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Friction Stir Welding of Small Diameter Aluminum Tubes

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***Abstract*—Friction stir welding (FSW) is a semisolid welding technique. This technology has the advantages of being an energy efficient process and welds environmentally friendly and non-weldable alloys. In this work, an FSW tool has been designed and manufactured as well as a fixation for welding the circular tubes of 2024 Al alloy. The manufactured equipment for FSW is compatible with vertical milling machines. Heat is generated between the mating surfaces of the tool-pins and the two tubes that are butted against each other and secured to the support bar. The resultant heat makes the material soften very fast, before reaching a melting state, and permits the pin to move along the welding path. The effect of different working parameters, i.e., rotational speed, and transverse speed was investigated. The results showed that the proposed FSW technique is able of joining, with significant success, Al tubes with small diameters. Improvements in the mechanical properties and microstructure of the weld section can be attributed to the nature of the applied process. It has low heat input and no melting at the welding stage. This is indicated by a microhardness measurement of the entire weld cross-section. It is considered that the increase in microhardness with the increase in rotation speed of the pin may be related to the uniformity of strain distribution in the nugget region as well as the heat-affected zone (HAZ). More details on microhardness and weld microstructure will be presented and discussed.**

Keywords — FSW, 2024 Al alloy; Al Tubes, Microhardness,

I. INTRODUCTION

Friction Stir Welding (FSW) was invented and patented, in 1992, by The Welding Institute (TWI), a British research and technology Institution [1]. Some of the applications of technique include aircraft and aerospace vehicle's structure, modern marine industries and decks for car ferries, trucks, railroads, and assembling large tank's structure [1,2]. The FSW process involves plastic deformation and material welding at temperatures well below the melting temperature. The combination of both frictional heat and plastic deformation is the main cause of welding. This technique has been very successful in welding non-weldable metal alloys, both in the case of similar and dissimilar alloys. [3]. This technology achieves solid-phase joining by locally introducing frictional heat and plastic deformation by rotating the welding tool with the resulting changes in the local microstructure in the Al alloy [3-8]. The local microstructure of the material determines the mechanical properties of the joint.

Several works characterizing the microstructural changes resulting from FSW has been completed [3-9]. It is well established that aluminum and its alloys have many chemical and physical properties that affect their weld strength, although they can be welded in more ways than other metals [2,4-6]. The specific properties that affect the welding of aluminum alloys are the properties of its oxide; hydrogen solubility in molten aluminum; its thermal, electrical, and non-magnetic properties. It does not change color when heated, and its alloys have a wide range of mechanical properties and melting points [10-13]. Concerning age-hardenable aluminum alloys, microstructural studies of FSW in different Al alloys are represented [3-8,14]. The results of these studies indicate that the weld nugget or Dynamically Recrystallized Zone (DXZ) undergoes a dynamic recrystallization process to produce a equiaxed fine-grained structure with a tendency to high-angle grain boundaries [14].

According to the available scientific literature, few studied the capability of stir welding of Al tubes with small diameters. In recent decades pipes of all types and sizes are used in many applications such as gas and transporting lines of industrial fluids. Welding pipes have gained acceptance in construction and often takes place the beams, channels, angles, and other standard shapes. Welding is the easiest and simplest technique to join pipes and tubes and the limitations of the FSW technique are reduced through extensive research works. However, the principal limitations, at present are: (i) workpieces must rigidly clamp, (ii) backing bar is required, and (iii) existing of keyhole at the end of each weld [4,6].

The present work aims at introducing a proposed welding process for welding Al alloy tubes with a small diameter. A vertical milling machine has been adapted to weld samples of Al alloy tubes. The mechanical properties of the weld zones will be measured to ensure the soundness of the welds. Optical microscopy (OM) images have been captured to examine the microstructure evolution due to FSW process.

