

Corrosion Behaviour of Friction Stir Welded Aluminium Alloys AA6082-T₆

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Abstract In the present investigation, the corrosion behaviour of 6082-T₆ Al alloy plates joined by friction stir welding (FSW) were evaluated. The effects of weld process parameter like welding speeds as well as pin profiles on corrosion behaviour were investigated. The plates of AA6082-T₆ were friction stir welded at rotational speed of 1600-1650rpm using three different tool pin profiles like four flute pin, triangular pin and hexagonal pin, with different welding speeds (typically, 50, 62, 68, 70, and 74 mm/min). The corrosion tests of base alloy and welded joints were carried out in 3.5% NaCl solution at a room temperature. Corrosion current and potential were determined using potentiostatic polarization measurements. The pitting potentials of corrosion tested samples at various process parameters clearly indicated a greater corrosion resistance of weld metal than base alloy.

Keywords: friction stir welding, Al-alloys AA6082, corrosion behaviour

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1. Introduction

Although aluminium is a very reactive metal with a high affinity for oxygen, the metal is highly resistant to most environments and to a great variety of chemical agents. This resistance is due to the inert and protective character of the aluminium oxide film which forms on the metal surface. Aluminium welding still represents a critical operation due to his complexity and the high level of defect that can be produced in the joint. The main problems are related to the properties of aluminium is high thermal conductivity, high chemical reactivity with oxygen, and high hydrogen solubility at high temperature. All this factors can cause presence of defects on the weld bead. The Friction Stir Welding (FSW) represents a possible solution. Friction stir welding (FSW), a new solid state joining technique, was invented by The Welding Institute (TWI) in 1991. In FSW, the working temperature is high enough to plasticize the material but not to melt it, and this fact can drastically reduce the presence of defects giving also higher mechanical properties in respect to the conventional welding techniques. FSW technique is now increasingly used to join high strength aluminium alloys (2xxx, 6xxx, 7xxx and 8xxx series) for aerospace, automotive and marine applications. The marine atmosphere is generally aggressive against aluminium alloy, among the more corrosion resistant aluminium alloys, and widely used in the marine applications, are the 6xxx.

The corrosion behaviour of friction stir welded aluminium alloys has been described by various researchers in recent years [1-6]. Generally, it has been found that the weld zones are more susceptible to corrosion than the parent metal. Friction stir (FS) welds of aluminium alloys such as 2219, 2195, 2024, 7075 and 6013 did not exhibit enhanced corrosion of the weld zones [1,7,8]. FS welds of aluminium alloys exhibit intergranular corrosion mainly located along the nugget's heat-affected zone (HAZ) and enhanced by the coarsening of the grain boundary precipitates. Coarse precipitates and wide precipitate-free zones promoted by the thermal excursion during the welding are correlated with the intergranular corrosion. The effect of FSW parameters on corrosion behaviour of friction stir welded joints was reported by many workers [5,9,10]. The effect of processing parameters such as rotation speed and traverse speed on corrosion behaviour of friction stir processed high strength precipitation hardenable AA2219-T87 alloy was investigated by Surekha et al. [9]. The results indicate that rotation speed has a major influence in determining the rate of corrosion, which is attributed to the breaking down and dissolution of the intermetallic particles. Jariyaboon et al. [5] studied the effect of welding parameters (rotation speed and travel speed) on the corrosion behaviour of friction stir welds in the high strength aluminium alloy AA2024-T351. It was found that rotation speed plays a major role in controlling the location of corrosion attack. Localized intergranular attack was observed in the nugget region for low rotation speed

welds, whereas for higher rotation speed welds, attack occurred predominantly in the HAZ.

Ahmed S. Hassan et al. [10] investigated the corrosion behaviour of dissimilar A319 and A356 Cast aluminium alloys and observed the corrosion resistance of the welded zones to be reduced by increasing the tool rotational speed and/or reduction of the welding speed.

