Friction stir welding parameters and their influence on mechanical properties of welded AA6061 and AA5052 aluminium plates

Sindhuja M, Neelakrishnan S and Benjamin Shiloh Davidson
Department of Automobile Engineering, PSG College of Technology, Coimbatore-641004, Tamil Nadu, India
E-mail: munnangisindhuja77@gmail.com

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Abstract
Friction stir welding (FSW) process is the preferred technique for joining of dissimilar metals. This paper intends to provide comprehensive study on the mechanical and metallurgical properties of dissimilar friction stir welded aluminium alloys, AA6061 and AA5052. The objective of the study is to find the optimum welding parameters at which the maximum weld joint strength can be achieved and to identify the influence of those parameters on the weld strength and microstructure of the AA6061 with AA5052 welded joints. The FSW process parameters such as traverse speed, tool rotational speed, axial force and tilt angle were considered. The mechanical properties measured are yield strength, tensile strength and percentage of elongation. Scanning Electron Microscopy (SEM) and optical microscope were used to observe the microstructure of weld zone (WZ) and heat affected zone (HAZ) of welded samples. Energy Dispersive x-ray Analysis (EDS) was used to obtain the elemental composition at the weld zone. Visual inspection reveals that there is no existence of weld defects like voids and porosity developed on the surface of the joints. The welds produced by the dissimilar aluminium alloys exposed an equiaxed and fine-grained structure in the weld zone. Analysis of variance (ANOVA) Technique is used to check the adequacy of the developed mathematical model. The difference between calculated and adjusted R² is 0.2 which indicates that the model is adequate. The percentage error is also less for the estimated and predicted values of the properties of welded joints.

1. Introduction
Lightweight materials for vehicles result in lower overall weight of vehicle and in turn tend to reduce pollution produced by transportation vehicle. Over the last three decades, aluminium is one such material that has replaced ferrous metals in automotive applications, due to continuous efforts of the research fraternity in developing alloys of aluminium, which are lighter and stronger. Current applications involve use of different types of material based on its functional performance. Structures of light weight having high strength being used in transportation, aerospace and marine industries are benefited from dissimilar FSW. The joining of materials is a major deciding factor in the use of different materials in an assembly. FSW is one such joining technology allowing the joining of dissimilar materials.

FSW being a takes place in solid-state evades the problems like porosity and cracks formation occurred in conventional fusion welding processes and there is no need for consumables like shielding gas and filler material.

Functionality of a fabricated part can be achieved by joining similar and dissimilar components [1]. FSW has many advantages like better weldment strength and absence of distributed and residual stresses when compared to conventional welding process High performance welded joints can be attained by linear friction welding and conventional friction welding [2]. FSW exhibits superior performance than conventional fusion welding [3]. The tool traverse speed and high tool rotational speed are the key features for higher heat generation and plastic fusion. They can be controlled by several welding parameters which in turn affect the quality of the welded joint [4].
Tool rotational speed (RPM), tool traverse speed (mm min$^{-1}$), tilt angle (degrees), axial force (kN) and tool geometry and profile are considered as friction stir process parameters [5].

The FSW process works on the principle of a rotating pin that projects from a cylindrical shoulder and which is plunged between two pieces of sheet or plates and moved forward along the joint line leaving a solid stage bond between the two pieces to be joined due to the frictional heat. It is a welding process particularly for welding aluminum parts as mentioned by Prof. Bharat Raj Singh [6]. Rajkumar et al stated that heat treatable wrought Al-Mg-Si alloy welded plate has outstanding characteristics of welding over the high strength aluminium alloys [7]. Kumbhar et al mentioned that magnesium and chromium are the primary alloys of Al5052 alloy which is used in heat exchangers, sheet metal work and architecture applications [8]. W M Thomas et al found that FSW exhibited the solid-phase welding with less distortion [9]. V Firozduor et al reported that dissimilar metal welding is considered as a uppermost significance in materials welding and joining processes now-a-days, such as welding Mg to Al or steel to diminish weight [10]. Benjamin Shiloh Davidson et al mentioned that aluminium alloys are more frequently joined than any other types of nonferrous alloys because of their widespread applications and good weldability. Welding is one of the most common joining methods for Aluminium alloys [11]. M Ilangoavan et al reported that AA 5XXX and AA 6XXX aluminium alloys are corrosion resistive and have good ductility and strength to weight ratio. Material properties of these two alloys after dissimilar welding are used in military applications [12].