II. EXPERIMENTAL WORK

A. FSW Tool and Set-up

A FSW tool was designed and fabricated from carbon steel and then the tool was fitted on a specially designed tool holder shown in Fig. 1. Assembled the tool and its holder, then instead of the end mill. On the other hand, a new reduction unit was designed and produced to adapt the vertical milling machine to be used in welding the Al tube with small diameters. A photographic picture of FSW unit is shown in Fig. 2.

This equipment consists simply of a driving motor that held on special frame and connected with a gear reduction unit, with maximum reduction ratio (1:80). The reduction unit was made to transfer the rotating motion and power of the motor to a belt drive system. The workpiece rotates with different speed by using the indexing device of the mill with (1:40) reduction ratio and the belt drive system with two reduction ratios (1/8) and (1/5) rpm.

B. Material

The material of the tubes used in this work was 2024 Al alloy. The chemical composition of the alloy as has been received from the manufacturer was, 4.5%Cu, 1.5%Mg, 0.6%Mn, 0.35%Si, 0.3%Fe, 0.15%Zn, 0.1%Ti and the balance is Aluminum. The basic mechanical properties are shown in Table 1. The 2024 Al tubes were fabricated using normal tubes extrusion process and were supplied from Taigang Stainless Steel Co., Ltd.

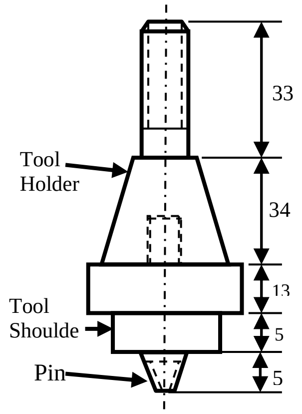

Fig. 1 FSW tool and its holder (dimensions in mm).

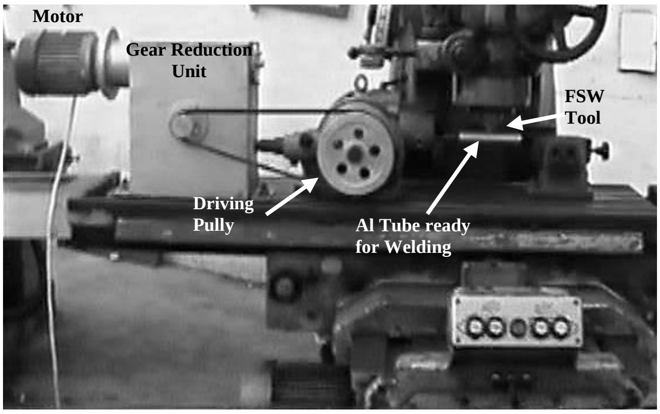

Fig. 2 A photograph of an end mill with the stir welding reduction unit set-up used for tube welding.

Table 1 The basic mechanical properties of the 2024 Al alloy used in this work.

Tensile strength, MPa	Yield strength, MPa	Elastic Modulus, GPa	Shear Modulus, GPa	Shear Strength, MPa	Possion's Ratio
240	130	73.1	28.0	124	0.33

C. FSW Process

Before welding begins, the tubes sample are rigidly fixed with the faces to be welded abutted each other. A backing rod is employed to assemble tubes and the other necessary parts. Fig. 3 shows a typical friction stir butt weld being undertaken with the material rigidly restrained and backing bar in position. The FSW process begins with making a hole at the starting point of contact with the rotating tool steel pin. When the tool penetrates the pipe sample, the friction caused by the tool and the shoulders causes friction heating and plasticizing the surrounding materials. The pin rotates stationary, and the tube moves forward in the welding direction with a specific traverse speed, shown in Table 2. As the tool proceeds, the friction heats the surrounding material and rapidly produces a plastic like zone around the tool pin. The material is extruded on the surface, but the shoulder of the die touches the outside of the tube, the deformed material is compressed between the shoulder, parent materials, and the backing bar. The pressure exerted by the shoulder presses the deformed material behind the pin where it hardens rapidly and forms a bond. A constant welding force of 9 KN is applied on all weld samples. The bond is not plastic, but it behaves in a way similar to the properties of plastic-like, making them very strong without damaging the base material. FSW of Al tubes has passed through two stages. The purpose of the first stage was to weld the curved ends by employing a conventional machine tool. Although a significant success has been achieved in terms of welding the curved ends of the tubes, a major problem had appeared at the end of welding path. The welding pin always leaves a hole at the end of each weld which is called a keyhole. A photograph of the keyhole is shown in Fig. 4. The keyhole appears at the end where the weld operation terminates. The second stage was an attempt to overcome this problem by moving the welded tubes horizontally away at the end of the welding closed path.