Many investigators studied the corrosion resistance of Al alloys weld joints made by using FSW and other conventional fusion welding techniques such as Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) [11,12]. Stefano and Chiara [12] reported a comparison of the corrosion resistance of AA6060T₅ and AA6082T₆ joints made by FSW and MIG, respectively. Corrosion resistance was detected via morphological analysis of the surface. The attack was localized (pitting), an index referred to the pit density was used for the comparison. The results indicated that joints welded using FSW are more resistant to corrosion than those welded using MIG. Squillace et al. [11] performed an experimental investigation on microstructure and corrosion resistance of weld butt joints of AA 2024-T₃ welded using FSW and TIG techniques. Polarization curve tests and electrochemical impedance spectroscopy showed a nobler behaviour of weld bead with respect to parent alloy. In FSW joints, however, the differences between the nuggets, thermo-mechanically affected zones (TMAZ) and heat affected zones (HAZ) were not so evident as in TIG joints; what is more, inside FSW weld bead, the retreating zone showed a behaviour nobler than the advancing one. Vincent Proton et al. [13] studied the corrosion behavior of a FSW joint in 2050-T₃ alloy in NaCl solution and the influence of T8 post-welding heat treatment on its corrosion susceptibility was analyzed. It has been found that most of the work carried out in the field of corrosion resistance of FSW is focusing on wrought Al alloys [1-12], especially, high strength alloys such as 7xxx and 2xxx series. Thus, the aim of this work is to investigate how corrosion behaviour can be changes in FSW of AA6082 controlled by the welding parameters.

2. Material and Methodology

In the current investigation, joints of aluminium alloys AA6082-T₆ were produced by using FSW technique. The plates of 5mm thickness were cut into the required size (300mm×150 mm) by power hacksaw cutting and grinding. The chemical composition of the AA6082 aluminium alloy (by weight percent) was 0.9% Si, 0.24% Fe, 0.9% Cu, 0.7%Mn, 0.7% Mg, 0.06%Cr, 0.04% Zn, 0.05% Ti and balance Al. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The weld direction was normal to the rolling direction. Single pass welding procedure was used to fabricate the square butt joint configuration. In present work three tool pin profile made of cold work die steel were used for the friction stir weld. The tool pin geometry used in experimental work is shown in Figure 1. The machine used for the production of FSW joints was Vertical Machining Centre. Friction stir weld conditions employed to join AA6082-T₆ plates are rotational speed 1600-1650rpm, welding speed 30-74mm/min, tool depth - 4.6mm, and tilt angle-0°.

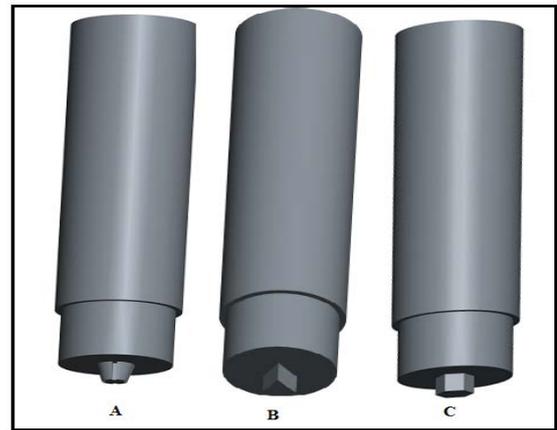


Figure 1. Tool pin geometry- (A) Four Flute (B) Triangular (C) Hexagonal

In this study, electrochemical corrosion test by polarization technique was carried out on base alloy AA6082 and weld zone of FSW samples in 3.5% NaCl at a room temperature to determine corrosion parameters such as corrosion potential (E_{corr} in mV), corrosion current (I_{corr} in $\mu A/cm^2$) and corrosion rate (mpy). The samples for corrosion test were carefully plated with about 5mm thickness and 25mm wide to be fitted in holder of apparatus. One square cm area of the weld joint which consists of weld nugget (WN), thermo-mechanically affected zone (TMAZ) and (HAZ), and parent metal were exposed to 3.5 %NaCl solution. The potentiodynamic scan was performed at scan rate of 0.5mV/sec. In this test, 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 graphite electrode was used as auxiliary electrode (AE).

3. Results and Discussion

3.1. Effect of Weld Parameters on the Microstructure

The macrograph of the AA6082-T₆ weld is shown in Figure 2 - Figure 5 which exposes the features of the adjoining regions of the joint. Based on optical micro structural characterization of grains and precipitates, three distinct zones have been identified such as weld nugget zone (WNZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). As can be seen from Figure 2, the slightly elongated and larger grain structure in the AA6082 base metals is significantly recrystallized in the WNZ. The largest plastic strain takes place in the nugget, where the temperature can reach to 500°C; consequently, the microstructure is entirely dynamically recrystallized.