Grain refinement and microstructure features can improve the tensile properties of the FS welded joints. Also, welding parameters like tool rotational speed and traverse speed influence the tensile strength of the welded joints as they govern the heat generation and grain size formed [13].

Intermetallic compounds can be minimized by material flow and mixing occurred due to tool design particularly during welding [14]. Raza Moshwane et al used a straight cylinder profiled tool for FSW, of AA 5052-O alloy plates and obtained defect free welded joints with good tensile strength [15]. Cylindrical pin is considered to be more efficient out of different pin profiles which includes cylindrical threaded pin, stepped pin, squared pin and tapered pin in FSW of AA6061 and AA2024 alloys [16]. It has been found that the pin geometry is the key factor for plastic diffusion during the friction stir welding [3]. Masoumi Khalilabad et al investigated that joining of AA2024-AA2198 with pin profiles such as cone, straight cylindrical, half threaded cylindrical, tapered cylindrical and square. They found that straight cylindrical, tapered cylindrical and cubic pin profiles produced the defect less joints [17]. Nikul Patel et al have studied the performance of different tool pin profiles for welding of Mg-AZ91 plates. They found that straight cylindrical pin profile tool caused minimal defect than other tool profiles [18].

Palanivel et al have studied welding of AA5XXX-H111 and AA6XXX-T6. They predicted that the tensile strength increases non linearly with high welding speeds [19]. S Shashi Kumar et al have studied the joining of AISI 316L austenitic stainless steel with different rotational speeds and found that the tool rotational speed influences the tensile strength of the welded joints [20]. Mohamed et al have found that the weld joint strength had been decreased with high tool rotational speeds [21]. Sevvel et al have found that, the solidification of the weld zone was occurred rapidly due to higher rotational speed and low feed rate during welding of AZ31B-Mg plates. This rapid solidification leads to strengthening of weldments without defects [22].

Jamshidi Aval et al friction stir welded AA5086 and AA6061 and stated that hardness in the two different alloys is influenced by the factors like recrystallization, grains formation in the nugget zone, size, volume fraction and precipitates distribution [23]. Beytullah et al found that, hardness traverse is caused by high tool rotation speed with Low welding speed by studying FSW of 5083-H111 and 6082-T651 aluminium alloys [24]. M Ilangoavan et al have found increased boundary of grains and IMC phase precipitation in the FS welded zones of AA6061-AA5086 plates [25]. Hamed Jamshidi Aval determined the coarsening, dissolution and precipitation of the intermets in FS welded AA6082 and AA7075 alloys [26]. Umashanker Das et al welded two AA6101 and AA6351 aluminium plates and stated that too much rise in the tool rotational speed declines the impact energy caused by high heat generation and refinement of grains at the nugget zone [27]. Q Wen et al found different formations of grains in different zones of FS welded AA2024 aluminium alloys. Base metal has elongated grains, stir zone has fine equiaxed grains due to dynamic recrystallization, TMAZ has distorted grains and grains in HAZ are similar to that of base metal due to thermal cycle [28].

Different modes of deformation were found in FSW joints as characteristic microstructures which shows significant influence on the mechanical properties of the FS welded aluminum alloys. The characteristic microstructure includes onion rings in the NZ which are described by grain size and orientation, segregation bands formed by sporadic material flow during welding, zig-zag lines formed due to lower heat input conditions and kissing bonds [29]. Presence of zigzag lines and kissing bonds leads to reduction in tensile strength of the FS welded joints [30, 31].

Intermetallic precipitates hold the tensile strength of alloy at higher temperature along with improved mechanical and thermal properties as mentioned by Karthikeyan Rangaraju et al [32].
D Devaiah et al studied the impact of different combination of welding parameters on dissimilar welded joints by using Taguchi design and L9 orthogonal array [33]. Chinmay Shah et al used Taguchi L9 array which is developed by MINITAB 16 software for design of experiments for friction stir welding of AlSiCp PRMMC [34]. There is a need for optimization of welding process parameters and evaluation of mechanical and microstructural properties to endorse the extensive applications of FS welding and FS processing and to ensure the safety and durability of the FSW/FSP components [29]. Response surface methodology (RSM) is employed to develop the mathematical model for welding process and Analysis of variance (ANOVA) Technique is used to check the adequacy of the developed mathematical model. The developed mathematical models can be used effectively at 95% confidence level [35, 36].