Welding details of the single-pass FSW pipes are shown in Table 2. The tool is then moved along the joint while welding the 2024 Al using rotational speeds of 900, 1120, 1200 rpm and traversal speeds of 54 and 92 mm/min. When the tool passes through the joint, the material is frictionally heated and plasticized by the leading edge of the tool, then transferred to the back of the pin, hardened, and finally formed a solid phase joint.

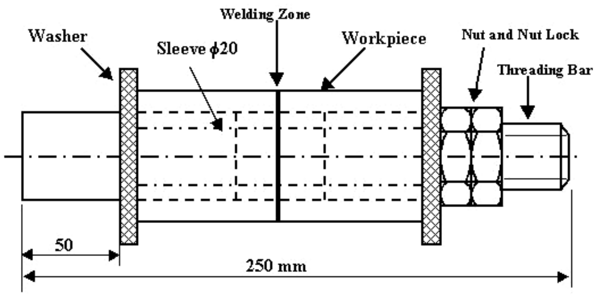

Fig. 3 Schematic illustration of an assemble two tubes with backing bar and the tubes rigidly restrained and in position ready for friction stir butt weld.

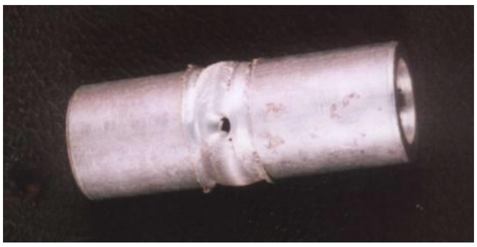

Fig. 4 A photograph of the keyhole remained after ending the FSW process.

Table 2 Welding details for FS welds.

Pin shape	Tilt angle	Downward force	Shoulder diameter	Rotational speed	Transverse speed
Thread	2.5°	9 (KN)	12 (mm)	900, 1120, 1200 rpm	54 and 92 mm/min.

D. Microstructure and Microhardness Measurement

The quality of the welded pipes was investigated by measuring microhardness and examining the microstructure. Microhardness measurements were made at the middle of the wall thickness and positions parallel to the centerline the welded tubes with a step of ~2 mm under applied load equals 1 N and 15 seconds time duration. Microhardness tests was undertaken according to ASTM E384 standard. These measurements were made over the midsection and extended from the base metal alloy, across the weld cross-section, and into the base metal alloy on the other side. The samples were cut and polished using standard preparation techniques and etched using Killer's reagent. Then, optical microscopy (OM) was employed to investigate the etched surfaces of the welded joint to find out the changes its internal structure.

III. RESULTS AND DISCUSSIONS

As mentioned previously, the existence of a keyhole at the end of the welding path is a major defect and must be overcome to obtain a good FSW joint. After several attempts, this problem was resolved by moving the FSW tool in a direction perpendicular to the tube axis. When the tool reaches the end of the welding path and to avoid the appearance of this keyhole, the weld joint moves horizontally in a direction that gradually withdraws from the welding tool. Fig. 5 shows two pictures of the FSW Al tubes as it was withdrawn from the welding tool.

