Study of Corrosion Behavior of Friction Stir Welded Aluminum Alloy (2024-T_3)

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Abstract--Friction stir welding (FSW) is a promising solid state joining process and is widely being considered for Al-alloys especially for joining aerospace and aircraft aluminum alloys. In this work, the microstructure and corrosion behavior of the FSW 2024-T3 Al-alloy are studied. The friction stir welding was carried out by using CNC milling machine at different tool rotational speeds and welding speeds. The microstructure of weld or stir nugget (SN), thermo-mechanically affected zone (TMAZ), heated affected zone (HAZ) and base metal were observed by optical microscopy. The corrosion tests of base alloy and welded joints were carried out in 3.5%NaCl solution at a temperature of 30°C. Corrosion current and potential were determined using potentiostatic polarization measurements. It was found that the corrosion rates of welded joints were higher than that of base alloy.

Keywords: Friction stir welding, Al-alloys , corrosion, microstructure

I. INTRODUCTION

Friction stir welding (FSW) has now become an important process in the joining of aluminum alloys and other materials which are soft relative to the material used as the tool for stirring the metal. Since there is no macroscopic melting involved,the controls needed in fusion welding to avoid phenomena such as solidification and liquation cracking,porosity,and loss of volatile solutes can be avoided. These recognized advantages of solid –state joining have led to attempts to use FSW for a wide range of alloys [1,2,3]. Recently aluminum alloys are used in automotive, shipbuilding and aircraft products, railway rolling stock industries and most likely others[4], because they are light in weight, easy to machine and have relatively high tensile strength. Age hardening heat treatment (T4 or T6) is generally used for increasing the strength in heat treatable aluminum alloys (2000, 6000 and 7000 series). In case of fusion welding processes such as (TIG) or (MIG), hot cracking often occurs in them without filler metals . These problems can by eliminate in FSW process [5].

Wert [2003][6] studied FSW of aluminum alloy 2024 welded to an aluminum matrix composite 2014/20%Al2O3, and observed grain boundary liquation and liquation cracking on the 2024 side of the weld. The 2024T3 aluminum alloy has been widely used as a structural material of the aircraft. But it is susceptible to localized corrosion such as pitting .Generally temperature humidity and salinity are the main factors taken consideration during the accelerated tests [7]. Venugopal et al [2004] [8] studied microstructural and pitting corrosion properties of friction stir weld of 7075 Al alloy in 3.5%NaCl solution. Corrosion resistance of weld metal is better than that of TMAZ and base metal. Friction stir welding of alloy 7075 resulted in fine recrystallized grains in a weld nugget which has been attributed to frictional heating and plastic flow. Cao and Kou [2005][9] studied FSW, gas metal are welding (GMAW) of alloy 2219. GMAW was conducted to provide a benchmark for checking liquation in FSW of alloy 2219. The microstructure of the resulting welds was examined by both optical and SEM. It was found that in GMAW of alloy 2219,(Al2Cu) particles act as in-situ micro sensors clearly in decanting the onset of liquation and show no evidence of induced liquation during FSW.

Ju Kang et al [2010][10] investigated the surface corrosion behavior of an AA2024-T3 aluminum alloy sheet after friction stir welding by using an ‘‘in-situ observation” method. SEM observations showed that the density and degree of the pitting corrosion in the shoulder active zone were slightly larger compared to the other regions on the top surface. The origins of the pitting corrosion were in the regions between the S phase particles and the adjacent aluminum base.

The aim of the present work is to study the microstructures and corrosion resistance of the 2024-T3 Al alloy welded by friction stir process.

II. EXPERIMENTAL WORK

A. *Welding Process*

The base metal used in this study was 2024T3 Al alloy. The thickness of Al-alloy was 5mm. The chemical composition is listed in Table 1. All specimens were prepared by cutting the 2024T3 Al alloy into 70mm x 100mm pieces. Because no specialized friction stir welding machine was available to conduct the welding process, the CNC milling machine (type Series 1, Bridgeport) was used for this purpose. All similar welds of 2024T3 were performed using a welding tool made of medium carbon steel (St45). The welding tool is composed of shoulder (20mm in diameter) and probe or pin (5mm in diameter and 4.7mm in depth).

TABLE I CHEMICAL COMPOSITION ANALYSIS OF 2024 T3 AL ALLOY

Elément	Cu	Mn	Mg	Si	Fe	Cr	Zn	Al
wt%	4.91	0.54	1.31	0.145	0.31	0.09	0.10	Bal.