The effects of differences in tool geometry and weld process parameters were investigated by means of a micrographic analysis at high magnifications. Figure 3 to Figure 5 shows the optical micrographs of the cross-sections perpendicular to the tool traverse direction of the FSW plates for all three pin profiles.

The weld nugget zone of FSW plates hexagonal pin has experienced high-temperature and extensive plastic deformation, and is characterized by a dynamically recrystallized, fine equiaxed grain structure (Figure 5).

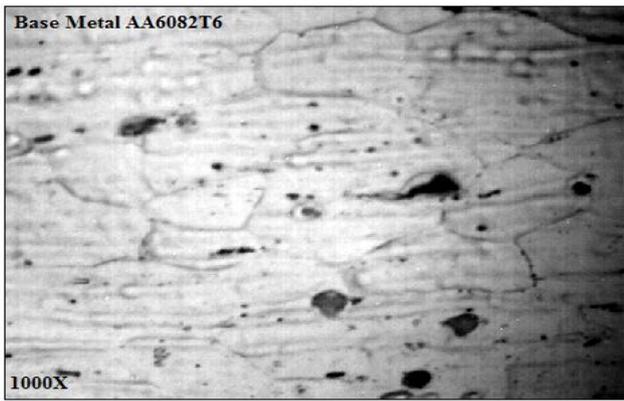


Figure 2. optical micrographs of base metal AA6082-T₆

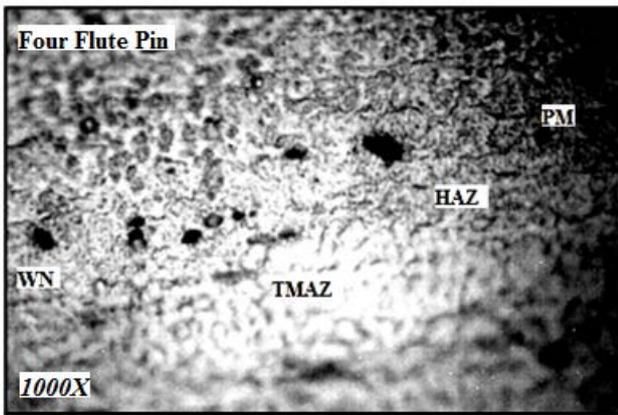


Figure 3. optical micrographs AA6082-T₆ for four flute pin

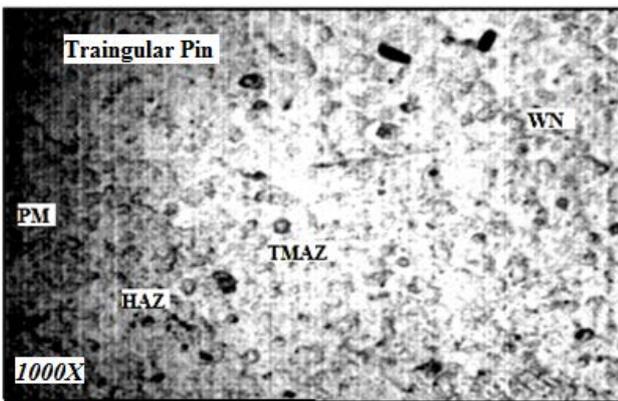


Figure 4. optical micrographs AA6082-T₆ for triangular pin

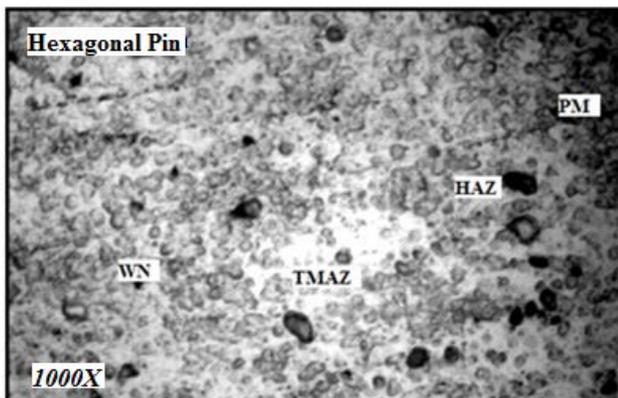


Figure 5. optical micrographs AA6082-T₆ for hexagonal pin

3.2. Effect of Weld Parameters on Corrosion Behaviour

Aluminium is highly reactive, with a negative standard electrode potential of -1660mV, and is therefore unstable in the presence of water. However aluminium reacts quickly with the oxygen in air or water to form a protective oxide film (alumina, Al₂O₃) that is stable in pH range 4-9 and prevents corrosion of the metal. In aqueous solutions, the oxide film is formed during the reaction:



This thickness of the oxide layer can be between 1-10nm [14], and the speed at which it grows is temperature and pH dependent [15]. The oxide layer forms within 1ms in aqueous environments and is protective as it is resistant to dissolution in neutral environments, and blocks the cathodic reaction as it is an insulator. Although surface oxide layer of aluminium acts as an efficient insulator preventing electron transfer to the surface, commercial alloys contain intermetallic particles that have thinner and more conducting oxide layers allowing electrons to pass through, so that anodic and cathodic reactions can take place [14,16].

