Effect of Surface Finishing on Microstructure and Corrosion Behavior of Friction Stir Welded Joints For Dissimilar Aluminum Alloys (AA2024-T3 with AA6061-T6)

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Abstract:
The aim of this work is to study the possibility of joining two plates from aluminum alloys, AA2024-T3 with AA6061-T6, using friction stir welding (FSW) technique. In this study, the plates were prepared by cutting with dimensions (100 x 50 x 5) mm by CNC milling machine with cutting speed of 1200 rpm and variable feeding speed of (25, 30, 35 & 40 mm/min). The FSW was operated by a vertical milling machine at a rotary speed of 930 rpm and linear welding speed of 30 mm/min to obtain welding joints of dissimilar plates. Microstructure, surface roughness and micro-hardness were examined. Corrosion test was also carried out by electrochemical methods for all specimens in 3.5wt % NaCl solution, and the corrosion rate was calculated by Tafel extrapolation method. The obtained results demonstrated that the feeding speed has a significant effect in decreasing the corrosion rate comparing with the base metal due to the plastic deformation that occurs at high feed speed. The decrease in surface roughness provided more connected between the two contact surfaces that contributed in the refinement of the microstructure. The sample welded at feed speed 40 mm/min offered the optimum results.

Keywords: aluminum alloys; corrosion behavior; friction stir welding; surface finishing

1. introduction

Friction stir welding (FSW) is defined as a solid state welding procedure, which means that the metal does not reach to the melting point through the welding process [1]. It is an important procedure specifically for aluminum alloys that have a low welding ability in fusion welding methods such as MIG and TIG. This method can also be used in the welding of dissimilar materials [2, 3]. The process is done by means of a rotary welding tool that have cylindrical form by a pin and a shoulder brace [4]. This tool is gradually implanted into the contact area of the plates to be soldered and the stitching process continues until contact is made. The welding tool works to heat the metallic plates and reache them to the maximum temperature (0.8 Tm) due to the friction among the welding tool and the upper surface of the sheets.

The mixing of the metal and the happening of plastic deformation at high temperatures present a microscopic structure with smooth-axis granules. The FSW joints have a nugget or stirred zone which is responsible on great distortion and heat, thermo-mechanical influence area (TMAZ) and a heat influence area (HAZ). It generally contains a very smooth structure [4]. However, the FSW of aluminum alloys is a great challenge since it involves many
complex phenomenon and mechanisms and needs deep understanding to get successful joints [5]. This weld zones are subject to corrosion comparing with base alloys (AA2024 and AA6061 alloys). FSW weld joint does not show an increase in corrosion of the weld areas but it is shown in inter granular corrosion chiefly that is placed on the length of stir zone, (HAZ) zone and was increased when the sediments of the grain boundary is coarsening and developed using the thermal trip through the connected of the joint with the inter granular corrosion [4, 6]. FSW process using different parameters as rotation speed and travel speed of the aluminum alloy AA2024–T351 was effected on the corrosion conduct which was perceived in the stir area at low rotational speed [6, 7].

During last years, many scientists and researchers have manipulated the subject with great findings and beneficial results. Zhitong et al. [8] studied the microstructure, mechanical equalities and corrosion behavior for AA6061 Al alloys joints using FSW process. The results showed that FSW can offer dynamic recrystallized structures in HAZ and original material (BM). Tensile consequences presented that a break happened in the areas among TMAZ and HAZ. Moreover, HAZ had a good corrosion resistance compared to other areas. Amancio-Filho et al. [9] studied the microstructure and the mechanical characteristics of the weld joint of dissimilar Al alloys, AA2024-T351 with AA6056-T4, using FSW at the rotational speed (500, 800 & 1200 rpm) and welding speed (150-400 mm/min). The obtained results suggested that the factors extent of 800 rpm and welding speed at 150 mm/min are the optimum levels of the FSW parameters. Moreover, Raguraman et al. [10] studied the effect of FSW on the corrosion behavior of two Al alloys, AA7075 and AA 6061, with main focus to obtain dissimilar weld joints. The authors suggested that the changes in the microstructure after FSW have a significant effect on the corrosion behavior of the welded alloys as the corrosion rate in HAZ is more than other zones. Muna et al. studied the effect of FSW on the microstructure and corrosion behavior of similar joints of AA6061-T651 [11] and AA2024-T3 [12] in 3.5% NaCl solution. They concluded that the corrosion rate of welded joint is greater than parent alloy. Also, same researchers [13] have found that the dissimilar welded joint of AA2024-T3 with AA7075-T73 exhibits more tendency to corrosion compared to galvanic coupling of the same alloys. Also, the results showed that the dissimilar joints possess lower corrosion rates compared to the similar welds of AA2024-T3 and AA7075-T73.

