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Effect of Post Weld Heat Treatment and Welding Parameters on Mechanical and Corrosion Characteristics of Friction Stir Welded Aluminium Alloy AA2014-T6

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Abstract

This paper addresses the effect of post weld heat treatment methods on the mechanical and corrosion characteristics of friction stir welded Aluminum alloy AA2014-T6. Aluminum alloy AA2014 is mainly used in application where there is a greater demand for high strength to weight ratio like aerospace, marine and industrial applications. In this work, AA2014-T6 plates of 6 mm thick were butt welded using a tool with a square profile. The tensile strength, hardness and corrosion characteristics were compared between the as welded and post weld heat treated samples. It was found that the welded samples heat treated with the low ageing period (8hrs) show improved tensile strength irrespective of the welding process parameters compared to the as-welded samples. Whereas the samples heat treated with high ageing period (9hrs) show a decline in tensile strength for low tool rotation speed. The hardness of the samples has increased in welded samples heat treated with low ageing period. The welded samples heat treated with high ageing period show high passivity in the corrosion media.

Keywords: Friction Stir Welding, Aluminum Alloy AA2014-T6, Post weld heat treatment, Corrosion
1. Introduction

Friction stir welding (FSW) is a solid state joining process used widely for joining Aluminum alloys which are difficult to weld using conventional methods as the joints are free from defects like distortion and porosity. The alloy AA2014-T6 is used widely in aerospace, naval and defence industry due to its high strength to weight ratio. Various researchers have studied the mechanical and corrosion characteristics of friction stir welded high strength Aluminum alloys.

Gürel Çam and Güven İpekoğlu have reviewed the recent developments in the joining of aluminum alloys. They have presented that the joint performance of FSWed age-hardened Aluminum alloys can be increased by keeping the heat input sufficiently low and also by conducting post weld heat treatment (Çam and İpekoğlu 2017). Mosleh et al. have studied the microstructure and corrosion behavior of friction stir welded AA7020-O plates. They have observed that the corrosion resistance of thermomechanically affected zone is lower when compared with heat affected zone regions and dynamically recrystallized zones. They also observed that the corrosion resistance of the samples welded using tapered cylindrical pin tool is better than those welded using two flat-sided cylindrical pin (Mosleh et al. 2016). Ghorbanzade et al. have investigated the microstructural evolutions and mechanical characteristics of friction stir welded AA2024. They have presented that the rotational speed of the tool highly influence the mechanical parameters of the welded samples (Ghorbanzade et al. 2016).

The effect of post weld heat treatment methods on mechanical properties of Aluminum alloys was analysed by different researchers in the recent past. El-Danaf and El-Rayes have studied the effect of post weld heat treatments on the microstructure and mechanical properties of friction stir welded alloy AA6082. They have observed that the samples welded at lower welding speeds responded more to PWHT than that welded at higher speeds. They also have observed that the strength and hardness can be partially recovered by the suitable post weld heat treatment (El-Danaf and El-Rayes 2013). Sivaraj et al. have examined the effect of PWHT on the tensile properties of the FSW joints of AA7075 alloy. It was observed that the tensile strength of the FSW specimens subjected to Solutionizing and artificial aging (STA) treatment was higher than that subjected to artificial aging (AA) treatment (Sivaraj et al. 2014). Aydın et al. have studied the effect of post weld heat treatment on the mechanical properties of friction stir welded joints of AA2024-T4 alloy. They have reported that the T6 ageing treatment is beneficial in increasing the mechanical properties of the 2024-T4 joints (Aydın et al. 2010). The post weld heat treatment T6 condition results in
joints with higher strength compared to other treatments and the T6 treated welds are prone to corrosion (Kumar et al. 2015).

This paper addresses the combined effect of friction stir welding parameters and the post weld heat treatment methods on the mechanical as well as corrosion characteristics of friction stir welded Aluminum alloy AA2014-T6.

2. Materials and Methods

The AA2014-T6 Aluminum alloy plates purchased were tested for its composition before being welded. The chemical composition of the Aluminum alloy plates used in the experiments is shown in table 1. The Aluminum alloy AA2014-T6 plates of 6 mm thick were friction stir welded using a vertical machining centre (LMW Make – KODI 40 Model). The plates were welded in the direction perpendicular to the direction of rolling of the plate. Radiography was done to check the quality of the welded joints. The welds with defects were discarded and the ones with good quality are used in tests and experiments.

2.1. Welding Parameters

The Aluminum alloy plates were welded with two different tool rotation speeds (1000 rpm, 1400 rpm) and weld speeds (20mm/min, 35mm/min). The tool was tilted to an angle of 2° during welding. The tool used for friction stir welding was made up of H13 tool steel with a square profile. The length of the pin was 5.5 mm and the tool shoulder diameter was 18mm (Kadaganchi et al. 2015). The profile of the tool is shown in figure 1. The figure 2 shows the friction stir welded sample.

