Investigation of Friction Stir Welding of AA2024-T4 Thin Sheets for Industrial Applications

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Abstract: The welding of aluminum alloys thin sheets is a complicated process no matter what the technology used. A 2024-T4 AL sheets of 1.2mm thickness were welded using stir welding method and then examined for their mechanical and microstructure characteristics. The process included the use of specifically designed fixture along with cylindrical tool. Thin sheets welding of aluminum alloy is a complicated process either in conventional or newly developed methods. In this approach the friction stirs welding (FSW) is used. Tensile test and microstructure test were conducted to analyze final product properties. The cylindrical rotating tool was used to create a joint which is specifically useful in the welding of aluminum alloys in particular. It was found that All tested samples were defects free. Mechanical properties show that ultimate tensile strength of samples is below the base metal. Two rotational speed were applied (900 and 1400) rpm with welding feed rate of (20, 40 and 80) mm/min respectively. The tool has a 1.2mm diameter pin of 1 mm height and 8mm shoulder diameter. A rotation speed of (900) rpm and feed rate of (40) mm/min gave the best quality product in which an increase of (72%) in ultimate tensile strength was observed.

1. Introduction

Some physical properties of aluminum (Al) and their alloys make it difficult to weld by traditional technologies. For example, high thermal expansion coefficient of aluminum and their alloys results in distortion during fusibility welding. And high conductivity heat transfer of aluminum complicates the use electrical and laser welding [1,2]. The Welding Institute (TWI) developed one of the most modern joining techniques in recent times named Friction Stir Welding (FSW). FSW uses the concept of plastic deformation which is used in process forming for metallurgical joining of mechanical parts with the advantage of controlling its mechanical properties. It’s preferable because it does not require any external supply of head during the process of forming [3].

The main metallurgical advantage of this new process is that it involves a solid state welding without reaching the melting point of the base material thus leading to less distortion, lower residual stresses and fewer weld defects in comparison to other welding techniques [4]. FSW provides large number of opportunities and creates new applications in welding fields. Similar and dissimilar metals joined together, and non-metallic materials have been joined successfully using this process. Low temperatures generated during FSW make it possible to weld very thin sections 1000 μm (1 mm) [5]. Moreover, this method is considered as a modern green industrialization technique since it is environmentally friendly and energy efficient [6]. The appeal of FSW is in elimination of solidification cracking and porosity [7]. FSW was at first developed and applied to join aluminum alloys. However, since its creation, the application area of the process has been expanded to weld different materials: titanium, copper, nickel, steel, magnesium, stainless steel and polymers [8].

The carry on technological and scientific interesting to decrease vehicle weight and emissions generated in a diffuse. Therefore, Al alloys was employed as a metal substitute for steel in different
applications that were previously dominated by steel [9]. However, one of the most advantage of FSW was the ability to weld all kinds of aluminum alloys, especially the 2xxx series alloys [10,11]. These alloys in particular are non-weldable using fusibility welding technique because of oxidation problems, solidification, shrinkage, crack sensitivity, solubility of hydrogen and porosity problems [12]. Other applications of this technique can be found in outer fuel tanks of rockets, cryogenic tanks, marine applications, aerospace industry and shipbuilding industries [13,14].

Many researchers have studied this method. S. Sattari et al. (2012) [2] designed a special fixture, for ultra-thin sheets to weld 0.8mm thick 5083 Al sheets by FSW with the aid of a simple cylindrical tool. Micro hardness test and tensile test were conducted. All tested samples were defect free. Mechanical properties of samples welded at speed rate from 18.58 to 34.84 rpm have better micro hardness and tensile strength. During welding, indicated temperatures measurement between 430°C to 510°C gave free of defects joints.

D. Andre (2016) [4] analyzed mechanical properties of friction stir welding joints of 8 mm thickness of (AA7050-T7451) Al alloy. Two different approaches were compared for their mechanical properties, single and double side of stir welded joining. The outcomes of the study show that the deformations of single side FSW were lower than those of double side FSW.