Research gap found in the above literature review is lack of focus on impact of FSW parameters on tensile strength and heat affected zone which determines the quality of the weld and optimizing and identifying important process parameters. Keeping in view of these research gaps, it is planned to investigate and report the mechanical and microstructural properties of FS welded AA6061/AA5052 joints which are used in automobile and aerospace applications.

Aluminium is preferred alternative material to high density materials owing to its high strength to weight ratio. Further, AA 6061 is a heat treatable alloy used in crossmembers, wheels, receiver tanks and propeller shafts. AA 5052 is non heat treatable alloy with corrosion resistance and formability and is used in meter display panels and AT drums.

The unique contribution in this work is studying heat affected zone (HAZ) which is a key factor in determining the strength of the FS welded joints.

### 2. Materials and methods

AA6061 is a precipitation-hardened aluminum alloy consists magnesium and silicon as its key alloying elements. It shows good weldability and has good mechanical properties. AA5052 mainly consists of magnesium alloy. Tables 1 and 2 shows the chemical composition and physical properties of AA 6061 and AA 5052. AA 6061 is placed on the advancing side and AA 5052 on retreating side because placing AA6061 on advancing side leads to

#### Table 1. Chemical composition of the AA6061 and AA5052.

|       | Al    | Cr     | Cu     | Fe    | Mg    | Mn    | Si    | Zn    |
|-------|-------|--------|--------|-------|-------|-------|-------|-------|
| AA6061| 95.8–98.6 | 0.04–0.35 | 0.15–0.4 | <0.7 | 0.8–1.2 | <0.15 | <0.4 | <0.25 |
| AA5052| 95.7–97.7 | <0.1   | <0.4   | 2.2–2.8 | <0.1 | <0.25 | <0.1 |       |

#### Table 2. Physical properties of the base metals AA6061 and AA5052.

| Material | Yield strength (MPa) | Tensile strength (MPa) | Modulus of elasticity (GPa) | Impact strength (MPa) | Percentage of elongation (%) | Vickers hardness |
|----------|----------------------|------------------------|-----------------------------|-----------------------|-------------------------------|-----------------|
| AA6061   | 179                  | 200                    | 68.9                        | 25                    | 23.4                          | 102             |
| AA5052   | 167                  | 193                    | 69.3                        | 47                    | 24.2                          | 61              |

Figure 1. Photographic view of NC FSW machine.
Table 3. Specifications of NC FSW machine.

| Specification                  | Range of values |
|--------------------------------|-----------------|
| Spindle speed                  | 3000rpm         |
| Spindle tilt angle             | +/−5 degrees    |
| Z—axis thrust force            | 30 KN (max)     |
| Z—axis travel                  | 300 mm (servo)  |
| X—axis travel                  | 300 mm (servo)  |
| Y—axis travel                  | 100 mm (servo)  |
| Table to spindle node          | 100 mm/400 mm   |
| Controller                     | Rexroth         |
| Data acquisition software      | Spindle rpm, torque axis force and velocity against time and distance |
| Weldable material              | Steel, copper, Aluminium |

Table 4. Welding parameters.

| S.no | Welding parameters                  | −2  | −1  | 0   | 1   | 2   |
|------|-------------------------------------|-----|-----|-----|-----|-----|
| 1    | Tool rotational speed (RPM)         | 1000| 1200|1400 |1600 |1800 |
| 2    | Tool traverse speed (mm min⁻¹)      | 20  | 25  |30   |35   |40   |
| 3    | Axial force(kN)                     | 1   | 1.5 |2    |2.5  |3    |
| 4    | Tool tilt angle (degrees)           | −2  | -1  |0    |1    |2    |

Figure 2. Cylindrical tool and welded plates (25 no’s).

