Effect of welding speed on mechanical properties and corrosion resistance rates of filler induced friction stir welded AA6082 and AA5052 joints

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Abstract
Friction Stir Welding (FSW) was carried out to examine the influence of filler materials and varying process parameters on the microhardness and the joints corrosion resistance properties. Aluminium alloys 6082 and 5052, having 8 mm thickness was joined by varying parameters. The primary process parameters are rotational speed, tool travel speed, plunge depth, filler holes centre distance and filler ratio. The hardness at the weld nugget zone and corrosion rate evaluations were analyzed. The best results were obtained for the parameter combinations of 1150 rpm tool rotation, 130 mm min\(^{-1}\) tool travel, 0.2 mm tool plunge, the filler holes centre distance 2 mm and a powder filler made of 95% magnesium and 5% chromium.

1. Introduction

Friction stir welding (FSW) is a more suitable metal welding method for aluminium alloys than other fusion welding processes. The working temperature of the FSW is to plasticize the material and not to melt it. In this process, the presence of defects is reduced drastically and also improved mechanical properties as compared with conventional metal joining techniques. The corrosion characteristics of friction stir welded aluminium alloys; the weld zones were more vulnerable to corrosion than the parent metal [1]. The non-heat-treatable 5xxx series and heat-treatable 6xxx series are the most popular aluminium alloys used in corrosive environments. This series of alloy joints produces well-balanced strength, weldability and formability [2]. The 6xxx series aluminium alloys are stronger but exhibit high corrosion rate than the 5xxx series. The AA6082 is extensively used in ship hull frames due to its great joint strength. Due to the high corrosion resistance property of AA5052, it is widely used in corrosive environments like marine and manufacturing. While clubbing these two aluminium alloys, a product with high strength and corrosion resistance property can achieve, and these combinations have wide engineering applications from automobile to space [3].

The welding speed has a significant role in the FSW process. The stir zone is mainly affected by the high heat generation due to the lower welding speed. The high heat generation produces turbulence of the plasticized metal in the weld region, which enhance the weld nugget zone hardness. The results show that the initial increase in the temperature improves the weld’s mechanical properties and corrosion resistance properties [4–7]. A hexagonal pin profile produced the high heat metal stirring action and sound joint strength of the weld zone. The hexagonal pin profile in FSW of AA 6082–T6 influenced the corrosion resistance properties when the welding speed varies [8, 9]. The research aims to enhance the weld’s joint strength, nugget zone microhardness and improve corrosion resistance properties by changing welding speed. The filling powders are magnesium (Mg) and chromium (Cr), respectively.
2. Experimental arrangement

In this investigation, plates of AA6082 and AA5052 were selected, with 8 mm thickness. The milling process formed the required rectangular size of 75 mm width and 150 mm length. The chemical compositions of the aluminium alloys AA6082 and AA5052 (data from the materials certificate) are provided in table 1.

| Table 1. Aluminium alloys chemical compositions. |
|-----------------------------------------------|
| Alloys       | AA5052 | AA6082 |
| Si           | 0.049   | 1.0    |
| Cr           | 0.196   | 0.05   |
| Mg           | 2.629   | 0.82   |
| Mn           | 0.016   | 0.52   |
| Fe           | 0.186   | 0.27   |
| Cu           | 0.006   | 0.02   |
| Zn           | 0.009   | 0.1    |
| Ni           | 0.04    | —      |
| Ti           | 0.016   | 0.03   |
| Al           | Balance | Balance |

| Table 2. Aluminium alloys mechanical properties. |
|-----------------------------------------------|
| Alloys       | AA5052 | AA6082 |
| UTS (MPa)    | 217    | 330    |
| YS (MPa)     | 168    | 279    |
| Elongation (%) | 19.5  | 13     |
| Hardness (VHN) | 85    | 120    |
| Density (g/cm³) | 2680 | 2700   |
| Melting point (°C) | 607  | 555    |

Figure 1. (a) Hexagonal pin profiled tool geometry. (b) FSW tool schematic 3D view.
The mechanical properties of aluminium alloys given in the materials certificate are provided in table 2.

AA6082 alloy has good joint strength, and AA5052 has good corrosion behaviour in a critical environment. It is widely used in the automotive and marine industries [10].

