Lienert, 2003; and Mishra, 2005).

Figure 2: Turn Table and Clamping Device for FSW of Circumferential Weld

RESULTS AND DISCUSSION

Visual Inspection During Welding Process

The 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 3. 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 4. External surface behavior (rough or smooth) and that depends on welding

Figure 3: Slight Weld Flash on Trailing Edge that has Exhibited More Good-Quality Welds at 1400 rpm Speed

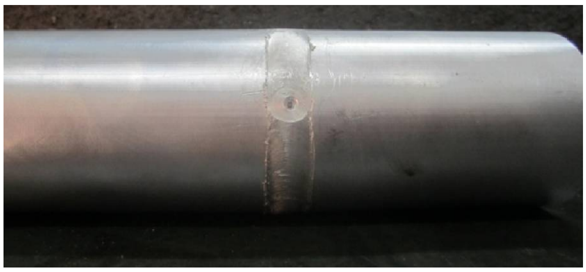


Figure 4: Excessive Weld Flash on Trailing Edge at 485 rpm Speed

parameters from rotational speed of tool and welding speed.

Tensile tests were conducted for each welding joint that produced welding. 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. Figure 5 show the tensile tests results and welding efficiency for each welding.

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 5 show the tensile test results for five rotational speed (485, 710, 910, 1120 and 1400 rpm) with travel speed (4 mm/min) and from above results we see increasing in tensile strength with increase the rotational. 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 (Gerçekcioglu *et al.*, 2008; Weis Olea, 2008; and Qasim and Bashar, 2012). Figures 5 and 6 show the relation between the rotational speed for the stir tool with tensile strength of the welded joint. The result above the tensile strength increase when the rotational speed increases from 1400 with joint efficiency 78.7%.

Figure 5: Relation Between Ultimate Tensile Strength and Speed (at feed 4 mm/min)

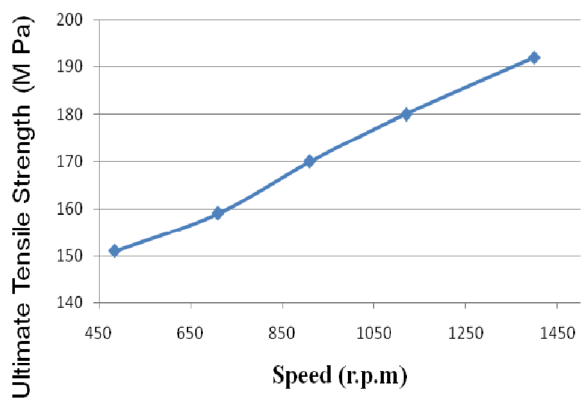
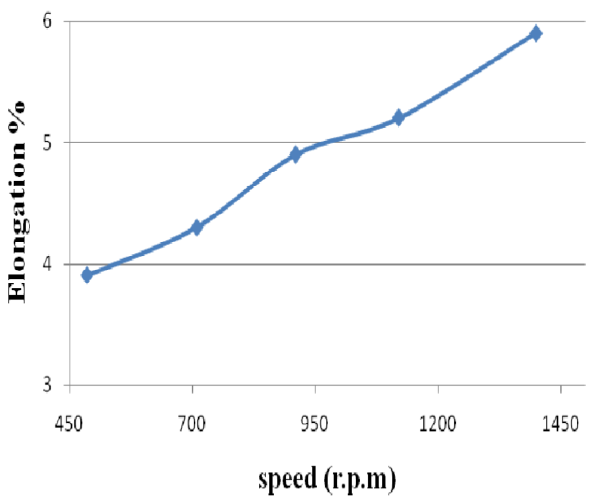
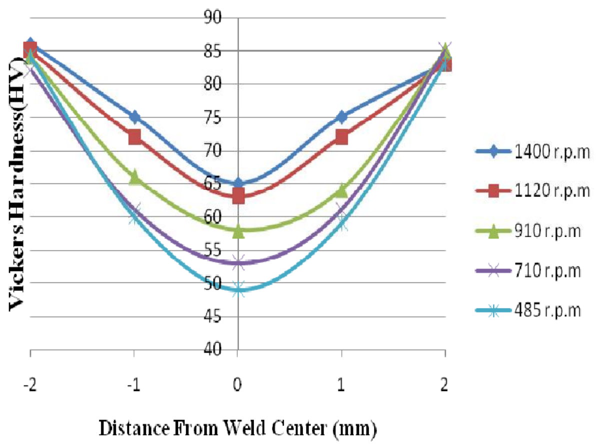


