Formability of Friction Stir Welded and Processed AA 2024 – O Aluminum Alloy Sheets

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ABSTRACT
Friction Stir Welding (FSW) is one of the most effective solid states joining process, FSP is used to modify the microstructure of FSW welded zone. These processes used in many applications that require sheet forming process. In comparison to other welding processes FSW have better formability. The objective of this experiment was to show the effects that varying rotational speed and travel speed on the formability of a friction stir weld. In this work, the joining of 3 mm AA 2024-O aluminum alloy was achieved using the friction stir processing FSP and friction stir welding FSW using the rotational speeds (rpm) 1000 , 1250 , and 1500 rpm rotational speed and 40, 60, 80 mm/min travel speed. The formability of friction stir welded AA 2024-O aluminum alloy sheets were investigated by means of Load–Deflection curve with bending test. From the force-displacement behaviour for the aluminum welds it can be concluded that because of no cracking was observed in the weld zone for most weld sheets, which confirms the good formability compared to base material performance. The best result obtained at 1250 rpm and 40 mm/min rotational speed and travel speed respectively for face and root FSW bending test, and at 1000 rpm and 80 mm/min for FSP. It is possible to conclude that the formability behavior of the FSW and FSP welds depends mainly on the micro and macrostructure in addition to their mechanical properties that related with the process parameters i.e. rotational speed and travel speed.

KEYWORDS: Friction stir welding, Friction stir processing, AA 2024-O Aluminum alloy, bending test, formability.

INTRODUCTION
Wayne Thomas in 1991 developed the FSW which is a solid state welding process. His research was conducted to be used in the fabrications of space applications in an effort to find a welding method that would not add weight to orbital spacecraft. A major advantage of friction stir welding is that it is a solid state weld where the base material does not reach the melting point. Therefore, it does not exhibit the same deficiencies as fusion welding, which is associated with cooling from the liquid phase [1]. Different shapes of the final joint of FSW may be obtained similar to onion ring nuggets, and zigzag shapes (Fig. 1). All these configurations of the final welded joint are resulted depending upon the welding conditions. The shape of the nugget will determine the flow of the material at the joint, in addition to the other mechanical properties. This helps the analyzing and the formation of the resulted joint. This was attracted many researchers and they applied different techniques of analyzing the material flow [2].
FSP was discovered to improve the surface of the joint depending upon the new solid-state welding conditions. In order to produce a refined microstructure, the pin is plunged into the material using the stirring process [3].

The AA 2024-O Aluminum alloy has many advantages of mechanical properties, starting from the weldability and high stiffness or strength/weight ratio which have been confirmed experimentally by many researchers. Sik and Onder [5], reported that the compare mechanical properties of 4mm thick AA 2024-O sheets welded by using TIG and FSW processes, the results show that friction stir welded plates provide better hardness, tensile and fatigue properties. Hiba [6], investigated the mechanical properties of 2024-O aluminum alloy after determined the best values of rotational speed and welding speed to produce best welding efficiency, The maximum efficiency for joints was 89% of the ultimate tensile stress of the base metal. Vural et. al. [7], proposed that the friction stir welding capability of the EN AW 2024-O and EN AW 5754-H22 Al alloys, Welding performance of EN AW 2024-O is reached to 96.6 %. This value is 57 % for EN AW 5754. Ayad and Hamza [8], used a finite element simulation based on ANSYS software to study the temperature distribution of friction stir welding of AA2024-W aluminum alloy. Numerical simulations are developed for thermal conductivity, specific heat and density to know the relationship of these factors with peak temperature. Variation of temperature with input parameters is observed. The simulation model is tested with experimental results. The results of the simulation are in good agreement with that of experimental results.

Their findings indicated many important features of resulted welded joints and the factors that must be taken into consideration, such as tool geometry which determines the quality of the manufactured joints. Other factors affecting the type of the welded joint are the rotational speed, tilt angle, pin geometry and the welding speed and their effects on the properties and joint performance of 2024 aluminum alloy. Some researchers studied and evaluated the bending of similar materials especially on aluminum alloy, such as 6082 [9], 7020-T6 [10], 7075-T651 [11]. Other investigations have been studied the bending strength for dissimilar alloy produced by of FSW and FSP, between 6111 and 5083 [12], 6061-T6 with 6082-T6 [13], and 6061-T651 with 7075-T651 [14].