A. El-Morsy et al. (2018) [15] investigated the traverse and rotational speeds effects on 1.5 mm thickness 2024-T4 Al alloy sheets. Five traverse speeds changing from (11) to (45) mm/min and five rotational speeds changing from (560) to (1800) rpm have been utilized. Mechanical properties (tensile, bending and micro hardness) and microstructure of the sheets welded have been studied. The results expose that by changing the welding parameter, almost high performance and sound joints can be successfully created at the traverse speed of 35 mm/min and the rotational speeds of (900 and 700) rpm.

A. Kubit et al. (2018) [7] welded 1mm thickness 2024-T3 Al sheet metal by initial pre-heating of the sheet metal and a special fixture bed. The tests show that the pre-heating of thin sheets leads to a reduction in the deformation size of the joined sheets. It was found that the smallest deformation of the joined sheets was observed in the case of joining sheets heated up to a temperature of 200 °C. Pre-heating of the joined sheets decreased the size of the deformations by 57.62 %. It’s aimed in this research to design and fabricate a proper fixture and tool for welding a (1.2) mm thick 2024-T4 AL alloy sheet free of defects with good mechanical properties joints.

2. Friction Stir Welding (FSW)

The main idea of FSW relies on introducing a rotating cylindrical tool into the contact with the joined elements and moving it along the seam of the joint. As a result, the friction, which generates heat, plasticizes the material to create a mechanical-plastic joint. In these conditions, the materials penetrate each other in the solid state by rotating around the axis of the tool, ensuring stirring in the area of the joint without reaching to the melting point. After making the joint, the tool is removed from the work zone [7].

As a result of the heat generated during the use of the tool, four areas (zones) created. These zones differs in metallurgical properties (microstructure observation) named: Base Metal (BM) or Parent Metal (PM), Nugget Zone (NZ) or Stir Zone (SZ), (TMAZ) and (HAZ) are Thermo-Mechanically Affected Zone and Heat Affected Zone; depending on the distance from welding area (temperature gradient) [16].

![Figure 1. zones of FSW process](image-url)
These zones are shown in Figure (1) and illustrated as follows. BM or PM is a zone where the material was not deformed, also may be undergo to thermal cycles but there is no mechanical or microstructural change [2]. The size and direction of the granules in other zones (SZ or NZ, TMAZ and HAZ) are varies with BM. In SZ or NZ zone, the pin passes through it which recrystallization is completely occurred and increases strength and hardness of welded metal. In this zone fine grain size can be seen because of severe deformation at high temperature. On other side, the TMAZ zone is the area next to the SZ on either side up to the diameter of the shoulder. In this zone, the temperature is not in the level to make recrystallization, however grains are plastically deformed [2, 5]. The following zone on either sides, the HAZ, has minimum temperature but the thermal cycles modified its microstructure and/or the mechanical properties without any plastic deformation zone [17]. Substantially the heat concentrated with highest value at the center of the joint (SZ) and reduced gradually far from that place. Change in the size of grains and plastic deformation are results of thermal cycle in the SZ, HAZ and TMAZ [16]. In order to ensure that the joining conditions are stable, many critical welding parameters must be accurately identified and controlled such as follows:

A. Spindle rotational speed and weld tool travel speed. Welding speed or travel speed (advance speed) means the speed at which the tool moving over the work piece, on other hand spindle rotational speed mean the speed at which the tool moving around itself. These two significant parameters influence the heat input to the weld and must be chosen with care to ensure the efficient and successful of welding cycle. Moreover, the relation with heat input was complex, increasing or decreasing the rotation and traverse the speed will result in a good weld quality and also a hotter weld; the large temperature gradients, like in traditional welding, generate thermal stresses [18]. A travel speed is very fast, however it may not ensure that the heat generated is enough. As a result, insufficient mixing of the work piece metal and the formation voids in the SZ are happen. When the temperature is too low, the joint is a result of adhesion, which can be characterized as having low strength. When the pressing force is too large, the weld is concave and its transverse section is smaller. In FSW, Travel speeds can vary from 20mm/min to 6m/min in some industrial applications. When high-melting point alloys are processed, they are initially heated in order to decrease their yield stress an increase in the rotational speed of the tool leads to an increase in the process temperature as well. On the other hand, an increase in the feed rate lowers it [7, 19].