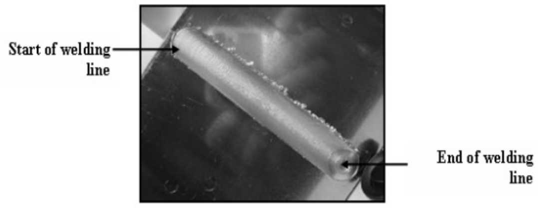


Figure 1 The start and end of the welded joint

The welding tool was rotated at high speed and plunged into the joint line between two plates to be butt welded together. This stirring action of the rotating tool yields a heavy deformation in the alloy. The frictional heat generated by the welding tool makes the surrounding material softer and allows the tool to move along the joint line. The softened material starts to flow around the probe resulting in transferring of material from the leading edge of the tool to the side [1]. Figure 1 shows the start and end of the welded joint. Effects of some welding parameters such as welding speed and tool rotation speed on microstructure and corrosion resistance of the welding joints were investigated. Table 2 summarizes all welding conditions for (FSW) joints.

B. *Samples Preparation for Microstructure Examination*

The samples made from welds and base metal were ground, polished and etched and observed under optical microscope in sequences steps. Wet grinding operation with water was done by using emery paper of SiC with the different grits (220,320,500, and 1000). Polishing process was done to the samples by using diamond paste of size (1µm) with special polishing cloth and lubricant. They were cleaned with water and alcohol and dried with hot air. Etching process was done to the samples by using etching solution which is composed of (99% H_2O+1%HF). Then the samples were washed with water and alcohol and dried. The friction stir welded joints samples were examined by using Nikon ME-600 optical microscope provided with a NIKON camera, DXM-1200F.

TABLE II. WELDING CONDITIONS USED IN THIS STUDY

Joint symbol	Tool rotation speed Rpm	Welding speed mm/min
FSW1	1000	10
FSW2	1000	20
FSW3	1400	10

C. Corrosion Tests

- *Electrochemical Cell*

Polarization resistance tests were used to obtain the corrosion rates. In the tests, cell current readings were taken during a short, slow sweep of the potential. The sweep was taken from (-100 to + 100) mV relative to (OCP). Scan rate defines the speed of the potential sweep in mV/sec. In this range the current density versus voltage curve was almost nearly linear. A linear data fitting of the standard model gives an estimate of the polarization resistance, which is used to calculate the corrosion current density (Icorr) and corrosion rate [11]. The tests were performed by using a WENKING Mlab multi channels potentiostat and SCI-Mlab corrosion measuring system from Bank Electroniks-Intelligent controls GmbH, Germany 2007.

In this study, aluminum alloy (2024-T3) and FSW samples were used as working electrode (WE), a saturated calomel electrode immersed in the salt solution was used as reference electrode (RE), and a platinum electrode was used as auxiliary electrode (AE).

- *Samples Preparation for Corrosion*

In addition to the steps, mentioned in section *(B)*, additional one has been implemented; the samples were carefully measured. The plates had dimensions of about 5 mm thick and 25 mm wide to be fitted in special holder supplied with such apparatus. One $1cm^2$ area of the weld joint which consisted of thermo-mechanically affected zone (TMAZ) and (HAZ), and base metal were individually exposed to 3.5%NaCl solution.. The potentiodynamic scan was performed with scan rate of (10mV/sec) by using potentiostat supported by corrosion measurement software.

III. RESULTS AND DISCUSSION

A. Micro structure Results

The microstructures resulted by friction stir welding (FSW) process in aluminum alloy 2024T3 (precipitation hardenable Al alloy) are different from that of base metal microstructure or cast structure of fusion weld. These changes can bring a difference in corrosion behavior of the weld. FSW is essentially a hot-working process where a large amount of deformation is induced into the work piece through pin and shoulder and the temperature never exceeds 0.8 Tm [10]. The heat and deformation generated during FSW produce macrostructurally distinct regions across the weld as shown in Figure 2 An FSW joint consists of four zones:

Figure 2 Photograph picture of joint welded at welding speed (20mm/min) and tool rotational speed (1000 rpm)

1- Stir nugget (SN) or stir zone (SZ) which is fully re-crystallized region at the weld center.

2- Thermo-mechanically affected zone (TMAZ) which is affected by heat and deformation, but not re-crystallized.

3- Heat affected zone (HAZ) which is affected only by heat with no plastic deformation.

4- Base metal (BM)

Figure 3 shows the microstructure of the cross section area of welded joint observed at a welding speed of 20 mm/min and a tool rotation speed of 1000 rpm. The microstructure of stirred zone (SZ) consists of equiaxed grains in much smaller size compared to the large elongated grains of base metal (BM).