Figure 6: Relation Between Elongation and Speed (at Feed 4 mm/min)



The hardness tests were conducted on the static tests specimens; show Figure 7 at intervals of 2 mm along the mid-plane of the plates. The variations in the measured hardness values are respectively plotted in the joint Al 6061 have uniform hardness distribution on HAZ. The hardness of the HAZ, in case of 485, 710, 910, 1120 and 1400 rpm rotation speeds, is uniformly distributed and shows less variation, which ranges from 50 to 55 HV. In contrast, the hardness of the HAZ of 10 mm/min welding speed shows a very scattered value as.

Figure 7: Relation Between Hardness Profile Measurements and Speed (at Feed 4 mm/min)



Optical Microscope (OM)

Optical microscopes observations have been done on the FS welded 6061on the base and near the weld zone Figures 8a and 8b. Optical photographs are taken in 20X scales from optic microscope with video capture. General pore structures on the surface can be seen clearly. Structure of FS welded aluminum base and joint materials are shown in Figures 8 and 9 structures are become homogenous and pore. Also grain boundaries appeared notably in Figure 9. Grain necks are constituted notably

Figure 8a: Weld Cross-Section Macro of AL6061 (at 1400 rpm) and 4 mm/min

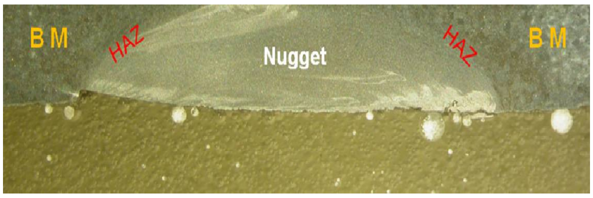
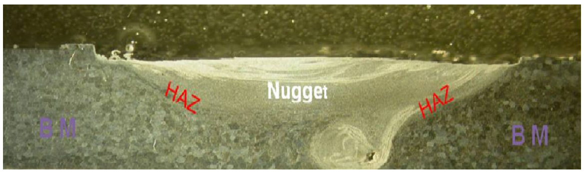


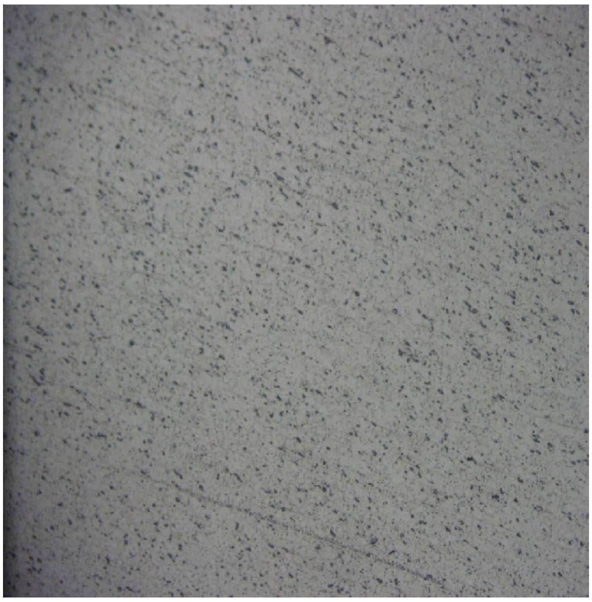
Figure 8b: Weld Cross-Section Macro of AL6061 Joints Welded at (485 rpm) and 4 mm/min



and homogeneous structure obtained, smooth and less porosity surface can be seen in Figure 9 Shrinkage of the pores initiated with 20X in Figure 5.