Figure 3. Tensile and impact samples.
high temperature and heat generation. A numerical control operated FSW machine is used for dissimilar welding of AA6061-AA5052 and is shown in figure 1 and the specifications of the machine is given in table 3. The weld tool made of H13 was used to produce the weld joints which is shown in figure 2. The FSW machine has a maximum spindle speed of 3000 RPM and maximum thrust force of 30kN. The tool with cylindrical pin profile is used for welding as it is found to be efficient from literature than the other tool pin profiles. The size of the base metal used for welding was 200 mm \( \times \) 100 mm \( \times \) 6 mm. The tool pin is of straight cylindrical profile, with shoulder and pin diameters of 16 mm and 6 mm respectively and the pin length of 5.8 mm. There are a total of four input parameters, with five levels of operation. This gives us a full factorial design with \( 5^4 = 625 \) experiments to be performed.

The L25 Taguchi array, with four parameters and five levels was used to study the effect of various combinations of process parameters on FS welded joints. Based on the range of parameters of the FSW machine used for welding, four different tool rotational speeds (1000 RPM, 1200 RPM, and 1400 RPM, 1600 RPM,

Table 5. Mechanical properties of welded samples.

| FSW operating conditions | Tool rotational speed (RPM) | Tool traverse speed (mm min\(^{-1}\)) | Axial force (kN) | Tool tilt angle (Degrees) | Tensile strength (MPa) | Yield strength (MPa) | Percentage of elongation (%) |
|-------------------------|----------------------------|--------------------------------------|-----------------|--------------------------|-----------------------|-------------------------|-------------------------------|
| 1                       | -2                         | -2                                   | -2              | -2                       | 163                   | 138                     | 11                             |
| 2                       | -2                         | -1                                   | -1              | -1                       | 176                   | 151                     | 10.9                           |
| 3                       | -2                         | 0                                    | 0               | 0                        | 115                   | 101                     | 3.8                            |
| 4                       | -2                         | 1                                    | 1               | 1                        | 61                    | 48                      | 1.5                            |
| 5                       | -2                         | 2                                    | 2               | 2                        | 26                    | 23                      | 1.6                            |
| 6                       | -1                         | -2                                   | -1              | 0                        | 120                   | 108                     | 5.4                            |
| 7                       | -1                         | -1                                   | 0               | 1                        | 50                    | 42                      | 1                              |
| 8                       | -1                         | 0                                    | 1               | 2                        | 70                    | 61                      | 1.3                            |
| 9                       | -1                         | 1                                    | 2               | -2                       | 161                   | 140                     | 5.2                            |
| 10                      | -1                        | 2                                    | -2              | -1                       | 100                   | 88                      | 2.6                            |
| 11                      | 0                          | -2                                   | 0               | 2                        | 19                    | 16                      | 0.2                            |
| 12                      | 0                          | -1                                   | 1               | -2                       | 175                   | 157                     | 12.7                           |
| 13                      | 0                          | 0                                    | 2               | -1                       | 168                   | 143                     | 6.6                            |
| 14                      | 0                          | 1                                    | -2              | 0                        | 171                   | 147                     | 8.4                            |
| 15                      | 0                          | 2                                    | -1              | 1                        | 101                   | 87                      | 2.3                            |
| 16                      | 1                          | -2                                   | 1               | -1                       | 172                   | 153                     | 12.8                           |
| 17                      | 1                          | -1                                   | 2               | 0                        | 121                   | 108                     | 10.3                           |
| 18                      | 1                          | 0                                    | -2              | 1                        | 81                    | 68                      | 5.1                            |
| 19                      | 1                          | 1                                    | -1              | 2                        | 63                    | 54                      | 2.8                            |
| 20                      | 1                          | 2                                    | 0               | -2                       | 177                   | 153                     | 8.5                            |
| 21                      | 2                          | -2                                   | 2               | 1                        | 105                   | 92                      | 4.5                            |
| 22                      | 2                          | -1                                   | -2              | 2                        | 45                    | 41                      | 1.9                            |
| 23                      | 2                          | 0                                    | -1              | -2                       | 179                   | 161                     | 11.9                           |
| 24                      | 2                          | 1                                    | 0               | -1                       | 152                   | 129                     | 4.7                            |
| 25                      | 2                          | 2                                    | 1               | 0                        | 150                   | 129                     | 7.6                            |

Figure 4. Effect of welding parameters on tensile strength.
1800 RPM), tool traverse speeds (20 mm min$^{-1}$, 25 mm min$^{-1}$, 30 mm min$^{-1}$, 35 mm min$^{-1}$, and 40 mm min$^{-1}$), axial forces (1 kN, 1.5 kN, 2 kN, 2.5 kN and 3 kN) and tilt angles ($-2^\circ$, $-1^\circ$, $0^\circ$, $1^\circ$ and $2^\circ$) were used to produce the weld joints which are mentioned in table 4.