Due to the higher wear resistance properties and longer tool life, tungsten carbide was adopted for FSW tool fabrication. A hexagonal profiled tool pin of 7.6 mm length and 8 mm diameter, with a flat shoulder of 20 mm diameter, was selected, and it is given in figure 1. A vertical milling machine with a maximum rpm of 1800, with a capacity of 7.5 HP, is used to conduct this experiment [11]. The experimental arrangement for this friction stir welding is given in figure 2.

The chromium (Cr) powder and magnesium (Mg) powder were selected as the filling agents to join the different alloy plates of AA5052 and AA6082. The Mg promotes the mechanical properties of the weld joint. The Cr improves corrosion resistance property as well as the microhardness. The weight percentage ratio of Mg and Cr fillers was obtained by volume fractions of the weld zone based on elemental composition. Besides the plate edges to be welded, the volume composition of the joining area is calculated [12]. From the chemical composition of the parent metal, the weight percentage of the powder-mixing ratio is gained. The volume of the
weld zone is calculated from the weld dimensions and then transformed to weight. The average weight percentage of the fillers at the weld stir zone was also calculated. The weight percentage ratio was gained from the weight percentage average of Cr and Mg material in the weld stir zone.

A hole with 2 mm diameter and 3 mm depth was made all along the plate’s butting area along the centerline, and then it filled with powder material having 95% Mg and 5% Cr. The centre distance between two drilled holes was maintained at 4 mm along the plate’s butting surface. The AA6082 and AA5052 plates were placed butting against each other, as shown in figure 3. AA5052 and AA6082 plates were placed in a fixture on the advancing side and retreating side, respectively. The drilled holes were arranged in a criss-cross position to get a 2 mm centre distance between the adjacent holes [13]. The weld nugget region’s microhardness was measured using Vickers’s microhardness testing machine with a 0.05 kg load at 15 s. The specimens for microhardness inspection were sectioned to the required sizes from the joint friction stir zone (FSZ), thermomechanical affected zone (TMAZ), heat affected zone (HAZ) and base metal (BM) regions. The surfaces were polished using different grades (300, 500, 800 and 1200) of SiC emery papers.

For each sample, the tensile testing specimens are machined out as per ASTM E8M-04 standard. The experiment was conducted on FSA made M100 model universal testing machine at 100 kN load [14].

The corrosion samples were prepared in the dimensions of 10 mm × 10 mm × 8 mm. The pieces were polished on the exposure surface using different grit size of SiC paper (400, 600, 800, 1000, 1200, and 1500), as shown in figure 4. The polished surface is washed with distilled water and dried with hot air.

The corrosion rates of the welded dissimilar aluminium alloys (AA 6082 and AA 5052) were evaluated by using the weight loss method. The initial weight of the sample was measured. The sample surfaces were wound with Teflon tape except for the exposure surface. The samples were immersed in a solution of 3.5% of NaCl for 24 h (ASTM G31), as shown in figure 5.
3. Results and discussions

A maximum microhardness of 93 HV was obtained by rotational tool speed of 1150 rpm, welding speed 130 mm min$^{-1}$, plunge depth 0.2 mm, centre distance between the holes 2 mm and powder mixing ratio (95% of Mg and 5% of Cr) [15]. For the below stated three different parameters combinations, the friction stir welding process was executed. The welding speed was 100 mm min$^{-1}$, 130 mm min$^{-1}$ and 160 mm min$^{-1}$. The remaining process parameters were tool rotational speed 1150 rpm, plunge depth 0.2 mm, the centre distance between the filler holes 2 mm and the powder-mixing ratio of 95% Mg and 5% Cr. The constant process parameters were selected by reviewing the literature regarding aluminium alloys 6082 and 5052 FSW process parameters [16].

In this literature [17], the same aluminium alloys butt-joint configuration was joined without using fillers, and the results show that the tensile strength gained was 149 MPa and microhardness gained was 78 HV. These results clearly indicate that fillers have a paramount influence on the mechanical properties of FSW joints.

3.1. Influence of welding speed on the tensile strength

Tensile tests for the friction stir welded specimens are carried out as per ASTM E8M-04 standard. The tensile strength (MPa) obtained for the specimens are given in table 3. The images of the test specimens after conducting the experiments are shown in figure 6.