Figure 9a: Image at 200 um Magnification of 6061 Showing the Base Metal, HAZ (at 1400 rpm, Feed 4 mm/min)

Figure 9b: Image at 200 um Magnification of 6061 Showing Weld Nugget Zone (at 1400 rpm, Feed 4 mm/min)



Figures 9 and 10 show the tip of the crack, which is progressing from left to right. It can be seen that the crack is preceded by a large number of voids that formed all the way along the remains of the weld line down to the root of the weld.

Figure 10a: Image at 200 um Magnification of 6061 Showing the Base Metal, HAZ (at 485 rpm, Feed 4 mm/min)

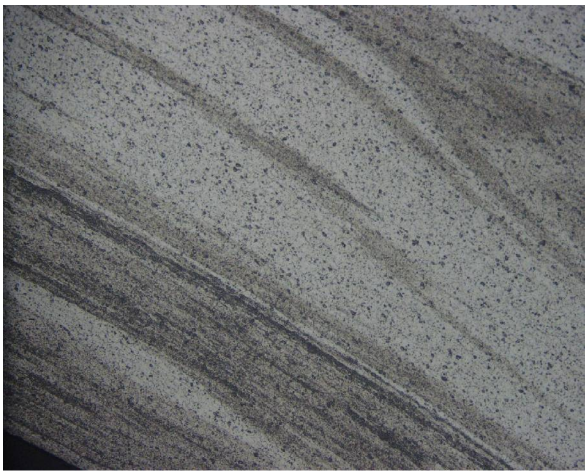
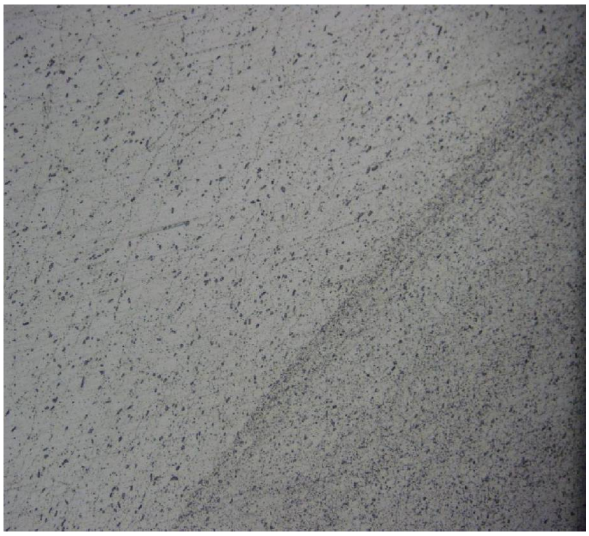


Figure 10b: Image at 200 um Magnification of 6061 Showing Weld Nugget Zone (at 485 rpm, Feed 4 mm/min)



CONCLUSION

In this study, the effective of rotational speed of stir on the outer surface of friction stir welding has been investigated. To investigate the deformation on the welding surface, it was studied at different rotational speed-485, 710, 910, 1120 and 1400 rpm-counter clockwise rotation speed in the FSW. The results showed that plastic deformation of tubes is increased if stirrer's speed is increased. Therefore, welding surface quality is obtained well. Both speeds of stirrer and tubes must be chosen available. Otherwise, some distorsion on the tubes is taken place at extreme stirrer's speeds. For this problem solution, some available apparatus can be adapted on the FSW equipment. Fine grain size microstructure obtained on weld nugget of all FSW joints. Hardness drop was observed in the weld region of FSW joints and an increase in values of hardness when increasing welding speed.

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