PAPER

Influence of tool pin profiles in the strength enhancement of friction stir welded AA5083 and AA5754 alloys

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Abstract

Friction stir welding (FSW) is a well-known technology for joining similar and dissimilar materials. The quality of the weld in FSW is affected by the various process parameters such as tool rotational speed (TRS), tool transverse speed (TTS) and tool pin profiles. This study aims to investigate the effect of three different tool pin profiles on the variation of microstructure and mechanical strength of friction stir welded AA5083 and AA5754 alloys joints. Both of these alloys combinations offer excellent corrosion resistance and formability. As a result, they’re commonly seen in tanks, pressure vessels, shipyards, and trucks. In this work, the FSW methodology focused on varying the TRS of 750, 1000, 1250 and 1500 rpm and TTS as 20, 30, 40 and 50 mm min⁻¹. The surface microstructures of the weldments were analyzed using an optical microscope and scanning electron microscope. Tensile and Microhardness tests were carried out on the weldments to determine the weld strength. Three variety of tool pins, namely straight square, threaded cylinder, and straight cylinder were used for this study. The microstructural and the mechanical properties analysis of the welded samples proved that the straight square tool pin profile is suitable for joining AA5083 and AA5754 alloys. The weldments prepared using a straight square pin profile exhibited good material stream behaviour, uniform spreading of plastic deformation in the weld zone and aided in the reduction of formation of macroscopic defects on the welded zone. Among the process parameters, it was detected that the pin profile displays more impact on tensile strength followed by tool rotation speed and welding speed. According to the findings, the dissimilar weld joint formed at the optimum process parameters had the highest tensile strength of 212 MPa and hardness of 88 HV were: Square Tool Profile, 1250 rpm TRS, and 40 mm min⁻¹ TTS.

1. Introduction

The aluminum alloys AA5083 and AA5754 are very widely used for marine applications, usually in the manufacturing of ship hull. Aluminum can provide the same strength given to steel by about one-third of the weight of steel. There are few other applications of these alloys are in aircraft, car parts and cryogenic tanks (Rastkerdar et al 2011). Both the basic components of AA5083 and AA5754 are used in the study are non-therapeutic alloys with a high magnesium content. The foremost properties of AA5083 and AA5754 alloys are their high ductility and specific strength, good weldability, and formability (Vaishnavan and Jayakumar 2021). The AA5083-H111 and AA5754- H111 could be welded by the application of both fusion welding and FSW methods. There are many types of welding flaws that may occur by traditional welding processes of these two alloys. However, the main issues with conventional welding are related to the solidification process and structure, such as alloying element loss, shrinkage, segregation and porosities, blowholes, and crack development in the weld joint. These issues may be resolved by using the fusion welding process called Friction stir welding (FSW), which provides an alternative via solid-state bonding with high joint...
The materials considered for the present study during FSW are 5 mm thick plates of AA5083 and AA5754. The strength of the FSW joints is mainly based on the heat input. The heat input is controlled by the tool pin parameters like shoulder to pin diameter ratio, tool pin profile (TPP), and welding parameters like tool rotational speed (TRS), welding speed/tool traverse speed (TTS), axial force etc. (Goyal and Garg 2019). Investigations on the influence of TPP that is made of different tool and shoulder geometries were tried and reported that the TPP has a major influence on the microstructure and weld strength (Mohanty et al 2012).

The effect of welding speed was investigated and the UTS of the welded joint found rises with welding speed and then further decreases beyond 160 mm min⁻¹ (Pramod et al 2020). In the discussion of the effect of various tool geometry, the square pin at 1200 rpm and 80 mm min⁻¹ feed exhibits a great potential to yield high strength weld (Joshi et al 2020). FSW was conducted on the Aerospace alloy of AA2019 using conical and triangular TPP and it was concluded that the triangular pin exhibited good mechanical and microstructural properties (Venkata Rao et al 2015). Examinations on the influence of TPP on Al alloys were done and have found out that the square TPP induced proper material mixing (Jamshidi 2015). The effect of tool pin eccentricity was studied using a cylindrical tool pin profile and has concluded that the eccentric TPP produces less heat than the non-eccentric TPP (Essa et al 2016). The influence of tool dimensions on the weld quality was studied and found that escalating the size of the pin reduces the mechanical and metallurgical properties of the weldments (Lambiase et al 2016).