2.2. Heat treatment method

The Aluminum alloy AA2014-T6 plates were successfully friction stir welded using a tool with square profile. Part of the welded samples was subjected to Solution Treatment followed by Artificial ageing (STA) (Ahmad and Asmael 2015). The solutionizing was carried out by heating the samples at 502°C for a soaking period of 1 hour and quenched in water followed by artificial ageing at 177°C for two different soaking periods of 8 hours (STA-I) and 9 hours (STA-II) (Elangovan and Balasubramanian 2008). Table 2 shows the sample ID for as welded and heat treated specimens welded with different process parameters.
2.3. Testing procedure

2.3.1. Tensile test

The tensile strength for the friction stir welded work pieces was determined as per the ASTM E8M standard testing procedure. Figure 3 shows the dimensions of the standard tensile specimen. The figure 4 shows the sample tensile test specimen.

![Figure 3. Specifications of the tensile specimen](image)

![Figure 4. Sample tensile test specimen](image)

2.3.2. Hardness test

The hardness of the friction stir welded plates was measured using the Vickers hardness tester (Mitutoyo–HM113). The welded specimens were cut perpendicularly to the weld direction and hardness was measured along the transverse cross section at the mid thickness (Hejazi and Mirsalehi 2016). Hardness measurements were taken at every 1mm from the center of the weld region up to the parent metal on either side. The load employed was 300 gf with the dwell time of 15 seconds.

2.3.3. Corrosion test

Specimens for electrochemical test were cut along the weld zone. Different zones (advancing, retreating and nugget) were exposed to the electrolyte in all the experiments. The remaining unaffected areas of the specimen were painted to protect it from the corrosion environment. Electrochemical experiments were performed using CHI660C electrochemical work station controlled through a personal computer. The setup of electrochemical experiment is shown in figure 5.

![Figure 5. Electrochemical cell and electrochemical work station](image)

Surfaces of the specimens were mechanically polished using silicon carbide sheets (grade starting from 100 to 1200, ANSI) and then they were rinsed in distilled water before being used for each electrochemical test.
experiment. Corrosion test was carried out in 3.5% of NaCl solution. The reference electrode employed in this experiment was Ag/AgCl electrode. All the potential data taken were referred to this Ag/AgCl reference electrode potential. The counter electrode used here was platinum wire loop and work piece was working electrode (Sato et al. 2011).

3. Results and Discussion

3.1. Tensile strength

The as welded and heat treated plates were subjected to tensile test as per ASTM-E8 standards and the tensile strength values of as-welded and heat treated samples are shown in figure 6. All the tests were replicated thrice and the average values were taken for comparison.

Figure 6. Tensile strength of as-welded and heat treated samples

The as-welded samples show an average tensile strength of 349 MPa which is 31% lower than the tensile strength of the unwelded parent metal. (Sabari et al. 2015). The heat treated samples show an average tensile strength of 363 MPa for STA-I and 366 MPa for STA-II which is lower than the tensile strength of the unwelded parent metal by 27% and 16% respectively (Chu et al. 2017). The results indicate that the welded samples heat treated with the low ageing period (8hrs) (A1,B1,C1 and D1) show improved tensile strength irrespective of the welding process parameters compared to the as-welded samples (Muruganandam et al. 2015). Whereas the samples heat treated with high ageing period (9hrs) show a decline in tensile strength for low tool rotation speed and show improved tensile strength for high tool rotation speed.

The decline in the tensile strength for heat treated samples welded with low tool rotation speed may be due to the high heat input during welding and the coarsening of precipitates. It is also evident that for the samples welded with high tool rotation speed along with high welding speed the tensile strength has declined.

3.2. Hardness

The hardness profiles of all the samples are shown in figure 7 (a)-(d). The hardness plots of as welded and heat treated samples are plotted together for samples welded with same process parameters to compare the effect of heat treatment on the hardness of samples.
Figure 7. Hardness profiles of as welded and heat treated samples

Figure 7. (a) shows the hardness profile of the samples A, A1 & A2. The heat treatment STA-I shows very marginal improvement on the hardness value, whereas heat treatment STA-II show higher improvement in the hardness of the samples. (Krishnan 2002). The hardness profiles of samples welded with the parameters (1000rpm, 30mm/min) are shown in figure 7(b). From the plot it is inferred that the samples aged for 9 hrs. has resulted in a drop in the hardness values compared to the ones aged for 8 hrs. (Hu et al. 2011). Comparing the two plots 7(a) and 7(b), for the same tool rotational speed (1000 rpm) the lower ageing time (8 hr.) shows a marginal improvement on the hardness profile at almost all regions of the weld compared to the as-welded specimens.

The hardness profiles of samples welded with a tool rotational speed of 1400 rpm are shown in figure 7(c) and (d) with weld speeds of 20 mm/min and 30 mm/min respectively. The hardness in the nugget region of these samples has increased considerably. The hardness of the welded samples has increased considerably irrespective of the aging period compared to the as welded samples. The samples with higher aging period show increased hardness than the samples with low aging period (Essa et al. 2016).