In this work, the effects of FSW and FSP operating conditions on the bending characteristics of AA2024-O aluminum alloy are investigated experimentally by considering the results at root and face bending test of the welded joints.

**Experimental Program:**

The alloy used in this work is AA2024-O Al alloy. The alloying elements are Copper Cu, and Magnesium Mg. The industrial applications of such types of these alloys are the light and high strength in addition to the high fatigue resistance such as aircraft structures elements fuselage, wing and ailerons. The specimens fabricated of these alloys are not weldable with moderate of machining characteristics.[15]

In this study AA 2024-O was selected. The standard mechanical properties and chemical composition of AA 2024-O are given in tables 1 and 2 respectively. To achieve the FSW experimental work, two aluminum sheets 3 mm in thickness, 200 mm length, and 100 mm width as shown in Fig. 2. To fix the samples, a clamping fixture was designed and used in order to fix the specimens on a CNC milling machine as shown in Fig. 3. Taper cylindrical tool was machined to the required dimensions depends on sheet thickness. The length and diameter of the pin were 2.8 mm and 4 mm respectively, the shoulder diameter was 15 mm. The welding tool was made of tool steel X38. The process design parameters are listed in table 3.
Table 1: Mechanical Properties Of AA 2024-O [16]

<table>
<thead>
<tr>
<th>Ultimate strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Elongation percentage</th>
<th>Hardness HB</th>
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<tr>
<td>185</td>
<td>75</td>
<td>73</td>
<td>20</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 2: Chemical Composition Of AA 2024-O

<table>
<thead>
<tr>
<th></th>
<th>Actual</th>
<th>Nominal [17]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>0.06</td>
<td>0.25</td>
</tr>
<tr>
<td>Cu</td>
<td>3.87</td>
<td>3.8-4.9</td>
</tr>
<tr>
<td>Fe</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Ni</td>
<td>0.02</td>
<td>Balance</td>
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<tr>
<td>Mn</td>
<td>0.38</td>
<td>0.3-0.9</td>
</tr>
<tr>
<td>Ti</td>
<td>0.005</td>
<td>0.15</td>
</tr>
<tr>
<td>Si</td>
<td>0.16</td>
<td>0.5</td>
</tr>
<tr>
<td>Mg</td>
<td>1.39</td>
<td>1.2-1.8</td>
</tr>
<tr>
<td>Cr</td>
<td>0.006</td>
<td>0.1</td>
</tr>
<tr>
<td>Al</td>
<td>93.83</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Fig. 2: Al 2024-O SHEET DIMENSIONS

Fig. 3: Experimental Setup At 1500 Rpm And 60 Mm/Min
Table 3: Fsw Process Parameters

<table>
<thead>
<tr>
<th>symbols</th>
<th>Travel speed (mm/min)</th>
<th>Rotational speed rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td>F2</td>
<td>60</td>
<td>1000</td>
</tr>
<tr>
<td>F3</td>
<td>80</td>
<td>1000</td>
</tr>
<tr>
<td>F4</td>
<td>40</td>
<td>1250</td>
</tr>
<tr>
<td>F5</td>
<td>60</td>
<td>1250</td>
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<tr>
<td>F6</td>
<td>80</td>
<td>1250</td>
</tr>
<tr>
<td>F7</td>
<td>40</td>
<td>1500</td>
</tr>
<tr>
<td>F8</td>
<td>60</td>
<td>1500</td>
</tr>
<tr>
<td>F9</td>
<td>80</td>
<td>1500</td>
</tr>
</tbody>
</table>

The welding process was achieved using the butt joint configuration of two Al alloy sheets. The welding is in a direction normal to the rolling direction of sheet. The sheet dimensions are 200 mm * 100 mm using three rotational speeds 1000, 1250, and 1500 rpm and three translational speeds 40, 60, and 80 mm/min as shown in Table 4. The bending strength of both FSW and FPW resulted from the welding are compared with the bending strength of the base metal. The bend tested specimen size is 150mmx10mmx3mm.

Three point bending test was carried out to determine the maximum bending force of the welded joints. Nine joints were manufactured with the selected range of design parameters to estimate the bending strength limitations. Face and root bending test are carried out at room temperature by TESTOMETRIC instruments. To determine the ductility and toughness of the welded joint by using FSW and FSP a bending test was adopted for the weld samples which passed 90° bend test. Bend testing was set up as illustrated in Fig 4.