B. Tool Design. The welding tool consists of two parts, a pin and the shoulder. Different pin geometries have been suggested such as threaded cylinder with flattened sides, threaded cylinder, etc. The shoulder generates a pressure to the material in order to make the material is soften around the pin. It also creates heat over friction and plastic deformation in a thin layer beneath the shoulder surface. By using perfect tool, it can enhance both the maximum welding speed and quality of the weld [14]. Therefore, it is desirable that material of the tool is sufficiently has hard wearing strength, and tough at the welding temperature with low thermal conductivity and good corrosion resistance. For example tool steel (AISI H13) is good to weld Al alloys at thickness range of (0.5 – 50) mm, but more developed tool materials are necessary for more demanding applications like strongly abrasive metal composites or higher melting point [18]. The size and shape of the tool (tool geometry) depend on the thickness and material of the work piece [19]. Because of the different geometrical characteristics of the tools, the material motion around the pin could be very complex and different from one tool to another [6].

C. Sink depth. Sink depth is the depth of the lowest point of the tool body with a pin and a shoulder below the surface of the welded plate (end of the weld tool). The shoulder increases the pressure on plate welding surface below the tool and ensures enough forging of the material at the rear of the tool. The pin and shoulder of the weld tool provide the necessary work surfaces for stirring and containing the joint material during FSW. The pin extends from the end of the weld tool and is the part of the tool that is forced into and along the joint interface between the two sheets to be welded up to a proper tool sinking depth, and then it is moved along the seam being joined [20]. The shoulder generates the largest component of heat in the process. The pin causes localized heating and plastic deformation of the material around the pin [21].

D. Welding forces. During the welding number of forces have effect on the tool. These forces are: the downward force to maintain the location of the tool, the traverse force which acts parallel to the
tool movement, and the torque needed to rotate the tool. In order to prevent breakage and reduce the severe wear and tear of the tool and machinery associated with it, the welding cycle need to be adjusted by locate the best welding parameters combination [18].

E. Materials or metal alloys and thicknesses. Because it determines the effectiveness of joints, Materials or metal alloys and thicknesses plays a key role in the FSW. The material flow relies on the tool geometry material to be welded and process parameters. It is important to realize the material flow properties in order to design a tool ideally and process parameter collections. Many models of FSW processes had been introduced for the calculation of materials flow and heat transfer [13].

F. Temperature distribution. The heat generated by friction in (FSW) process, between the work piece and the tool. It is difficult to measure the temperature exactly during the stirred area. This is because of the strong plastic deformation that is created by the translation and rotation of the tool. It is important to get information about the temperature distribution in the (FSW) process via numerical analysis [14].

The FSW process offers some advantages [7]:
- Elimination of the need to bevel sheet metals.
- Higher resistance to brittle cracking of the joint.
- High static and dynamic strength properties, higher than those achieved by conventional methods.
- The possibility of conducting the process on conventional milling machines.
- Simple tooling technology.
- No overheating of the heat-affected zones, which are consequently not weakened.
- Lack of heat cracking as a result of welding.

3. Experimental Part
3.1. Materials Used
A section of 200x100x1.2 mm of aluminum alloy AA2024-T4 perpendicularly to the direction of rolling was supplied to produce friction stir welded joints.

Aluminum alloy AA2024 attainable in multiple forms of products and tempers, which is a heat-treatment Al-Cu alloy. The change of properties is a function of temper T3 and T4 type tempers that were well-known as high toughness. In this paper, an AA2024 –T4, aluminum alloy, reasonable due to its tensile strength, high toughness and elongation. Universal testing machine 80-tons were used to check the tensile properties of the aluminum alloy AA2024-T4. The standard tensile test is used to inspect specimen according to (ASTM-E8) as shown in Figure (2). Table (1) shows the mechanical characteristic of the aluminum alloy AA2024-T4 material.