In this work, the manufacturing process of the plate surface using CNC milling machine at a variable feeding speed was used to prepare the plate for FSW. The effect of the surface finishing on the corrosion behavior was also studied for dissimilar aluminum alloys AA6061-T6 and AA2024-T3.

2. Materials and Methods

Two aluminum alloys of AA6061-T6 and AA2024-T3 were chosen for this study. The chemical compositions of these alloys are listed in Tables 1 and 2 respectively.

| Table 1 Chemical composition analysis of AA 6061- T6 |
|------------------|---|---|---|---|---|---|---|---|
| Element (wt%)    | Si | Fe | Cu | Mn | Mg | Cr | Zn | Al |
|------------------|---|---|---|---|---|---|---|---|
Table 2 Chemical composition analysis of AA2024-T3

| Element (wt%) | Ti  | Cr  | Zn  | Si  | Fe  | Mn  | Mg  | Cu  | Al  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| measured value| 0.6 | 0.4 | 0.3 | 0.12| 1.0 | 0.2 | 0.18| Rem.|     |
| standard value [12] | 0.4-0.8 | Max 0.7 | 0.15-0.4 | Max 0.15 | 0.8-1.2 | 0.04-0.35 | Max 0.25 | Rem. |  

The plates were prepared for FSW joint from aluminum alloys at different feeding speed (25, 30, 35 & 40) mm/min and fixed rotational speed of 1200 rpm. The plates were supported in position using mechanical clamps. Single pass welding procedure was used to fabricate the butt weld joints. For creation butt welds joints, vertical semi-automatic milling machine at rotation speed tool of 930 rpm and welding speed of 30 mm/min was used. High carbon steel was used in manufacturing of tool with dimensions of 20 mm shoulder diameter and pin of 5 mm diameter and 4 mm length, as shown in Fig. 1. Fig. 2 shows the obtained weld joint.

![Friction stir welding process](image1)

**Fig. 1 Friction stir welding process**

![Weld joint obtained by FSW process](image2)

**Fig. 2 Weld joint obtained by FSW process**
X-ray radiography was used to test the weld joint. The welded joint without defects was used for corrosion test from weld zone with dimensions of (1.5*1.5*3) cm according to ASTM (G71-31). The preparations of samples were classified into four sets as shown in Table 3.

Table 3 Specimens categorization.

| Specimen | State                                      |
|----------|--------------------------------------------|
| AA2024-T3 | As received                                |
| AA6061-T6 | As received                                |
| A        | Specimens preparation at feeding speed 25 mm/min |
| B        | Specimens preparation at feeding speed 30 mm/min |
| C        | Specimens preparation at feeding speed 35 mm/min |
| D        | Specimens preparation at feeding speed 40 mm/min |

The specimens were prepared for the microstructure examination using grinding operation by different grits of SiC emery papers, and then polished using diamond past of particles size of 1 μm, followed by a special polishing using Al2O3 solution as coolant. Etching process was carried out using solution of (99% H2O + 1% HF). Afterward, specimens were washed with water and alcohol and finally dried with hot air. Optical microstructural examination was performed using optical microscope type (Metallurgical incident light microscope MBL3300) connected with computer and camera.