The microhardness tests were employed as indication of the mechanical properties of the FS welds. As is known, weld cross sections are usually divided into four basic areas. These areas are far from the weld zone, heat-affected zone (HAZ), thermomechanical zone (TMAZ), and finally the weld nugget. The weld joint has different features for the microstructure of weld zones. The best strength recovery occurs in the weld nugget, which is the central part of the weld zone. Softening occurs in the HAZ region and the microhardness decreases significantly as it approaches the TMAZ region [4,5]. Figs. 6 show the results of microhardness measurements in which the microhardness plotted against the distance from the weld center. The microhardness was measured on section parallel to the tube center line. The microhardness of unaffected base material was approximately 128 HV; 1 N and was practically increased across the weld due to hardening process in weld region. It is obvious on comparing the data shown in these figures that the value of microhardness increased gradually to reach its maximum value at the center of the weld joint. As shown in Fig. 6.a, the highest the rotational speed the highest microhardness and the microhardness at the nugget is two orders of magnitude higher than that at the base material. These results also found in Fig. 6.b, in which same observations are typically clear but the microhardness values are higher with higher traverse speed compared with those in Fig. 6.a. One of the observations about the orientation of the rotary FSW tool and its advance during the FSW process is that the receding microhardness is slightly higher than the advancing microhardness.

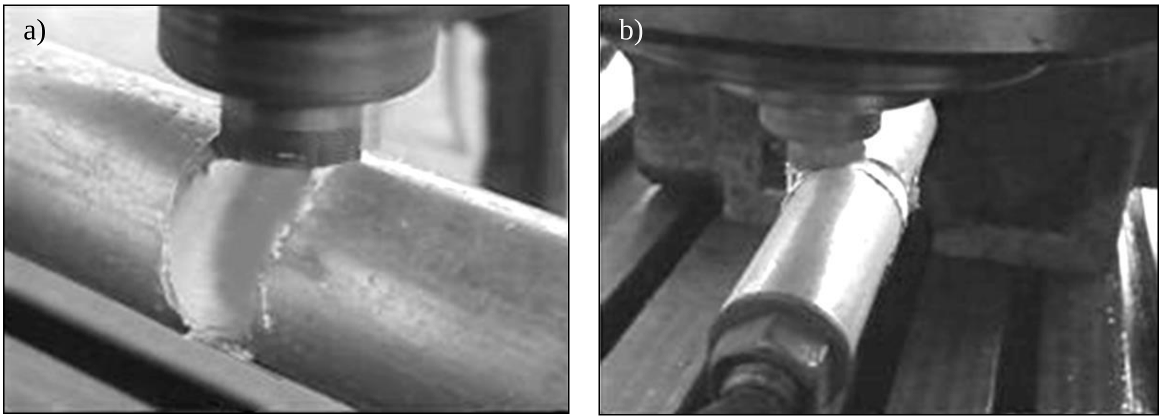

Fig. 5 FSW, butt joint of two Al tubes. a) the tool reached the end of weld path and b) the FSW joint moves horizontally for withdrawing it from the tool.

Fig. 7 show typical OM images of the four FSW zones. Fig.7.a shows the base metal: in which nearly large and equiaxial grains are obtained. As expected, the material in the nugget region of the FSW undergoes more deformation as it is dragged around the rotary tool more than that in the lower part of the submerged hole. Fig. 7.b shows the grains of HAZ, where large and elongated grains were developed. As seen, the grain refinement in this zone is clearly observed. Fig. 7.c shows the grain refinement of TMAZ in which small and elongated grains were observed. and final Fig. 7.d shows the microstructure of the weld nugget, where small and homogenously distributed grains are obtained. The welded nugget is characterized by a relatively homogenous microstructure with small, equiaxed grains and a weak grain shape fabric. Small grain structures are found in the nugget region generally considered to be beneficial for mechanical properties.