The potentiostatic polarization curves for the base alloy in 3.5%NaCl at room temperature is given in Figure 6.

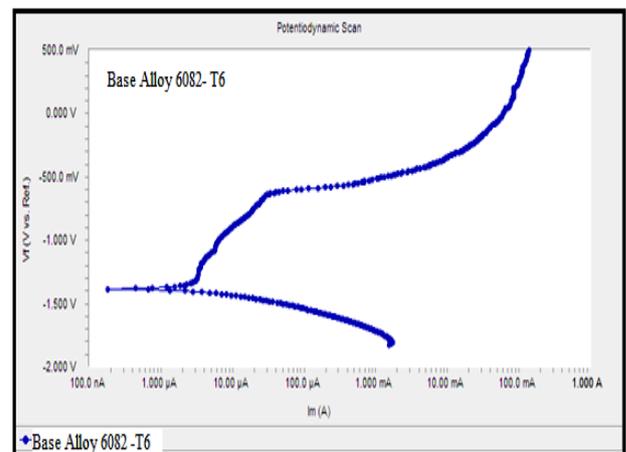


Figure 6. Polarization curves of base alloy AA6082-T₆

Table 1. Result analysis of potentiostatic corrosion test

Pin Profile	I _{corr} (µA/cm ²)	E _{corr} (mV)	Corrosion Rate (mpy)	Weld Speed (mm/min)
Four Flutes	3.39	-760.0	1.55	40
	127nA	-870	58.08e ⁻³	30
	80.30	865	36.71	50
	5.610	-1.09V	2.565	60
Triangular	22.60	-920.0	10.32	50
	1.010	-1.05V	460.8e ⁻³	62
	1.300	-1.240V	594.7e ⁻³	68
	41.50	-836	18.95	70
	35.50	-936	16.24	74
Hexagonal	1.820	-1.040V	832.1e ⁻³	50
	262.0nA	-878.0	119.7e ⁻³	62
	45.1	-771.0	20.60	68
	533nA	-1.27V	243.5e ⁻³	74
Base Alloy 6082-T6	4.270	-1380V	1.950	

Figure 7 - Figure 9 represents the potentiostatic polarization curves for FSW samples in 3.5% NaCl at room temperature at different weld speed. From Table 1 it is observed that the pitting potentials of most of the corrosion tested samples at various weld parameters clearly indicated a better corrosion resistance of weld metal than base alloy. This is attributed to the precipitates present in the alloy promote matrix dissolution through selective dissolution of aluminium from the particle. These precipitate deposits are highly cathodic compared to the metallic matrix, which initiates pitting at the surrounding matrix and also enhances pit growth.

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. It is also found that in few FSW samples, the rate of corrosion resistance is very high. The poor pitting corrosion resistance of these weld joints is due to difference in pitting potentials across the weld region or stir nugget. The friction stir welded samples also show the passivation after longer time of exposure to corrosion media. In case of cylindrical four flute pin, with increase in welding speed from 30 to 50 mm/min (Figure 7), the corrosion rate is increased but it will decrease at 60mm/min and has highest active potential (-1.09V) among all.