The tensile strength given in table 3 shows that sample A achieves a tensile strength of 153 MPa, which is less than the other two specimens; This reveals that the frictional heat generated by the tool at 100 mm min$^{-1}$ welding speed produces high heat, this excess heat makes the parent metals too plastic, and the Mg and Cr

| Specimens | Tensile Strength (MPa) |
|-----------|------------------------|
| Sample A  | 153                    |
| Sample B  | 177                    |
| Sample C  | 147                    |

Figure 6. Tensile specimens after testing.
powder will be dragged out slightly. Due to this improper mixing and the heat-affected zone generated by the excess heat reduced the strength of Sample A. The sample B produced at 130 mm min\(^{-1}\) welding speed gained a tensile strength of 177 MPa. The microstructure examination of this specimen shows that the fillers are mixed well in the stir zone, and a refined grain structure is achieved; This indicates that the welding speed is sufficient to produce a better joint [18]. While examining sample C, the strength gained was comparatively less than the other two samples. The heat generated by the welding speed of 160 mm min\(^{-1}\) is not sufficient to plasticize the metals and the fillers, and the higher welding speed drags the fillers and produces tunnel defects, which eventually reduces the strength of the joint.

### 3.2. Influence of welding speed on the microhardness

This investigation was carried out at three different levels of welding speed, and its responses were observed. There are three samples taken for the analysis of microhardness. The samples process parameters and microhardness values were given in Table 4. The experiments were conducted on Mitutoyo Micro Vickers hardness testing machines HV-110 system with a test forces range from 0.3–30 kg.

The microhardness values were measured in the butting surface plate of the weld region and plotted in the graph shown in figure 7.

The microstructure is one of the most influencing factors that affect the alloy’s physical properties, and the microstructure evaluation reveals the properties of the material. This evaluation helps to predict the defect of a component in certain conditions [19, 20]. The microstructure is a microscopic scale structure of a material. It is defined as the prepared surface of material revealed by an optical microscope above 25× magnification. The microstructure is also characterized by the arrangement and number of certain lattice defects. The material property of microhardness is mainly dependent on the microstructure. FSW process parameters significantly

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**Table 4. Effect of fillers with process parameters on microhardness.**

| Specimens | Process parameters | Response (Microharness in HV) |
|-----------|--------------------|-------------------------------|
| Sample A  | Rotational speed—1150 rpm Tool travel speed—100 mm min\(^{-1}\) Plunge depth—0.2 mm Filler holes centre distance—2 mm Filler ratio—95:05% | 76 |
| Sample B  | Rotational speed—1150 rpm Tool travel speed—130 mm min\(^{-1}\) Plunge depth—0.2 mm Filler holes centre distance—2 mm Filler ratio—95:05% | 93 |
| Sample C  | Rotational speed—1150 rpm Tool travel speed—160 mm min\(^{-1}\) Plunge depth—0.2 mm Filler holes centre distance—2 mm Filler ratio—95:05% | 81 |

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![Figure 7.](image-url)
affected the dissolution of strengthening particles, material mixing, and defects [21]. Samples microstructure of AA6082 and AA5052 joints shown in figure 8. The filler materials were uniformly mixed with base materials revealed in sample B compared with sample A, and sample C is shown in figure 8(b). However, the welding speed increases with a minimal rise in the grain size. The Scanning Electron Microscopy (SEM) revealed that decreasing the welding speed increases the frictional heat in the stir zone leads to plasticization of the metal and fillers in the nugget zone, leading to the decrease in the grain size and the size of the second phase particles. The weight percentage of alloying elements are represented in the Energy Dispersive X-ray Spectroscopy (EDS) graph.

Figure 8. Microstructure of AA6082 and AA5052 joints.
Sample A is the lowest Microhardness of 76 HV due to the lower welding speed of 100 mm min\(^{-1}\). High heat input is generated due to the lower welding speed [22]. This formation gives the lower hardness of the weld zone. Figure 9 shows the FESEM image and EDS results of Sample A. In this, the result provides a low hardness of the weld region. The weight percentage of Mg is nearly 1.62, and Cr is around 0.35. The reduced amount of Mg and inadequate filler mixing in the joining area does not improve the joint’s microhardness.

Sample B is enhanced the higher weld hardness of 93 HV. The figure 10 FESM image shows that the filler materials are homogeneously distributed with base metal in the weld region. The homogeneous distribution of filler materials has gained the weld zone’s hardness due to 130 mm min\(^{-1}\) tool travel speed. The EDS results represented that the weight percentage of Mg is 3.34 and Cr is 0.48. The rich amount of magnesium and uniform distribution of filler in the weld zone improves the weld hardness [23].