It can be seen from the above literature that the tool pin profile shows a crucial role in the strength of the weldments. Many researchers have tried to join different aluminum alloys using FSW, whereas only a few research papers can be found on the tool pin optimization for FSW of 5xxx aluminum alloys. Hence welding of 5xxx aluminum alloys is important. In this research work, an effort is made to find out a proper tool pin profile that can produce better strength FSW joints of AA5083 and AA5754 alloys. The metallurgical and the mechanical strength of the weldments were analyzed in detail.

### 2. Experimental procedure

The materials considered for the present study during FSW are 5 mm thick plates of AA5083 and AA5754. The base materials were cut into the size of 150 × 55 mm. The chemical composition of the parent materials as stated in table 1. Table 2 lists the tensile and hardness values of the base materials (BM). The AA5083-H111 alloy is always placed on the advancing side (AS). The welding was carried out at the different TRS and TTS. The FSW was carried out using an automatic friction stir welding machine and the fixture that holds the workpiece is shown in figure 1. The FSW machine has a maximum spindle speed of 3000 rpm, maximum power of 30 hp and maximum axial force of 25 kN.

After FSW, the standard size tensile samples as per ASTM-E8 standards were excavated along the crosswise direction of the weldments using the wire electric discharge machining (WEDM). Tensile tests were conducted using a universal testing machine (UTM) (Bluestar make, model LDW 50) to find out the ultimate tensile strength (UTS), yield strength (YS) and percentage elongation (%El) of the weldments. The microstructural samples were also extracted along the crosswise direction of the weldments using the WEDM. The extracted samples were polished then etched using keller’s reagent for revealing the microstructure. The surface microstructures were analyzed using an optical microscope (OM) and scanning electron microscope (SEM) to

| Table 1. Parent Material - Chemical composition (wt%).
| BM | Mg | Mn | Fe | Si | Cu | Cr | Zn | Ti | Al |
|----|----|----|----|----|----|----|----|----|----|
| AA5083 | 4.25 | 0.53 | 0.26 | 0.98 | 0.35 | 0.11 | 0.1 | 0.02 | 93.3 |
| AA5754 | 3.6 | 0.5 | 0.4 | 0.4 | 0.1 | 0.3 | 0.2 | 0.15 | 94.4 |

| Table 2. Parent Material - Mechanical properties.
| BM | HV | UTS (MPa) | YS (MPa) | Elongation (%) |
|----|----|-----------|-----------|---------------|
| AA5083 | 84 | 321.3 | 197.4 | 22.3 |
| AA5754 | 76 | 224.67 | 95 | 33.7 |
study the grain boundaries, size, and orientations. The hardness measurements was done on the transverse direction of the weldments using Vickers microhardness tester (ESEWY make, model EW – 423DAP) as per ASTM E384 standards. The hardness examination was done at an equiaxed distance of 0.5 mm by applying a 1kg load for 30 s dwell time.

2.1. Methodology
The detailed methodology used in the present investigation is shown in figure 2. The effect of three different pin profiles, TRS and TTS during the FSW of the selected dissimilar aluminium alloys joints was analysed in terms of mechanical and metallurgical properties.

Figure 1. Close view of FSW.

Figure 2. Scheme of Research work.
2.2. FSW Tool dimensions
The FSW tool was manufactured using D2 tool steel that has a hardness of 65 HV1. Three TPP, namely, straight square (SS), threaded cylinder (THC) and tapered cylinder (TAC) were fabricated. The images of the tools used for the study are shown in figure 3. All the tool pins are made using the constant shoulder diameter of 15 mm and a pin diameter of 5 mm. The shoulders used in the study are flat in shape. The pin length is kept as 4.7 mm for all tools.

2.3. FSW Process parameters
In trial-and-error mode, most tests were performed with a different set of selected parameters, namely welding speed, tool rotation speed and pin profiles of tools. The test suggestion proceeded in the following order: the first column is assigned to the tool pin profile, the second column is the rotation speed of the tool, and the third column is the welding speed. The experiments were performed according to the selected orthogonal scheme for each combination of FSW parameters and are shown in table 3. For each pin profile, 16 experiments were conducted by varying TRS and TTS. Therefore, a total of 48 trials were performed for the selected three FSW pin profiles to cover the maximum possible number of combinations of experiments and are listed in table 4.