The specimen for tensile test was prepared according to ASTM E8 standard, and are shown in figure 3. Computer controlled universal testing machine of Instron model 1125 was used for carrying out the tensile tests. The impact test was carried out on Krystal Elmec model KI-300 machine to find the impact strength of weldments at two different points and the mean of the two measurements was taken as average impact strength value. Vickers hardness (HV-15) test was performed for determining the hardness profile of weldments in three different regions which are base metal, heat affected and weld zones.

The cross sections of the metallographic samples were polished finely using emery papers of different grades and were etched using Keller’s reagent. The microstructure of the resultant joints was mainly observed and characterized using scanning electron microscopy (SEM), EVO 18 model with low vacuum facility, optical microscope, Dewinter model and energy dispersive x-ray analysis (EDS) for elemental composition at the weld zone.

3. Results and discussions

Table 5 shows the result of the L25 Taguchi array. Figure 4 shows how the strength of the welded joints is affected by welding parameters.

3.1. Tensile strength

It is observed that the higher tool rotational speeds improve the tensile strength. This is because the tensile strength of the welded joints is sensitive to the tool rotational speed and generation of heat is enough for the grains to be solidified rapidly during welding. This agrees with the work done by Sevvel et al in their investigation for analyzing microstructural and mechanical properties of FSW welded AZ31B Mg alloy [22].

The strength of the welded joint generally increases with the tool rotational speed due to the greater effect of material mixing during welding and also it strengthens the plastic deformation. The tool traverse speed controls the temperature distribution and residual stresses [37]. Increase in tensile strength of the weld is accredited to grain refinement which is formed by the lower heat input condition with lower rotational and higher traverse speeds [13]. Weld joint strength can be improved by less heat input formed by increasing weld traverse speed which lessens grain growth and recovery [38].

It is observed from figure 4 that the tensile strength for dissimilar welding seem to be decreased with higher weld traverse speeds. However, slight increase in traverse speed is been noticed from 25–35 mm s$^{-1}$ of weld traverse speed. Lower heat input condition is observed with higher weld speeds where it leads to generation of defects which reduces joint strength [37]. Excess heat input generated due to high tool rotational speed and constant traverse speed will increase metal fluidity which leads to cavity formation [39]. Metal fluidity is low at highest and lowest rotational speeds which leads to defects in the weldments [40]. Flow of the material is good when more heat is generated through increase in rotational and traverse speeds [41].
It is observed that, by applying axial force, frictional heat is generated which allows the material to be joined with appropriate temperature and produces good and defect free welded joints [42]. Strength of the welded joints was also decreased with increase in tilt angle as observed in figure 4. This is due to the less contact between
tool shoulder and base material as the plunge depth becomes low and the flow of plasticized material is reduced [43]. Whereas negative tilt angles pressure under the tool as the plunge depth is high and ensures good material flow.

Results also showed that the increase of rotational speed causes ring or layer pattern presence in weld zone as shown in figures 8(a) and (b) [44]. Dimple formation and larger groove curvature observed in figures 9(a)–(c) indicates the increase in heat input and good material flow for better joint bonding [45].

Rotational speeds above 1200 RPM and gradual rise in tool traverse speed is revealed to produce joints with good tensile strength because of high heat generation and proper material flow leading to the coalescence occurring between the plates without defects. The lowest tensile strength is observed at weld joint produced at 1400 RPM, 20 mm min$^{-1}$, 2kN and 2° tilt angle. Combination of moderate tool rotational speed, low traverse speed and positive tilt angle leads to poor material flow around the rotating pin and contributes to lack of fill void formation and dilapidation of tensile strength of welded joints.

### 3.2. Yield strength

Yield strength of the welded joints fabricated is shown in table 5. The joint fabricated with 1800 rpm, 30 mm min$^{-1}$, 1.4 kN and −2 degrees showed higher yield strength of 161 MPa, tensile strength of 179 MPa, elongation of 11.9%. Similarly, the joint fabricated at 1400 rpm, 20 mm min$^{-1}$, 2kN and 2 degrees has shown lesser tensile strength of 19 MPa, yield strength of 16 MPa and % elongation of 0.2. It is observed that yield and tensile strengths of all welded joints are lower than that of base material regardless of tool rotational speeds used for welding. Increase in yield strength with increase with tool rotational speed which is observed in figure 5 is because, the strength of the friction stir welded joints was sensitive to the tool rotational speed which increases the heat generation.

