Effect of rotational speed and tool pin profile on the corrosion rate of friction stir welded AA6061-T3

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Abstract. In this study, the corrosion behaviour of friction stir welding (FSW) of AA6061-T3 alloy was investigated. The FSW was performed under two different rotation speed (850 and 950 rpm) and constant travelling speed (22 mm/min). Two tool pin profiles (straight cylindrical and conical types) were utilised to study their impact on corrosion resistance. The corrosion behaviour of the base metal (BM) and weld zone were studied by Tafel polarisation cell using 3.5wt.% NaCl and 3.5wt.% KCl solutions at ambient temperature. The results showed that the welded alloy exhibits lower corrosion resistance than the BM. Lower rotational speed (850 rpm) produced weld with higher corrosion resistance in both NaCl and KCl media. Conical tool pin profile produced weld with corrosion resistance higher than the straight cylinder pin in both NaCl and KCl media. NaCl recorded higher corrosion rate with almost twice of the KCl for all welding conditions.

1. Introduction
Aluminium alloys are primary materials used in many fields, including structures, transport, and shipbuilding [1]. The desirable mechanical properties, good corrosion resistance, lightweight, and suitable weldability are the critical reasons for using aluminium [2]. One of the significant industrial technology used in aluminium alloy manufacturing is welding as part of the production process [3]. However, for manufacturers and designers, the welding of aluminium and its alloys has always been a challenge [4]. When concentrating on heat-treatable aluminium alloys, the heat produced by the welding process can cause deterioration of mechanical properties by prompting phase transformations and leading to alloy softening [5]. Authors reported that small variations in weld composition and microstructure have been found to produce an electrochemical potential difference between different areas in the welded joint and thereby cause localised galvanic corrosion [2,6] It has been shown that welding defects such as porosities, cracks, residual tension, and improperly chosen filler in the fusion welding processes cause less resistance to corrosion; elimination of these defects dramatically increases the corrosion resistance, which can be accomplished by utilising solid-state welding processes such as friction stir welding (FSW) [7]. FSW is considered one of the most capable joining methods for aluminium alloys since it gives exceptional mechanical properties [8]. Due to the heating and the high level of plastic deformation, FSW produces a fine recrystallised grain structure and a novel texture in the weld region. [3]. However, this modification in microstructure has been reported to influence the mechanical and electrochemical behavior of welds in terms of corrosion [9,10]. Age hardenable aluminium alloys such as AA6061 are very sensitive to change in microstructure during
welding [11]. AA6061 contains Mg-Si-Cu as an alloying element; the high quantity of the alloying elements added to raise the strength contributes to precipitate of large intermetallics during casting. Authors showed that such intermetallics are very large to be substantially impacted by following thermomechanical processing [2,12]. Tool pin profile and travelling speed in FSW strongly influence the change of the microstructure in the various friction welding zones and therefore plays a major role in corrosion behaviour [13]. It has been reported that the change in pin shape controls the grain size in the weld [14]. However, most of the previous research on tool design has focused on optimising the profile of the tool pin with regard to microstructure and mechanical properties. Therefore, the purpose of the present investigation is to study the corrosion behaviour of AA6061-T3 alloy welded by FSW using two tool pin profiles, conical and straight cylindrical profiles in different corrosive media.

2. Experimental procedure

In the present research, plates of aluminium alloy AA6061-T3 with dimensions of 150 × 170 × 6 mm³ were employed for FSW experiments. The chemical composition of the base metal (BM) is provided in Table 1. The plates were butt friction stir welded in a single welding pass, perpendicular to the rolling direction, using a milling machine with welding tool in the spindle part of milling machine and the BM plates fixed to the milling table as shown in Figure 1. The tool and shoulder diameters were 16 mm. The pin was 5.2 mm in height with two different profiles, straight cylindrical profile with 4 mm diameter and conical profile with 4 mm diameter at the base and 2 mm diameter at the tip, as shown in Figure 2. The tool and pin were made of high-speed steel. Operating parameters used for FSW are listed in Table 2. The samples for the corrosion test were extracted from the nugget zone with dimensions of 10 × 10 × 6 mm³. To remove any left dirt and contamination, the samples were mechanically ground to 1200 grit using SiC papers then washed with water and alcohol. The corrosion test was conducted by Wenking M-Lap potentiostat instrument at ambient temperature in two different corrosive media (3.5wt.% NaCl and 3.5wt.% KCl). Ag and Pt were used as the two electrodes of the corrosion test device, and the test duration was 30 minutes. Equation (1) was utilised to calculate the corrosion rate.