3. Results and discussion
The metallurgical and mechanical characterizations of the weldments were analyzed. The surface microstructural characterizations on the welded samples were studied using OM and SEM. The mechanical characterizations on the welded samples are studied using tensile tests and a microhardness survey. The fractured surface of the tensile samples was analysed using SEM to know about the type of fracture.

3.1. Tensile properties
Tensile studies were done on FSWed samples to find out the UTS, YS and %El. The dimension of a typical tensile sample (L = 100 mm, W = 10 mm, and t = 5 mm with a gauge length of 25 mm) is shown in figure 4. Three samples were evaluated on every weldment and the average values were taken for the study.
3.1.1. Influence of various tool pin profiles on the UTS of joints at various tool rotational speed

In general, very high rotational speed affects the recrystallization process through the strain rate, which in turn, interrupts the joining process (Cabibbo et al 2007). The heat is generated by the friction sandwiched between the FSW tool and workpiece surfaces and gets extensive according to the rotational speed. At higher TRS, this heat generated would be more, which also leads to a slow cooling rate after welding. At the lower TRS, the heat contribution to the workpiece material would be low, resulting from a lack of stirring and this decreases temperature distribution across the weld zone (Ahmed et al 2021). Hence, the TRS is a significant parameter that impacts the joint properties.

### Table 4. FSW experiments and results.

| Exp. No. | TRS (rpm) | TTS (mm min⁻¹) | TPP   | UTS (MPa) |
|----------|-----------|----------------|-------|-----------|
| 1        | 750       | 20 Straight    |       | 180       |
| 2        | 1000      | 20 Square      |       | 188       |
| 3        | 1250      | 20             |       | 195       |
| 4        | 1500      | 20             |       | 183       |
| 5        | 750       | 30             |       | 190       |
| 6        | 1000      | 30             |       | 192       |
| 7        | 1250      | 30             |       | 202       |
| 8        | 1500      | 30             |       | 195       |
| 9        | 750       | 40             |       | 192       |
| 10       | 1000      | 40             |       | 200       |
| 11       | 1250      | 40             |       | 212       |
| 12       | 1500      | 40             |       | 203       |
| 13       | 750       | 50             |       | 189       |
| 14       | 1000      | 50             |       | 199       |
| 15       | 1250      | 50             |       | 204       |
| 16       | 1500      | 50             |       | 198       |
| 17       | 750       | 20             |       | 165       |
| 18       | 1000      | 20             |       | 173       |
| 19       | 1250      | 20             |       | 181       |
| 20       | 1500      | 20             |       | 174       |
| 21       | 750       | 30             |       | 177       |
| 22       | 1000      | 30             |       | 184       |
| 23       | 1250      | 30             |       | 192       |
| 24       | 1500      | 30 Threaded    |       | 186       |
| 25       | 750       | 40             |       | 180       |
| 26       | 1000      | 40             |       | 188       |
| 27       | 1250      | 40             |       | 194       |
| 28       | 1500      | 40             |       | 191       |
| 29       | 750       | 50             |       | 176       |
| 30       | 1000      | 50             |       | 185       |
| 31       | 1250      | 50             |       | 190       |
| 32       | 1500      | 50             |       | 187       |
| 33       | 750       | 20             |       | 162       |
| 34       | 1000      | 20             |       | 171       |
| 35       | 1250      | 20             |       | 177       |
| 36       | 1500      | 20             |       | 170       |
| 37       | 750       | 30             |       | 173       |
| 38       | 1000      | 30             |       | 180       |
| 39       | 1250      | 30             |       | 184       |
| 40       | 1500      | 30             |       | 179       |
| 41       | 750       | 40             |       | 177       |
| 42       | 1000      | 40 Tapered     |       | 181       |
| 43       | 1250      | 40             |       | 186       |
| 44       | 1500      | 40             |       | 180       |
| 45       | 750       | 50             |       | 174       |
| 46       | 1000      | 50             |       | 180       |
| 47       | 1250      | 50             |       | 182       |
| 48       | 1500      | 50             |       | 177       |
The effect of various tool pin profiles on the UTS of welded joints at diverse TRSs is represented in figure 5. At a tool rotating speed of 1500 rpm, all the tools indicated a loss in weld strength, which is attributable to a considerable quantity of heat created by friction and the release of undesirable stirred material at the top surface. Additionally, the slower cooling rates resulted in the formation of voids in the stir zone, which contributes to a reduction in weld strength. The friction and heat input are reduced at a low tool rotational speed of 750 rpm, resulting in incorrect material dispersion and lack of stirring at the weld zone. The SS pin yielded good tensile property than the THC and TAC tool pins. This shows that the pulsating action caused by the flat surfaces of the SS profile during the welding process enhances the tensile property of the weldments (Balamurugan et al 2021 and Biplab Ghosh et al 2022). The sides of the SS tool cause the base materials to flow in batches when the tool traverses the joining face, whereas threaded and tapered tool profiles do not cause pulsating action because of the absence of flat surfaces. Hence the straight square tool yields high weld strength (Elangovan and Balasubramanian 2008). From the graph shown in figure 5, it was found that the maximum UTS value was observed as 212 MPa for the combination of TPP as square, TRS as 1250 rpm and TTS as 40 mm min⁻¹.