### 3.3. Percentage of elongation

Yield strength and percentage of elongation were improved with increase in tool rotational speed and showed less performance when the rotational speed is decreased as observed from table 5. All the fabricated welded samples show less percentage of elongation when compared to that of base materials as shown in figure 6. It is also observed that all the welded joints showed lower elongation than that of base materials. Rotational speeds from 1400 RPM to 1800 RPM showed good % elongation.
3.4. Microstructure characterization
Figure 7 shows the optical microstructure of friction stir welded samples for the operation conditions of experiment 23, 11 and 3. From the metallographic investigation, it was found that, the grain size of a1 revealed the fine grains with uniform distribution throughout all the heat affected and weld zones.

The grain size of the sample b1 was measured as 23 μm, whereas the grain size for the a2 is about 31 μm. From this investigation, it is clearly depicted that the grain size has been refined to the maximum for the samples which possess higher tensile strength. This observation has also good agreement with previous studies that the grain size has influenced the tensile strength. The grain refinement is purely attributed to the rapid cooling of heat affected zone. The strength of the weld is confirmed by microstructure through grain refinement. Grain refinement in the weld zone during FS welding results from the dynamic recrystallization [46, 47]. Uniform grain refinement and extreme plastic strain can be induced by high tool rotational speeds [48].

A comparison of the microstructure in different locations in the samples, acquired through optical microscope and Images of the weld zone and HAZ are shown in figure 7. Heat affected zone is subjected to heat and softening of the metal takes place which leads to less deformation in the welded joints. Figures 7(b1) and (b3) shows highly coarsened grains in the heat affected zone by FS welding process [49]. Weld zone is subjected to high heat and strain because if tool stirring action leading to dynamic recrystallization and size of grains is finer when compared to base metals. Equiaxed grains in the weld zone as in figures 7(a1), (a2) and (a3) suggest strains with microstructural evolution occurred due to dynamic recrystallization [49].

Partial bonding defects can be seen in figures 7(b1), (c3) and (b3). Joined boundaries were seen in figures 7(c1) and (c3) due to recrystallization and fine grains formation [45]. Dislocations in the grains due to compression are grown into grain boundaries can be seen from figures 7(a2) and (a3) [50]. It is apparent from the figure 8 that the friction stir process has established fine equiaxed microstructures in the weld zones. This occurs due to high temperature and rapid metal plasticization in the weld zone which stimulated the occurrence of fine and equiaxed grains [51]. Grain structure in HAZ and base material looks alike because heat affected zone is only affected by the high temperature due to stirring effect [52].

3.5. SEM Analysis of friction stir welded surface
The SEM analysis of FS weld joint surfaces were obtained and given in figures 8 and 9 for operating conditions exp 23 and 11. From SEM analysis, it is clearly shown that the wear pattern of friction stir welded surface along with 8b and 8c and 9a, 9b and 9c zones. It is confirmed that the wearing of the weld zone of the sample have been noticed at higher degradation than that of HAZ due to the higher temperature during FSW. However, the
welded surface has been noticed with acceptable welded surface finish. The microstructure obtained at the heat affected zone and weld zone of the specimens obtained with a straight cylinder tool profile are shown in figures 8 and 9. The microstructures of the welds (23, 9, and 11) produced with different weld parameters are presented in figures 8 and 9.

By observing the microstructure in figures 8(a) and 9(a), it can be seen that spacing between the welded material edges through longitudinal sections grows due to high temperature distribution caused by the straight cylindrical tool profile. Also, the high temperature leads to material mixing which gives strength to the welded joints. The parallel lines in the macrostructure are formed due to the pin rotation in the weld nugget zone.

In spite of the rough surface, no other obvious defects such as voids or tunnel were observed throughout the whole weld. The welds were free of porosities. A longitudinal section through the welds observed in figures 8(a)–(c) discloses the layered structures that may correspond to the onion rings due to metal flow during welding. The material withstands plastic deformation due to the existence of dynamic recrystallization in the HAZ as it is agreed in the work done by J H Ouyang et al [49].