Some research work [2,4,11] found that the onset of FSW deformation process occurs at a temperature close to 200 °C. This temperature remains well below the recrystallization temperature of the 2024 Al alloy. Therefore, the deformation of the bottom of the submerged hole is presumed to be a precursor to the strong deformation that occurs in the mass of FSW. Although there is a clear extrusion behavior around the touring pin, this process is characteristic of solid flow promoted by adiabatic shear, creating a dynamic recrystallization regime to accommodate large deformation at high strain rates [10]. Many studies on the microstructural characteristics and mechanical properties of FSW joints have indicated that hardening occurs in the FS welded of heat-treatable Al alloys and strain hardened aluminum alloys [15-17]. In principle, any FSW joint can be composed of finite thin-layers in the direction of thickness, and any thin-layer is different from the other ones in mechanical properties because they experience different thermo-mechanical actions during FSW [15,16]. If the mechanical properties of some weak thin layers of the weld joint can be raised, the mechanical properties of the whole weld joint will be improved. However, the real difference in mechanical properties between thinner layers is still unknown. This paper reveals some useful information for improving the mechanical properties of the joints of this specific Al alloy.

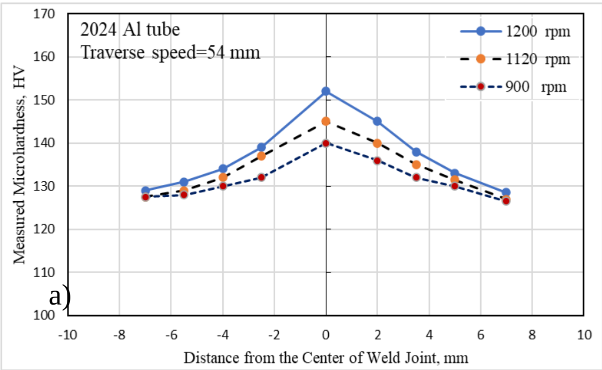

Fig. 6.a Microhardness of FSW Al tubes for different speeds and at 54 mm traverse speed.

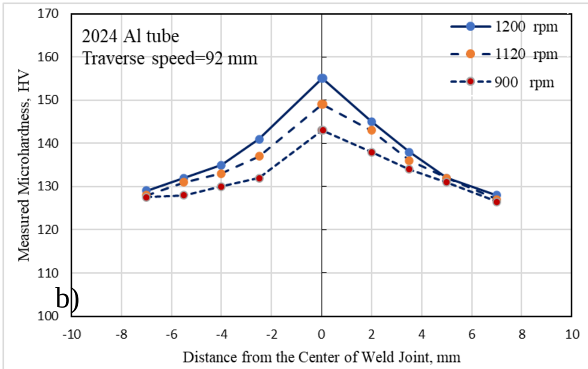

Fig. 6.b Microhardness of FSW Al tubes for different speeds and at 92 mm traverse speed.