The Vickers micro-hardness tester (Digital Micro-hardness Tester TH714) was used to measure the micro-hardness distribution in different welding zones for FSW specimens (A, B, C & D) on a cross section perpendicular to the welding line and at a load and time of 200 gm and 15 s, respectively.

The surface roughness tester (type: Proket Surf) was used to measure the surface roughness of FSW specimens (A, B, C & D) using Ra (µm) factor which is the center-line average of adjacent area. Table 4 shows the results of the surface roughness measurements.

Table 4 Results of surface roughness measurements

| Specimen | surface roughness (µm) |
|----------|------------------------|
| A        | 0.19                   |
| B        | 0.17                   |
| C        | 0.063                  |
| D        | 0.033                  |

Corrosion examination was carried out using a WENKING Mlab potentiostat and SCI-Mlab corrosion measuring system, Germany. The corrosion test was based on the standard of ASTM (G71-31). The tested specimens were immersed in 3.5% NaCl solution at 6.7 PH. The potential is obtained from (-250 to + 250) mV comparative to open circuit potential (OCP). The main corrosion parameters like corrosion potential (Ecorr), corrosion current density (Icorr) and corrosion rate were estimated.

3. Results And Discussion

Fig. 3 shows the microstructures of the base metals, i.e. for aluminum joints of AA2024-T3 and AA6061-T6. The figure reveals microstructural features of a coarse dendritic structure and elongated grains with very fine precipitates of Al2Cu and Mg2Si phases that were uniformly distributed in 2024-T3 and 6061-T6, respectively. The 2024-T3 alloy contains Cu
and Mg as major alloying elements which in turn presented a substantial increase in strength due to the effect of precipitation hardening. However, this effect caused a reduction in the corrosion resistance, ductility and weldability. On the other hand, 6061-T6 alloy includes long and large grains with regular repartition to strengthening precipitation of Mg$_2$Si phase [15, 16]. It is important to mention here that the original alloys have a greater strength because of the presence of alloying elements such as Cu, Si and Mg which could cause a precipitation hardening. The precipitation of Al$_2$Cu and Mg$_2$Si phases with dark or black spots in the grains of AA2024-T3 and AA6061-T6, respectively, can be clearly observed from Fig. 3.

![Microstructures of the base alloys](image)

Fig. 3 Microstructures of the base alloys (A) AA2024-T3 and (B) AA6061-T6 at 400x

Fig. 4 shows the microstructures of FSW specimens (A, B, C & D) in weld zone or stir zone for AA2024-T3 and AA6061-T6. Furthermore, Fig. 6 demonstrates the microstructures of different welding zones, weld zone (WZ) or stir zone (SZ), thermo-mechanical affected zone (TMAZ), heat affected zone (HAZ) and base metal (BM) or base alloys of AA2024-T3 and AA6061-T6 for FSW specimens (A, B, C & D).

![Microstructures of stir zones](image)

Fig. 4 Microstructures of stir zones for FSW specimens (A, B, C & D) at 400x
It can be seen from Fig. 5 that the stir zone (SZ) has equiaxed and finer grains as compared to the base metals. This is may be related to the effect of mechanical forces and recrystallization process which may be resulted through welding process. Here, advantageous results with respect to different mechanical qualities can be anticipated. It was known that the temperature difference between tool shoulder side and base side, along with the temperature difference between tool centerline and an edge of weld nugget, could cause a significant variation in the grain size, which may contribute in improving the corrosion resistance. This is due to the increase in feeding speed used for the plate preparation of welding process, that could cause a decrease in surface roughness (see Table 4) and provide more connected points between two contact surfaces. All these results contribute in a significant refinement of microstructure along with an increasing in hardness value in stir zone of weld zone (WZ). This is because of the increase in the force for moving the pin across the welded plate, that may contribute in increasing the micro-hardness in stir zone or weld zone comparing with TMAZ, HAZ and base metals of both AA2024-T3 and AA6061-T6, as shown in Fig. 6. This figure indicates the hardness distribution in different welding zones for FSW specimens (A, B, C & D) at fixed welding conditions. These results are in good agreement with references [17, 18], as stir zone has the highest hardness values as compared to TMAZ and HAZ. Recently in (2020) Muna et al. [19,20] concluded similar results in case of friction stir welding of similar and dissimilar aluminum alloys of (AA5086 –H32 with AA6061-T6).