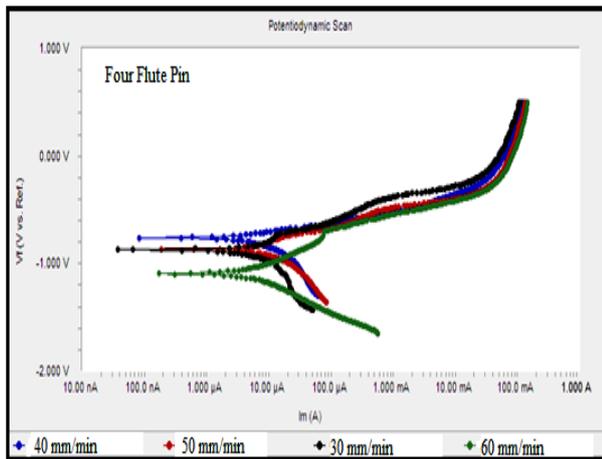


Figure 7. Polarization curves of AA6082, four flutes pin at different welding speed

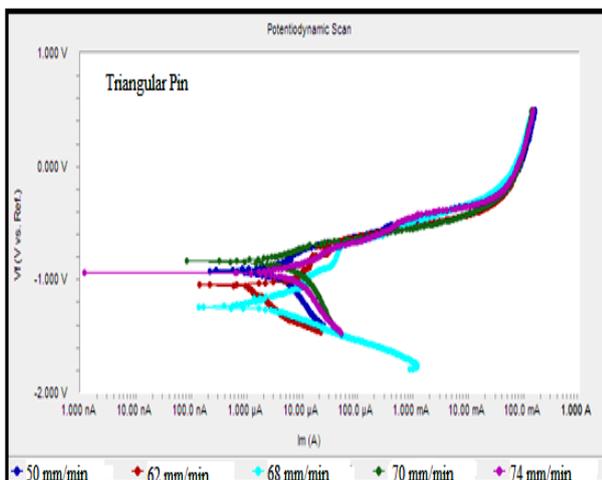


Figure 8. Polarization curves of AA6082, triangular pin at different welding speed

The corrosion rate is very low and more active potential for the welding speed of 62-68 mm/min but it is more for 50, 70 & 74mm/min welding speed for triangular pin (Figure 8).

In hexagonal pin, the corrosion rate is very slow; about 0.1197 mpy at weld speed of 62mm/min (Figure 9). During the entire discussion it is found that in hexagonal pin profiles the resistance to corrosion is more among the other pin profiles with respect to welding speed (Table 1).

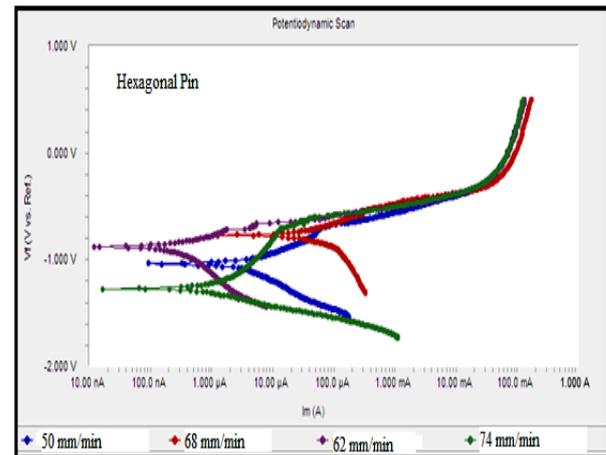


Figure 9. Polarization curves of AA6082, hexagonal pin at different welding speed

4. Conclusions

The corrosion character of the friction stir welds is influenced by the weld processing parameters. With the present range of parameters chosen, the weld speed and pin geometry has influence on the corrosion behavior. The corrosion resistance increased with decreasing the weld speed. Pitting corrosion resistance of weld metal is better than the base metal. Corrosion potential (E_{corr}) of base alloy is poor than that of welded joints. In this study, among all three pin profile used for friction stir welding of AA6082-T6 at different weld speed, the hexagonal pin has greater corrosion resistance with respect to weld speed.

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