![Testometric Bending Test Instrument](image)

Fig. 4: Testometric Bending Test Instrument

RESULTS AND DISCUSSIONS

The obtained results indicated that the mechanical properties resulted from the solid state fabrication process (FSW) are in good agreement with those found for the base material. In FSW the induced friction may soften the metals of the welded joint region in a temperature less than the melted point of the metal. Due to rotational speed, the softened metal underneath of the shoulder of the joint is in an extrusion state which results in a joint free of distortions and few of residual stresses. [18]

The ductility and toughness of FSW were visualized by using face bend test. The welded specimens were passed the 90 bend test. Most of the welds presented good ductility, some of the welded aluminum alloy samples did not fail in bend test and they can be formalized. Ten samples were chosen and tested in a bend test.
They have shown a breakage during the test. This is due to the improper mixing of the metals and the downward forces are not enough to achieve the test.

Since the temperature increase for FSP4 was not sufficient to soften the original metals and they are not plasticized in order to achieve the stirring and the forging processes i.e less than bending strengths. It was noticed that the defects of the welded joints are not in the root of the welded region. The defects are called Tunnel hole defect. It was observed that the appearance of the welded joints is a good tunnel defect which are found in the advancing side of the stirred weld region. Because of the heat generation is not enough to plastized the welded metal under the shoulder. This can be avoided by choosing a proper process factors such as increasing the rotational speed and reducing the welding speed. At the FSW4, FSP2 and FSP3, the temperature is increased in a level to soften the metal and increased the bending stiffness of the joint. The precipitate distributions are greatly affect the hardness profile of the AA 2024-O Al alloy and not the grain size of the welded metals. The precipitated metals create coarsening and the result is a hardness of SZ to be less than that of the BMs. In the welding zone, the plastic deformation in the TMAZ and due to insufficient strain levels [9], the recrystallization will not occur. Figs. (5a) and (5b) show the typical face and root bends for the bonded metals by using FSW and FEP.

![Typical Face And Root Bended Specimens Of A) Fsw, B) Fsp](image)

The experimental findings of bending strength for both face and root bending for the 9 samples for each type of bend test according to process parameters that listed in table 3.

Fig. 6 presents the force-displacement evolution for the aluminum maximum drawing force values.

Figs. 7 and 8 are show the maximum face and root bending force of the FSW and FSP for aluminum welds. The results indicated that because of no necking or cracking were observed in the weld zone for most of weld sheets, which confirms the good deformation behavior of these solid state welds.
For higher welding speed 80mm/min and rotational speed 1000 rpm a high bending strength for FSP. At 1000 rpm with FSP for each travel speed no clear different between face and root bending strength and these strength improved compared with FSW.

A. FSW3 (ROOT)

B. FSW4 (FACE)

C. FSW7 (ROOT)
D. FSW8 (FACE)

E. FSP2 (ROOT)

F. FSP3 (ROOT)
Fig. 6: Load Deflection Curve Of Aa 2024-O

Fig. 7: Maximum Face And Root Bending Force Of The Fsw
Conclusions:

Bend testing was a valuable tool in determining the strength of a weld compared to the parent material. When finding the initial process parameters the bend tests were used to detect kissing bonds in the welds. When a weld containing a kissing bond was bent, the loads would be extremely low compared to the parent material. In general the following conclusions are listed:

1. It was proved that the bend test is an effective tool for determination the toughness and ductility of the welded joints in FSW and FSP processes of AA 2024-O of thickness 3 mm and they passed the 90° bend test.

2. The AA 2024-O aluminum welds show no necking or cracking for most welded sheets in the punch force - displacement behavior which confirms the ideal deformation of the solid state welds.
3. From the force-displacement behaviour for the aluminum welds it can be concluded that confirms the good formability compared to base material performance. The best result obtained at 1250 rpm and 40 mm/min rotational speed and travel speed respectively for face and root FSW bending test, and at 1000 rpm and 80 mm/min for FSP.

4. It is possible to conclude that the formability behavior of the FSW and FSP welds depends mainly on the micro and macrostructure in addition to their mechanical properties that related with the process parameters i.e. rotational speed and travel speed.

REFERENCES