3.3. Corrosion rate

Electrochemical measurement methods can be used to determine corrosion rates of welded specimens. Polarization resistance is one of these methods, in which the specimens are polarized a few millivolts above and below the open-circuit potential and the current response is measured.

3.3.1. Open Circuit Potential

The open circuit potential (OCP) is the potential of the working electrode when no potential or current is being applied to the cell relative to the reference electrode. The figure 8. shows the open circuit potential plot for the sample B (1000rpm, 30mm/min, non-heat treated) in the nugget zone.

Figure 8. OCP plot for sample B (1000 rpm, 30mm/min)
The OCP fluctuates during the initial period of immersion and after a period it gets stabilized. It is evident from the plot that the open circuit potential gets stabilized around -0.58 V. In general the open circuit potential of the specimens range between -0.54v to -0.58v.

3.3.2. Polarization curve - TAFEL plot

The polarization plots are the curves drawn between the electrode current and the potential. The potential of the welded sample is scanned in set increments over a range as determined from the open circuit potential. All the samples are subjected to potentiodynamic polarization to obtain the Tafel plot and hence the corrosion rate.

Figure 9. Tafel Plot for as welded and heat treated samples

The figure 9(a) shows the Tafel plot of the samples A, A1 and A2. The plot indicates that the potential drop of all the specimens lies between -0.46V and -0.52V. The corrosion current of the sample A is 1.812 mA/cm$^2$, which is lesser than the remaining samples. The corrosion rate of the sample A is 1.546e+003 mils/year which is comparatively less than the sample A1 and sample A2.

The figure 9(b). shows the Tafel plot of the samples B, B1 and B2. The plot indicates that the potential drop of all the specimens lies between -0.38V and -0.50V. The corrosion current of the sample B2 is 2.298 mA/cm$^2$, which is lesser than the remaining samples. The corrosion rate of the sample B2 is 1.96e+003 mils/year which is comparatively less than the sample B and sample B1.

Tafel plot of the samples C, C1 and C2 are shown in figure 9(c). The plot indicates that the potential drop of all the specimens lies between -0.38V and -0.48V. The corrosion current of the sample C2 is 1.564 mA/cm$^2$, which is lesser than the remaining samples. The corrosion rate of the sample C2 is 1.334e+003 mils/year which is comparatively less than the sample C and sample C1.

The figure 9(d). shows the Tafel plot of the samples D, D1 and D2. The plot indicates that the potential drop of all the specimens lies between -0.44V and -0.50V. The corrosion current of the sample D2 is 4.614 mA/cm$^2$, which is lesser than the remaining samples. The corrosion rate of the sample D2 is 3.936e+003 mils/year which is comparatively less than the sample D and sample D1. It is observed that the post welded heat treated samples are more stable in the selected corrosion media (Oladele et al. 2017).
4. Conclusion

The Aluminum alloy AA2014-T6 was friction stir welded and subjected to heat treatment involving solution treatment and artificial ageing. The as welded and heat treated samples were tested for their mechanical and corrosion characteristics.

The tensile strength of the heat treated samples is higher when compared to the as welded samples for higher tool rotation speed. For samples with lower tool rotation speed the heat treatment method has a marginal negative effect on the tensile strength.

The hardness profile indicates that the increase in soaking time during ageing within limits has increased the hardness values of the samples irrespective of the process parameters.

The corrosion rate of the samples are analysed by conducting polarization test. The Tafel polarization plots are obtained using a three electrode electrochemical cell and an electrochemical analyser (potentiostat). The Tafel plots indicate that the samples subjected to ageing treatment have higher passivity than the as welded samples.

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References


List of Tables

**Table 1.** Chemical composition of AA2014-T6 plates.

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<tr>
<th>Element</th>
<th>Al</th>
<th>Cr</th>
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**Table 2.** Sample ID for different process parameters

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</tr>
<tr>
<td>1000</td>
<td>35</td>
<td>B</td>
</tr>
<tr>
<td>1400</td>
<td>20</td>
<td>C</td>
</tr>
<tr>
<td>1400</td>
<td>35</td>
<td>D</td>
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Figure 1. Friction stir welding Tool

21x14mm (300 x 300 DPI)
Figure 2. Friction stir welded sample

60x10mm (300 x 300 DPI)
Figure 3. Specifications of the tensile specimen

57x15mm (300 x 300 DPI)
Figure 4. Sample tensile test specimen

55x10mm (300 x 300 DPI)
Figure 5. Electrochemical cell and electrochemical work station

99x64mm (300 x 300 DPI)
Figure 6. Tensile strength of as-welded and heat treated samples

26x18mm (300 x 300 DPI)
Figure 7. Hardness profiles of as welded and heat treated samples

36x39mm (300 x 300 DPI)
Figure 8. OCP plot for sample B (1000 rpm, 30mm/min)

86x52mm (300 x 300 DPI)
Figure 9. Tafel Plot for as welded and heat treated samples

41x51mm (300 x 300 DPI)