![Figure (2a). Standard specimens of tensile test scheme](image-url)
Figure (2b). Photo of specimens

| Parameters | Hardening exponent (n) | Strength Coefficient (K) (MPa) | Hardness (BHN) | Elongation (%) | Yield Strength (MPa) | Tensile Strength (MPa) |
|------------|------------------------|--------------------------------|----------------|----------------|----------------------|------------------------|
| Actual     | 0.166                  | 790                            | 120            | 18             | 328                  | 462                    |
| Standard   | 0.210                  | 720                            | 120            | 20             | 325                  | 470                    |

The found chemical composition of aluminum alloy AA2024-T4 was obtained through the examination in (Poly Speck) as listed and compared in Table (2).

| Elements %) | Al   | Cu   | Mg   | Mn   | Fe   | Si   | Zn   | Ni   | Ti   | V   |
|------------|------|------|------|------|------|------|------|------|------|-----|
| Actual     | 92.7 | 4.6  | 1.6  | 0.534| 0.352| 0.113| 0.049| 0.014| 0.022| 0.01|
| Standard   | 94.7 | 4.9  | 1.8  | 0.6  | Max. | Max. | Max. | Max. | Max. | Max.|
|            | 0.5  | 0.5  | 0.25 | 0.05 | 0.15 | 0.05 |      |      |      |      |

3.2. Friction Stir Welding (FSW) Technique
The FSW process was performed by a tool made of High-Speed Steel (HSS) which has 56 HRC. The tool also had a featureless shoulder of 8 mm diameter and smooth pin of 1.2 mm diameter and 1 mm height. Figure (3) illustrates the tool which is used in making all weld trails.

Figure 3. HSS tool of FSW (all dimensions in mm)
The vertical milling machine was used to achieve all the FSW processes, as shown in Figures (4). The welding samples are secured into a backing plate made from carbon steel, in order to obtain the butt joint configuration as shown in the Figure (4). The backing plate fastened it into the milling machine table and adjusted to have same level surface. The rotating tool direction was moved counter-clockwise during welding process. Then, the moving of tool was in same rolling direction of the alloy. The welding parameters values that are used in the FSW joints are shown in Table (3).

![Universal milling machine, fixture and plate to be welded.](image)

**Table 3.** FSW parameters for AA2024-T4 aluminum alloy

| Rotation speed (rpm) | Travel speed (mm/min) |
|----------------------|-----------------------|
| 900                  | 20,40,80              |
| 1400                 | 20,40,80              |

3.3. **Tensile Testing**

Tensile specimens were designed and manufactured for both parent metal and FSW plates and executed on CNC machine type TX32, as shown in Figures (5). The tensile test was performed as follows: the samples is taken based on the direction of the welding in order to find the tensile characteristic of the welding joints for welding processes. Both shape and dimensions of the transverse tensile are specimens according to (ASTM-E8) are shown in Figure (2). All tensile tests were done at constant loading rate (5mm/min) and by computerized universal testing machine (Zwick/Roell 100KN) as shown in Figure (6). It was also performed at room temperature. Then, the average of three specimens was taken to qualify the tensile performance of each welded joint.
3.4. Optical Microscope

Macro and micro surface structures were checked by a means of magnified lens and optical microscope to keep the homogeneity of the mixture and the presence of macro and micro voids. All microscopic examinations that using optical microscope (MEIJI–Japan) with digital camera are shown in Figure (7).
3.5. Vickers Hardness
The measurement of the Vickers hardness distributions in the joints were performed on the cross-section based on the welding direction. Figure (8) shows how the Reicherter Stiefelmayer micro hardness tester was utilized to find hardness profiles of the samples along with the center-lines of the cross-sections. The samples were taken every 10 s with a space between neighboring points that is measured of 1 mm under the load of 50 g.