Figure 4. Extraction of typical tensile sample from the welded specimen.

Figure 5. Variation of TRS against Tool pin profiles at different welding speeds.
The following polynomial equation has arrived for the relation between variation of UTS with TRS for the SS pin with welding speed or TTS of 20 mm min$^{-1}$ from the graph shown in figure 5. The coefficient of determination ($R^2$) value is closer to 0.9, which shows the closeness of the mathematical prediction model with experimental results. The same procedure can be used for modelling the remaining graphs.

$$Y = -5x^2 + 26.6x + 157.5, \quad R^2 = 0.8744$$

3.1.2. Influence of various tool pin profiles on the UTS of joints at various tool transverse speed

The effect of various tool pin profiles on the UTS of welded joints at different tool transverse speeds or welding speeds is shown in figure 6. The welding speed or tool transverse speed is the amount at which the tool moves along a definite path. Generally, the weld strength of any FSW joint differs on the ratio of the TRS to the welding speed of the joints. The UTS value is directly dependent on this ratio, and it also increases with the increase in the ratio of the rotational speed to welding speed (Palanivel et al 2012). In this ratio, a greater rotating speed combined with lower welding rates provides a large amount of frictional heat, whereas a lower rotational speed combined with higher welding speeds produces a lesser amount of heat input to the workpiece material during the FSW process.

In general, the tool rotating at a higher welding speed leads to insufficient heat generation and a lack of material stirring. Similarly, the tool rotating at a lower welding speed leads to low plastic deformation with the formation of a cavity in the welded joints. Pins with flat surface exhibits eccentric effects because of their variations in static and dynamic volumes of TPP. The eccentricity ratio of the straight square TPP during FSW is 1:1.6 (Ghangas and Singhal 2018). The result proves that the pulsating effect and the eccentricity effect of the square tool pin mix the materials more effectively than the threaded and tapered cylinder tool pins. A similar type of results was obtained on FSW of Al metal matrix composites for Vijay and Murugan (2010). From the graph shown in figure 5, it was observed the maximum UTS of 212 MPa was obtained for the same TPP, TRS and TTS.

3.1.3. Microstructure analysis using an optical microscope

The surface microstructure images of FSWed AA5083-H111 and AA5754-H111 using different TPP are shown in figure 7 at 100X magnification. Figures 7(a) and (b) show the OM images of BM AA5083 and AA5754, respectively. The OM images of the weld nugget welded with SS, TAC and THC were shown in figures 7(c)–(e), respectively. Since both the base metals that are used in this study are non-heat-treatable aluminium alloys, the material gains its strength primarily through solid solution strengthening. The 5xxx series aluminium alloys primarily attain their strength by substitutional solid solutions that are formed by Mg atoms replacing the Al.
atoms. The FSWed samples are divided into four main zones they are, base metal zone (BMZ), thermomechanically affected zone (TMAZ), weld nugget zone (WNZ) and heat affected zone (HAZ). The grains in the WNZ are very fine and recrystallized owed to the intense stirring done by the tool pin (Kumar and Vasu Kailas 2008). The reduction in grain size increases the tensile and hardness values at the WNZ as per Hall-Petch relation.