Figure 3-a shows the recrystallized grain structure at the center position of the stirred zone. Figure 3-b shows two different microstructures the first is a fine grain region at the left side resulting from the action of rotating probe. The second is an elongated microstructure at the right side remaining from base metal. The transition region between the weld nugget and (TMAZ) is clearly observed as being microscopically sharp described as adjacent to the fully recrystallized nugget containing grains that exhibit varying degrees of recovery and recrystallization to give equated grains. Figure 3-c & d shows microstructures of heat affected zone (HAZ) and base metal (BM) respectively. These microstructures results are similar to those of other researchers [10,12].

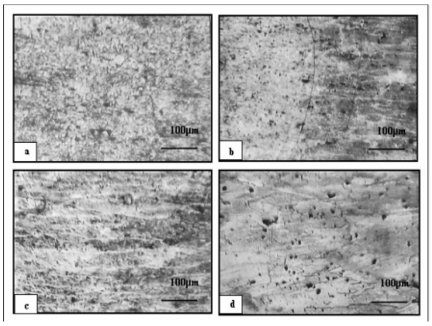


Figure 3 Microstructure of FSW2 welded joint

a- Stir zone (SZ) or stir nugget b- Thermo-mechanically affected zone (TMAZ)

c- Heat affected zone (HAZ) d - Base metal (BM)

According to microstructural observation in this study, the grain sizes in the weld nugget are significantly smaller than the parent metal and this can be attributed to the mechanical forces operative during welding which causes both refinement and re –alignment of the matrix grains and should be beneficial with respect to various mechanical properties. This is due to the temperature difference between the tool shoulder side and base size and the tool centerline and the edge of the weld nugget which causes the grain size variations [13].

B. Corrosion Results

- *Open Circuit Potential Measurements Results*

The variation in the open circuit potential (OCP) of base alloy 2024T3 (as received) and friction stir weld sample (FSW2) in 3.5%NaCl solution at temperature 30ºC has been measured as shown in Figure 4 and 5. The potential generally changes from an initial negative value (-890mV) (SCE), (-1102mV) (SCE), to the positive direction (-634mV) (SCE), (-1090mV) (SCE) within about 1500 sec, for base alloy and FSW2 sample respectively, after that the potential remains constant. The potential was measured every minute from the first minutes for the remaining time. This continuous increase in corrosion potential was most likely the result of oxide film build up or formation of corrosion products on surface. The variation in open circuit potential with time depends on many parameters such as chemical composition, surface treatments, oxygen content …etc) [14].

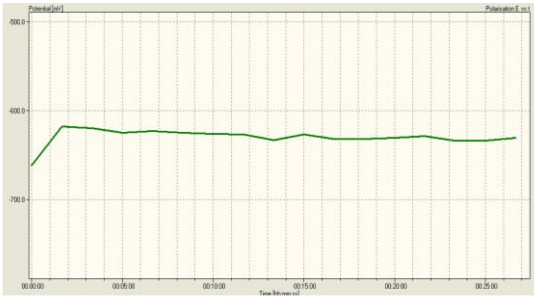


Figure 4 Open circuit potential of the base alloy 2024T3 in 3.5%NaCl solution

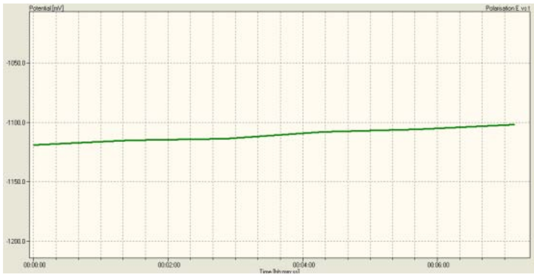


Figure 5 Open circuit potential of the friction stir weld in 3.5%NaCl solution

- *Potentiostatic Polarization Measurements Results*

Generally a passive oxide film can be readily formed on the surface of aluminum alloys, when exposed to air or water. However the corrosion rate could be very high due to the presence of chloride ions [15]. Further the corrosion behavior of Al-alloys largely depends on heterogeneity of their microstructures.

In this study, electrochemical corrosion test by Tafel extrapolation method was carried out on all samples of base alloy 2024T3 and FSW in sodium chloride solution of 3.5% NaCl to determine corrosion parameters. Such as corrosion potential (Ecorr.) and corrosion current (Icorr.) as shown in Table 3.