The weld hardness of sample C is higher than sample A and lower than sample B. The increase of welding speed increases the weld nugget hardness to a threshold value of 93 HV and then gradually decrease the weld hardness. In the stir zone, the powder mixture does not mix well. The cluster of filler materials precipitate is formed in the retreating side; this was happening because the retreating side is the area that opposes the tools transverse movement, which is shown in figure 11. The weight percentage of Mg is 3.18, and Cr is 0.46, represented in the EDS graph [24]. The improper mixing of filler and the weld defect decreases the weld hardness gradually.

### 3.3. Influence of fillers on corrosion properties

The corrosion particles were removed by using 50 g of chromium trioxide (CrO\(_3\)), 2.5 g of silver nitrate (AgNO\(_3\)), and 5 g of barium nitrate (Ba(NO\(_3\))\(_2\)) for 250 ml distilled water. Finally, the moisture content of the specimens was removed with hot air. The sample’s net weight loss was calculated by using this formula [25].

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\text{Corrosion rate (CR)} = \frac{(87.6 \times W)}{(A \times D \times T)} \\
\text{Where, CR = Corrosion rate in mm/year,} \\
W = \text{Weight loss in mg,} \\
A = \text{Exposed area (1 cm}^2\text{),} \\
D = \text{Density of the material (2.61 g cm}^{-3}\text{),} \\
T = \text{Exposure time (24 h).}
\]
The sample corrosion rate values were presented in table 5. Thus, results were plotted in figure 12. The samples of corrosion surface morphology are shown in figure 13. The corrosion rate of sample A has higher than sample B and sample C. The fillers with base metals are poorly plasticized due to the lower welding speed. The wormhole was produced due to the excess heat generation and metal transportation of base metals \[26\]. Sample B has obtained the lowest corrosion rate of the weld. The base metals with filler materials were well mixed at the process parameter conditions. The weight percentage of chromium in sample B is the higher value 0.48 than another sample A, sample C. Sample C has a lesser corrosion rate than sample A and more significant than sample B. The filler materials were poorly plasticized with base metal and associated with defect \[27\]. This phenomenon has affected the weld surface’s corrosion resistance properties.

4. Conclusions

The microhardness and corrosion rate of the dissimilar AA6082, AA5052 joints were investigated.

- Sample B achieved a better tensile strength of 177 MPa, an enhanced microhardness of 93 HV and a low corrosion rate of 0.814 mm/year.
- The higher microhardness and lower corrosion rate were obtained by rotational tool speed of 1150 rpm, tool travel speed 130 mm min\(^{-1}\), plunge depth 0.2 mm, the centre distance between the filler holes 2 mm filler-mixing ratio 95% of magnesium and 5% of chromium.
- The corrosion rate remarkably decreased up to 130 mm min\(^{-1}\) and then increased by increasing welding speed.
- A better corrosion rate was achieved due to the proper frictional heat generated by the tool due to sufficient welding speed and adequate fillers in the nugget zone.
Figure 11. FESEM image and EDS results of Sample—C.

Figure 12. Corrosion rate of specimen.

Table 5. Corrosion rate values.

| Sample | Corrosion rate (mm/y) |
|--------|-----------------------|
| Sample-A | 5.563                |
| Sample-B | 0.814                |
| Sample-C | 3.934                |
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Hosni E, El-Houd A and El-Shawesh F 2008 A study on the corrosion behaviour of aluminium alloys in seawater Mater. Des. 29 801–5
[2] Paglia C S and Buchheit R G 2008 A look in the corrosion of aluminium alloy friction stir welds ScriptaMaterials 58 383–7
[3] Mohan D G and S, G. 2021 Influence of In-situ induction heated friction stir welding on tensile, microhardness, corrosion resistance and microstructural properties of martensitic steel Engineering Research Express 3 025023
[4] S Gopi and K Manonmani 2012 Study of friction stir welding parameters in conventional milling machine for 6082-T6 aluminium alloy Australian Journal of Mechanical Engineering 10 129–40
[5] Prabhukhot A R 2015 Effect of heat treatment on hardness and corrosion behavior of 6082-T6 aluminium alloy in artificial sea water International Journal of Materials Science and Engineering 3 287–94
[6] Gopi S and Mohan D G 2021 Evaluating the welding pulses of various tool profiles in single-pass friction stir welding of 6082-T6 aluminium alloy Journal of Welding and Joining, The Korean Welding and Joining Society 6 8