Fig. 5 Microstructures of different welding zones, stir zone, TMAZ, HAZ and base alloys for specimens (A, B, C & D) at 400x
Fig. 6 Micro hardness distribution in different welding zones for FSW specimens (A, B, C & D)

Fig. 7 presents potentiodynamic anodic polarization plots of base alloys AA2024-T3 and AA6061-T6, along with (A, B, C, and D) samples in solution of 3.5 wt% NaCl. The average $E_{corr}$, $I_{corr}$ and corrosion rate were obtained using Tafel curves. Table 5 presents the main corrosion data of investigated base aluminum alloys and all FSW specimens.

Fig. 7 Polarization curves for base alloys for AA2024-T3 and AA6061-T6 with FSW specimens in 3.5% NaCl solution.
Table 5  Corrosion results for investigated specimens in 3.5% NaCl solution

| Specimen                  | $I_{corr}$  ($\mu$A/cm$^2$) | $E_{corr}$ (mV) | Corrosion rate (mpy) |
|---------------------------|-------------------------------|-----------------|----------------------|
| AA2024-T3, as received    | 50.57                         | -709            | 21.751               |
| AA6061-T6, as received    | 29.54                         | -652            | 12.7                 |
| A                         | 18.8                          | -765.1          | 8.08                 |
| B                         | 11.3                          | -765            | 4.859                |
| C                         | 10.75                         | -713            | 4.601                |
| D                         | 8.96                          | -762            | 3.853                |

It can be seen from above corrosion results that the base alloy AA2024-T3 has less noble behavior with further decrease in $E_{corr}$ along with higher values of $I_{corr}$ and corrosion rate comparing with that of the base alloy AA6061-T6. This is may be due to the presence of Cu in AA2024-T3, which acts as a helpful factor in formation of intermetallic compound Al$_2$Cu with less nobler behavior compared to AA6061-T6. In other words, AA2024-T3 alloy showed much more influence by corrosion attack as Cu may weaken the protective properties of oxide surface layer. Therefore, the anodizing process can be used to improve the surface oxide stability when the oxygen presents in the aggressive medium is negligible [21, 22]. On the other hand, the values of $I_{corr}$ and corrosion rate of specimens (A, B, C & D) are more lower (nobler) than that of base alloys AA2024-T3 and AA6061-T6. Among investigated FSW specimens, sample D showed the best corrosion resistance with the lowest values of $I_{corr}$ and corrosion rate compared to that of other samples (A, B & C). This result confirms the effect of FSW in modification the microstructure and rearrangement of the precipitated particles in Al matrix. Fig. 8 shows the optical micrographs of the corroded surfaces of investigated base alloys and FSW specimens. The figure reveals that pitting corrosion was occurred in all specimens after corrosion test in 3.5% NaCl solution.

Fig. 8  Micrographs indicating the pitting corrosion for all specimens after corrosion test in 3.5% NaCl solution at 100x.
4. Conclusions

The main conclusions of this study can be summarized as following:

1. The generated heat and plastic deformation resulting from the frictional process cause the grain refinement in stir zone, which led to increase the hardness in stir zone and decrease in the heat affected zone (HAZ) for all investigated specimens.

2. The increase in feeding speed used for preparation plates to be welded contributed significantly in improving the surface roughness and increasing the hardness in stir zone; the feeding speed at 40 mm/min is the best option.

3. FSW specimen prepared at feeding speed 40 mm/min showed the best corrosion resistance with lower corrosion rate than that of base alloys (AA2024-T3 and AA6061-T6) and other specimens.

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