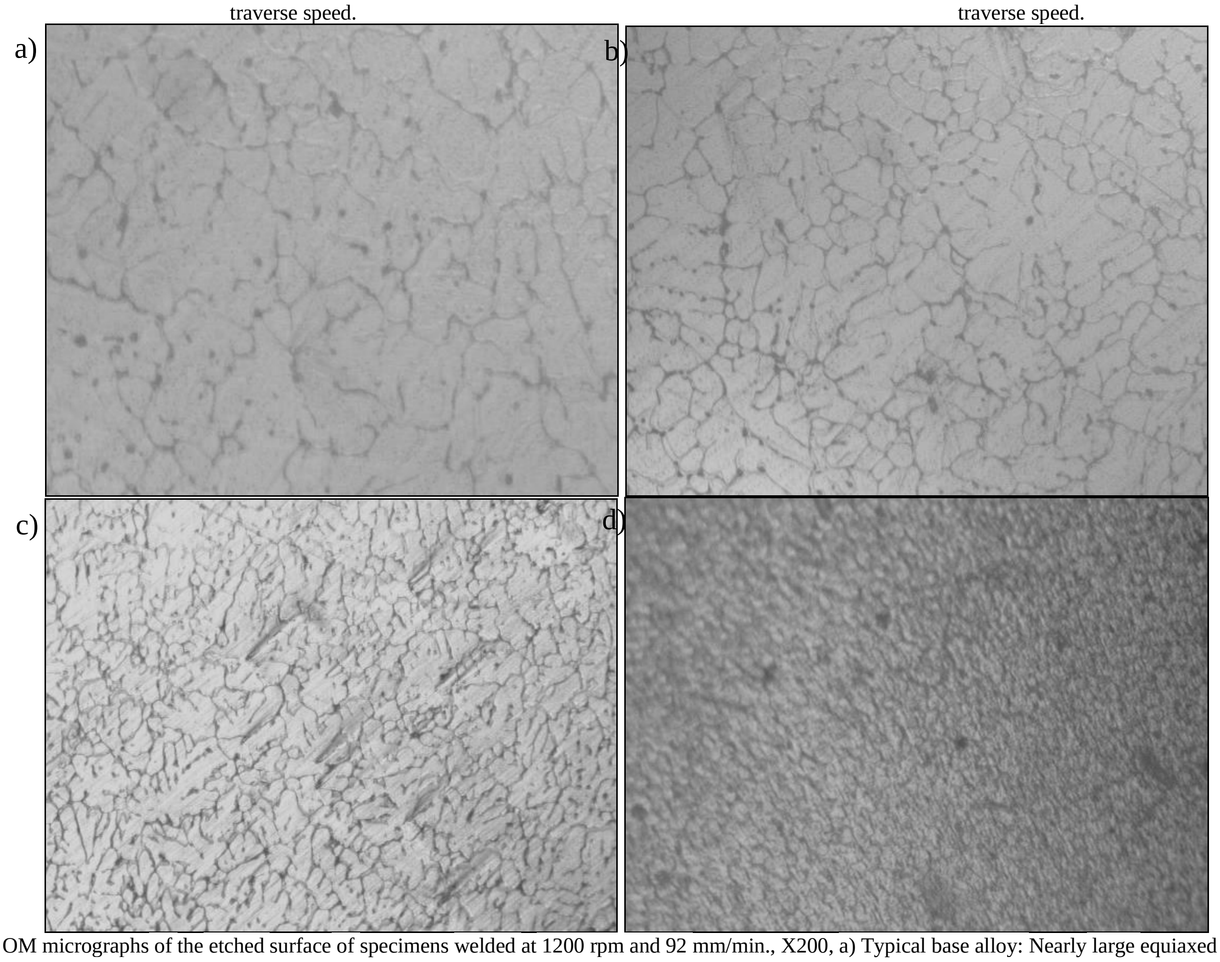

Fig. 7 OM micrographs of the etched surface of specimens welded at 1200 rpm and 92 mm/min., X200, a) Typical base alloy: Nearly large equiaxed grains are observed, b) The HAZ region: shows elongated grains, c) The TMAZ region: shows small and elongated grains, and Finally d) Nugget region: shows small and normally distributed grains.

IV. CONCLUSIONS

Based on the results achieved in this work and the success in welding 2024 Al tubes using the FSW process presented, the following conclusions can be drawn:

1. The present FSW technique provided a successful means for welding 2024 Al tubes. FSW causes increasing the microhardness in weld metal due to grain refinement. The homogeneity of the welded area shows that the FSW is very effective in Al tubes welding.
2. Using 1200 rpm -as rotational speed- and 92 mm/min -as traverse speed- of the tool made the microstructure more homogenous and the change in the microstructure between welded nugget and base metal is significant.
3. The microhardness in the nugget zone of friction stir welding shows the highest value compared to the other three zones.
4. The values of microhardness of welding area increased when the rotating speed increases and it is increased also when the traverse speed increases.

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