4. Results and Discussion
In thin plates of aluminum friction stir welding, main problems are high heat of welding because of high heat conductivity and difficult sheets separation from fixture; it is because of high heat conductivity of aluminum which becomes higher because of low thickness of ultrathin plates. This problem can be solved using a resistant plate under main plates. Figure (9) shows the welded plate at different rotational speed and feed rate. Figure (10) shows the fractures of all specimens tensile test that show brittle fracture because thin plate welding of aluminum alloy.
Figure 9. welded plate at different rotational speed and feed rate where: (1) 900 rpm, 20 mm/min. (2) 900 rpm, 40 mm/min. (3) 900 rpm, 80 mm/min. (4) 1400 rpm, 20 mm/min. (5) 1400 rpm, 40 mm/min. (6) 1400 rpm, 80 mm/min.

Figure 10. Fracture surface of brittle fracture

Figure (11) shows engineering stress-strain diagrams of all samples and parent metal that shows all samples is less than parent metal. Figure (12) indicates that engineering stress-strain diagram of rotation speed (900, 1400) rpm and same feed rate (20) mm/min and Figure (13) indicates that engineering stress-strain diagram of rotation speed (900, 1400) rpm and same feed rate (40) mm/min. Tensile strength of welded samples with rotational speed (900, 1400) rpm and same feed rate (20) mm/min have (72, 235) MPa, the other rotational speed (900, 1400) rpm and same feed rate (40) mm/min have (333, 50) MPa, and other rotation speed (900, 1400) rpm and same feed rate (80) mm/min have (315, 221) MPa. In low feed rate (20) mm/min welding tensile strength is lower than parent metal with increase in feed rate (40) mm/min results too tensile strength increasing and reaches to its pick and becomes near parent metal. with increase in feed rate (80) mm/min the tensile strength decrease again. the better tensile strength that give from feed rate (40) mm/min and rotational speed (900) MPa because of enough heat generated by FSW cause better recrystallization and grain size.
Figure 11. indicates that engineering stress-strain diagrams of all samples and parent metal

Figure 12. indicates that engineering stress-strain diagram of rotation speed (900,1400) r.p.m and same feed rate (20)
Figure 13. indicates that engineering stress-strain diagram of rotation speed (900,1400) r.p.m and same feed rate (40)

Figure 14. indicates that engineering stress-strain diagram of rotation speed (900,1400) r.p.m and same feed rate (80)

Figure (15) show the measured micro hardness at stir zone (SZ) is more than (TMAZ) and (HAZ) zones, the measured micro hardness of stir zone (SZ) is less than parent metal because of the process of rotational tool and feed rate cause dynamic recrystallization and result new grain giant.
The closest comparison was found with El-Morsy et al. [15] since they tried to weld the same material with the same rotational speed of 900 rpm, although; they used different feed rate and sheets thickness. Figure (16) shows an acceptable agreement between the current work (feed rate of 40 mm/min and sheet thickness of 1.2 mm) in which the product has a 72% performance and El-Morsy et al. [15] results for a feed rate of 35 mm/min and a thickness of 1.5 mm in which the performance was 86.3%.

The microstructure of base metal AA2024-T4 show below in figure (17) .
During FSW, all component that contribute to high-temperature exposure and intense plastic deformation within the SZ results in recrystallization and development of texture within the SZ. Figure (18) show FSW microstructure for all zones starting from (SZ), (TMAZ), (HAZ) depending on microstructural characterization of grains and precipitates, picture (a) with magnification (5X) show all zone (SZ),(TMAZ) and (HAZ). Picture (b ,c ,d ,e) with magnification (10x) show (TMAZ) zone from start to the end compare with (HAZ) zone . Picture (f) with magnification (20x) show (TMAZ) and (HAZ)zone . Picture (g) with magnification (20x) show the zone out of (HAZ) with new grain recrystallization. Picture (h , i) with magnification (20x) show the parent metal.
5. Conclusion
From the present study, the best result of mechanical properties for friction stir welding sample that obtained from rotation speed (900) rpm and feed rate of (40) mm/min. The measured micro Vickers hardness varied for each (FSW) zones and micro hardness of (FSW) at all zones it’s below the parent metal. Moreover, the microstructure and micro-hardness for all (FSW) show the zonal transition from the parent metal to (HAZ) , (TMAZ) and (SZ) in center of welded sample. And, the (HAZ) zone has the lowest micro-hardness compare with the welded zones and parent metal.

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