From figure 7(c), it was found that the SS tool pin has done proper mixing of both the base materials, whereas the threaded and tapered tool pins have not done proper stirring of materials and the base metals can be seen in two separate layers (figures 7(d) and (e)). This would result in low tensile strength on the samples welded with TAC and THC tool pins. Since the stirring of materials is not proper for samples welded with TAC and THC tool pins, the WNZ becomes weaker, and the failure occurs at the WNZ.

3.1.4. Microstructure analysis using SEM
The surface microstructure of the weldments at 1000X magnification in studied using SEM and is shown in figure 8. Figures 8(a) and (b) show the images of AA5083-H111 and AA5754-H111 base metal zones, respectively. Figure 8(c) shows the image taken at the WNZ of the sample welded using straight square TPP.

The SEM images of the base metals show many round precipitates which are spread throughout the materials. The strengthening precipitates which are present in the base metals are Al\textsubscript{3}Mg\textsubscript{2}, Al\textsubscript{6}(Fe, Mn), and Mg\textsubscript{2}Si. The strengthening precipitates are seen spread all over the material. It can be seen in figure 6(c) that the straight square pin has done proper mixing of both the base materials in the WNZ. In addition, the occurrence of dynamic recrystallization at the weld nugget zone contributes to the increase in strength. Due to the dynamic recrystallization, grain refinement occurs, and the size of the recrystallized grains is depended on the strain rate and peak friction stir welding temperature (Azimzadegan and Serajzadeh 2010). The proper mixing of materials and recrystallization at the weld nugget zone are escalated by the straight square TPP, which results in high strength weldments.
3.1.5. Fractography

The fractographic images were taken from the SEM and is shown in figure 9. The fractography images of the base metals AA5083 and AA5754 are shown in figures 9(a) and (b), respectively. The fractography image of the sample welded using straight square TPP is given in figure 9(c).

In figures 9(a) and (b), many dimples with various sizes are seen and this shows that the base metals AA5083-H111 and AA5754-H111 have good ductile properties. The figure 9(c) shows the fractography image of the sample welded with SS tool pin and it also has a lot of dimples on the fractured surface. The greater number of dimples on the fractured surface at WNZ denote that the mode of failure is ductile, and the plasticity of the material is higher (Hao et al 2013, Ahmed et al 2021). This shows that the straight square pin does not affect the ductility of the base materials.

Figure 8. SEM images (a) AA5083 BM (b) AA5754 BM (c) WNZ of SS TPP.

Figure 9. Fractography images (a) AA5083 BM (b) AA5754 BM (c) WNZ of SS TPP.
3.1.6. Hardness

Figure 10 shows the hardness survey of three samples are taken from each TPP which has high UTS values (UTS for SS-212 MPa, TAC-194 MPa and TC-186 MPa). The hardness survey was evaluated along the transverse direction of the welded samples. The weldments were tested in the Vickers microhardness tester with a diamond indenter. It is evident from figure 10 the value of hardness ranges between 75 to 85 HV on the AA5083-H111 and it varies between 65 to 75 HV on the AA5754-H111. The highest hardness value is identified at the WNZ, and the lowest value of hardness was identified at the HAZ/TMAZ of AA5754-H111 for all the samples.

The reduction in the size of the grain because of dynamic recrystallization at the WNZ is the reason for its high value of hardness (Esmailzadeh et al 2013). The lowest hardness value was identified at the HAZ of AA5754 as the result of grain growth and dissolution of strengthening precipitates caused mainly because of the high heat during the FSW process.

4. Conclusions

The welding experiments were conducted successfully to find out the influence of TPP on the microstructural and mechanical strength variation of FSWed AA5083 and AA5754 alloys joints. The conclusions obtained from the research work are as follows:

1. Among the three TPP, the straight square tool pin attained a better weld joint because of the pulsating effect created by the tool pin.
2. The surface microstructural evaluation of the welded samples proved that the SS tool pin profile had done proper mixing of the BM in the WNZ along with dynamic recrystallization, which made the grains finer.
3. The tensile results proved that the sample joined with the SS tool pin yielded better mechanical strength than samples welded with the other TPPs.
4. The SS tool pin exhibited the highest UTS of 212 MPa at TRS of 1250 rpm and 40 mm min$^{-1}$ welding speed.
5. The hardness survey on the welded samples recorded a high value of 88 HV at the WNZ of AA5083, whereas the lowest value of 71 HV was recorded at the HAZ of AA5754-H111.

Data availability statement

No new data were created or analysed in this study.

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