TABLE III. THE RESULTS OF CORROSION TESTS OF STUDIED SAMPLES IN SOLUTION 3.5 %NACL

Sample	**Ecorr (mV)**	**Icorr (µA /cm²)**
Base alloy	- 654	7.45
FSW1	- 711.1	25.93
FSW2	- 688.9	42.1
FSW3	- 689.9	22.1

Figure 6 shows the polarization curves of the base alloy 2024T3 and FSW samples in 3.5%NaCl at temperature of 30ºC. It is shown that the corrosion behavior of base alloy significantly varies from that of welded joints, and the friction stir welds have higher corrosion rates than base alloy. This is due to in homogeneity of microstructure in weld regions or zones while the unwelded base alloy 2024T3 (in aging condition) has a uniform microstructure i.e. uniform distribution of precipitates in aluminum matrix. The precipitates are more noble and promote anodic dissolution of the matrix.

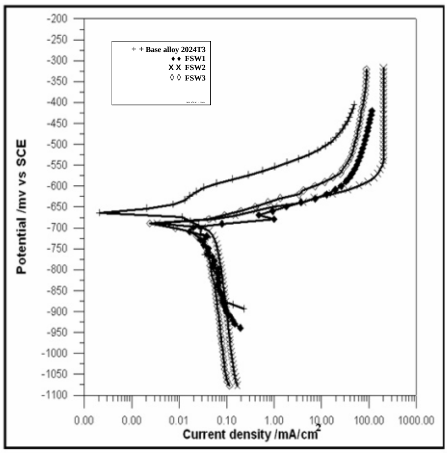


Figure 6 Polarization curves of the base alloy and friction stir welds in 3.5%NaCl solution at temperature 30ºC

Boger R.K [16] reported that the aged samples are more susceptible to pitting corrosion than solution heat treated ones. They attributed these results to the weak passive film formed on Al2CuMg, Al2Cu the strengthening phases (precipitates) in the aged alloyed. During FSW process only coarser precipitates could nucleate and grow but not finer ones. This aids in formation of passive film, which remained more intact on surface of the sample. These results are in agreement with the results of the researcher Cao and Kou [9]. They observed, in most friction stir welds large θ (Al_2Cu) particles appear to have formed during FSW process from agglomeration of fractured particles and the smaller ones of the θ (Al_2Cu) particles in the work piece. These particles have solution potentials differing from that of the solid solution matrix in which they occur localized galvanic cell may be formed between them and the matrix.

The microstructures of pitted surfaces is shown in Figure 7 a-d which reveals clearly that pit density of weld joint is much more than that of base alloy. It can be found that mean diameter of pits which is calculated from Image Analyzer Program for base alloy sample is lower than that of FSW samples. The mean µm and 65.27 µm for base alloy, FSW3, FSW1 and FSW2 samples respectively. The poor pitting corrosion resistance of weld joints is due to difference in pitting potentials across the weld region or stir nugget and base alloy because of inhomogenity of microstructures in those regions. Srinivasa Rao and Prasad Rao [2004][17] studied the mechanism of pitting corrosion of heat treatable Al–Cu alloys and welds. Pitting corrosion involves three stages, pitting initiation, metastable pitting and pitting growth.

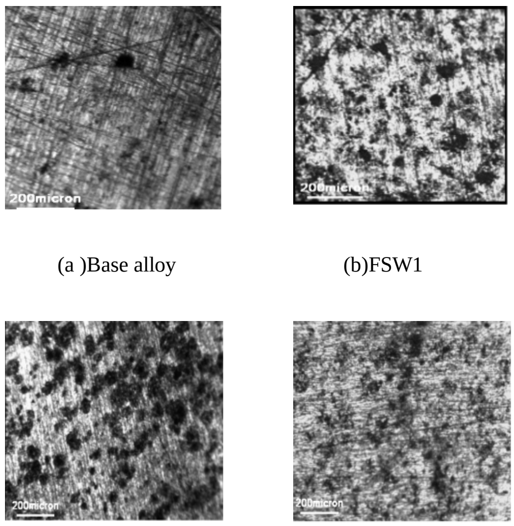
IV. CONCLUSIONS

1- Grain refinement in weld metal has been achieved due to frictional heating and plastic flow.

2- Corrosion resistance of base alloy (2024T3) has been found better than that of friction stir welded joints in 3.5%NaCl solution.

3- Corrosion potential (Ecorr.) of base alloy is more noble (less negative) than that of welded joints.

4- The weld samples were more susceptible to pitting corrosion than the base alloy of 2024-T3.



(a)Base alloy (b)FSW1

(c)FSW2 (d)FSW3

Figure 7 Microstructures showing pits after electrochemical in 3.3%NaCl solution

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