Figure 13. The macrostructure of AA6082 and AA5052 joints.
[7] Shaha P H and Badhekab V 2016 An experimental investigation of temperature distribution and joint properties of Al 7075 T651 friction stir welded aluminium alloys Procedia Technology 23 543–50
[8] Anil Kumar H M, Venkata Ramana V and Pawar M 2018 Experimental Study on Dissimilar Friction Stir welding of Aluminium Alloys (5083-H111 and 6082-T6) to investigate the mechanical properties Materials Science and Engineering 330
[9] Patil H S and Soman S N 2014 Corrosion behaviour of friction stir welded aluminium alloys AA6082-T6 American Journal of Materials Engineering and Technology 2 29–33
[10] Sakthivel T, Sengar G S and Mukhopadhyay J 2009 Effect of welding speed on microstructure and mechanical properties of friction-stir-welded aluminium Int. J. Adv. Manuf. Technol. 43 668–73
[11] Zhang Z, Liu Y and Chen J T 2009 Effect of shoulder size on the temperature rise and the material deformation in friction stir welding Int. J. Adv. Manuf. Technol. 45 899–95
[12] Choa, b H, Kima W and Leea C G 2014 Evolution of microstructure and mechanical properties during friction stir welding of A5083 and A6082 Procedia Engineering 81 2080–5
[13] Mohan D G and Gopi S 2018 Induction assisted friction stir welding: a review Australian Journal of Mechanical Engineering 18 119–23
[14] Silva-Maglaeas A et al 2019 In-situ temperature measurement in friction stir welding of thick section aluminium alloys J. Manuf. Processes 39 12–7
[15] Hwang Y M et al 2008 Experimental study on temperature distributions within the workpiece during friction stir welding of aluminum alloys Int. J. Mach. Tool Manuf 48 778–87
[16] Mohan D G, Gopi S and Sasikumar A 2021 Examining the mechanical and metallurgical properties of single pass friction stir welded dissimilar aluminium alloys tee Joints SVOA Materials Science & Technology 3 6–12
[17] Rajakumar S, Muralidharan C and Balasubramanian V 2011 Predicting tensile strength, hardness and corrosion rate of friction stir welded AA6061-T6 aluminium alloy joints Mater. Des. 32 2878–90
[18] Sasikumar A, Gopi S and Mohan D G 2019 Effect of magnesium and chromium fillers on the microstructure and tensile strength of friction stir welded dissimilar aluminium alloys Mater. Res. Express 6
[19] Mohan D G, Gopi S and Rajasekar V 2018 Mechanical and corrosion resistance properties of hybrid-welded stainless steel Mater. Performance 57
[20] Hatanlele O, Singh P M and Garmestani H 2009 Corrosion susceptibility of peened friction stir welded 7075 aluminium alloy joints Corros. Sci. 51 135–43
[21] Mohan D G, Gopi S and Rajasekar V 2018 Effect of induction heated friction stir welding on corrosive behaviour, mechanical properties and microstructure of AISI 410 stainless steel Indian J. Eng. Mater. Sci. 25 203–8
[22] Avinash Ravi Raja S K G, Vashista M and Yusufzai M Z K 2019 Material characterization of friction stir welded IS-2062 steel plate by hysteresis loop analysis Mater. Res. Express 6 11608
[23] Mohan D G and Gopi S 2017 Study on the mechanical behaviour of friction stir welded aluminium alloys 6061 with 5052 2017 8th Industrial Automation and Electromechanical Engineering Conf., IEMECON 2017 147–52
[24] Surekh K, Murty B S and Prasad Rao K 2009 Effect of processing parameters on the corrosion behaviour of friction stir processed AA 2219 aluminum alloy Solid State Sci. 11 997–17
[25] Xue P, Zhang X, Wu L and Ma Z 2016 Research progress on friction stir welding and processing, Jinshu Xuebao/ Acta Metall. Sinica 52 1222–38
[26] Gerlich A et al 2008 Material flow and intermixing during dissimilar friction stir welding Sci. Technol. Weld. Joining 13 254–64
[27] Mohan D G and Gopi S 2016 A review on friction stir welded T-Joint IJSTE - International Journal of Science Technology & Engineering 2 40–5