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CR = K_1 \frac{i_{cor}}{\rho} EW \quad \text{...(1)} \quad [15]
\]

Where, CR= Corrosion rate (mpy), \(K_1 = 0.1288\), \(i_{cor} = \) Corrosion current density (\(\mu\text{A/cm}^2\)), \(\rho = \) Density (gm/cm\(^3\)), \(EW= \) Equivalent weight.

| Table 1. Chemical composition of AA6061 BM. |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Si    | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Ti  | Al  |
| 0.4   | 0.7 | 0.4 | 0.14| 1.2 | 0.35| 0.25| 0.15| Bal.|

![Figure 1. FSW setup (a) Prior welding (b) during welding.](image)
3. Results and discussion

3.1 Effect of rotational speed and corrosion media on corrosion rate

Two different rotational speed (850 and 950 rpm) were used to study the corrosion behavior of friction stir welded AA6061-T3 using constant travelling speed (22 mm/min) and straight cylinder pin tool profile. The samples immersed in corrosion media contains 3.5wt.% NaCl. Potentiodynamic Polarisation curves (Figure 3.) show that the corrosion rate increases from 13.88 mpy at 850 rpm to 15.29 mpy at 950 rpm, which indicates that corrosion resistance decreases with increasing rotational speed. It is believed that this increment in corrosion rate is contributed to the coarse grains microstructure produced with a higher rotational speed due to the high heat generation [2].

Effect of different corrosive media was conducted using a solution of water with 3.5wt.% KCl. In this case, the corrosion behaviour was similar to NaCl, where the samples with higher rotational speed gave higher corrosion rate. However, at 850 rpm, the sample recorded the lowest corrosion rate, with 11.72 mpy as illustrated in Figure 4. This behaviour is due to the lower PH in KCl than NaCl. The high PH value leads to weaken the protective layer and accelerate corrosion [15]. A comparison in corrosion rate between different rotational speed and corrosion media is shown in Figure 5. Generally,
corrosion resistance of the weld was higher than that of AA6061-T3 BM.

![Figure 4](image)

**Figure 4.** Potentiodynamic polarisation curve of friction stir welded AA6061 using (a) 850 rpm rotational speed (b) 950 rpm rotational speed, using KCl corrosive media.

**Figure 5.** Corrosion rate of AA6061 BM and weldment at different FSW rotational speed and corrosion media.

### 3.2 Effect of tool pin profile on corrosion rate at different corrosion media

At constant travelling speed (22 mm/min) and 850 rpm rotational speed. Corrosion rate as a function of pin tool profile in FSW was investigated. Straight cylinder and conical pin tool profiles were utilised. Corrosion test was performed in a solution of water and 3.5wt.% NaCl. It was found that the corrosion rate is directly affected by the pin shape. When the straight cylinder pin profile was conducted, the corrosion rate value recorded 13.88 mpy. While with the conical pin profile, the corrosion rate decreases to 7.67 mpy, as shown in Figure 6. When KCl was used as a corrosive media, the conical pin profile gave 9.31 mpy corrosion rate, which is also lower than 11.72 mpy of cylinder pin profile as displayed in Figure 7. The tool pin with a conical shape generates lower heat and finer microstructure, which leads to better corrosion resistance [11,16]. The impact of tool pin profile on corrosion rate at different corrosive media is illustrated in Figure 8.
Figure 6. Potentiodynamic polarisation curve of friction stir welded AA6061 using (a) straight cylinder pin tool profile (b) conical pin tool profile, in NaCl corrosive media.

Figure 7. Potentiodynamic polarisation curves of friction stir welded AA6061 using (a) straight cylinder pin tool profile (b) conical pin tool profile, in KCl corrosive media.

Figure 8. Corrosion rate of AA6061 BM and weldment as a function of tool pin profile and corrosion media.
4. Conclusions
In the present study, the corrosion behaviour of AA6061-T3 welded by FSW using two different tool pin profiles (straight cylindrical and conical) were investigated by Tafel polarisation cell utilising 3.5wt.% NaCl and 3.5wt.% KCl solutions. Following points can be concluded from this study:

- BM had better corrosion resistance than the weld zone.
- Higher rotational speed produced weld with lower corrosion resistance in both NaCl and KCl media at constant travelling speed.
- Conical tool pin profile produced weld with higher corrosion resistance in both NaCl and KCl media.
- NaCl recorded higher corrosion rate with almost twice of the KCl for all welding conditions.

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