3.6. EDS analysis

Energy dispersive x-ray analysis (EDS) is a technique used for the elemental analysis or chemical characterization of a specimen. The elemental composition in some spots on the welded samples having highest and lowest tensile strength was analyzed by EDS technique. The dissimilar FSW between AA6061 and AA5052 exhibit a different microstructure than their base counterpart. The stirring action of the FSW has produced a fine recrystallized structure at the weld stir zone. Fine gains and intermetallic compounds which plays key role in deciding the weld joints strength are observed to be distributed homogeneously in the weld stir zone. The EDS analysis in figure 10 discloses the existence of alloying elements of both AA6061 and AA5052 and it also shows oxide layer which leads to increase of corrosion properties.

EDS analysis reveals that the weight % of the second phase particles is found to be increased which attributes to its higher tensile strength. The grain size measurement reveals that fine grains are found to occupy the stir zone. In figure 10, weld 11 has lowest tensile strength and is observed that Al is the most concentrated element with more weight % of 71.93, Mg of 3.77 weight percentage O of 13.26 and C of 11.04 weight percentages. In weld 23 which has highest tensile strength, the weight percentages of aluminum and oxygen are 84.52 and 15.48. Carbon evolves at the stir zone where the frictional heat is evolved due to tool rotational speed.

3.7. Development of mathematical model

Design expert software is a statistical software used to perform DOE (design of experiments), characterization and optimization. DESIGN EXPERT 11 software package is used to calculate the values of coefficients for different responses and the mathematical models are developed.
Table 6. ANOVA test results.

|               | Sum of squares | Mean squares | Degrees of freedom | F-ratio | R^2     | Adj R^2 | Remarks     |
|---------------|----------------|--------------|--------------------|---------|---------|---------|-------------|
|               | Regression     | Residual     | Regression         | Residual| F-ratio | R^2     | Adj R^2     |             |
| TS            | 56172.26       | 10836.80     | 14043.14           | 542.84  | 25.87   | 0.8380  | 0.8056      | Significant |
| YS            | 43370.24       | 8246.00      | 10482.56           | 412.30  | 26.30   | 0.8402  | 0.8083      | Significant |
| % of elongation | 263.97        | 147.30       | 65.99              | 7.36    | 8.96    | 0.6418  | 0.5702      | Significant |
The developed final mathematical model equations in the coded form are given below

\[
\text{Tensile strength (TS)} = 116.84 + D_1 + D_2 + D_3 - D_4
\]  
(1)

Where \( D_1 = 54.16, D_2 = 36.76, D_3 = 18.56, D_4 = -37.24 \)

\[
\text{Yield strength (YS)} = 101.52 + D_1 + D_2 + D_3 - D_4
\]  
(2)

Where \( D_1 = 48.28, D_2 = 31.28, D_3 = 17.08, D_4 = -34.12 \)

\[
\text{Percentage of Elongation} = 5.62 + D_1 + D_2 + D_3 - D_4
\]  
(3)

Where \( D_1 = 4.24, D_2 = 1.90, D_3 = 1.48, D_4 = -3.54 \)

The adequacy of the models so developed is then tested by using the analysis of variance technique (ANOVA). Using this technique, it is found that calculated F ratios are significant. Another criterion that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination \((R^2)\). For the models developed, the calculated \(R^2\) values are in agreement with adjusted \(R^2\) that is difference is less than 0.2. These values indicate that the regression models are quite adequate. The results of the ANOVA are given in table 6.

The results obtained are satisfactory as the percentage of error is also low as shown in table 7.

Typical scatter diagrams for all the models are presented in figure 11–13. The observed values and predicted values of the responses are scattered close to the 45° line, indicating an almost perfect fit of the developed empirical models.

4. Limitations and future work

The research work is limited to the FSW of AA6061 and AA5052 aluminium alloys within the welding parameters taken for this specific research. More understanding is required for the material flow behaviour since it is critical phenomenon during FSW. Hardness over the weld zone can be which impacts the grain refinement can be studied. Temperature variation during FSW and its effect on metallurgical properties and mechanical properties of the FW weldments can be studied.

5. Conclusions

Friction stir welding of dissimilar aluminium alloys was done successfully. Based on the observations, the following conclusions are arrived at:

1. The highest tensile strength of 179MPa is obtained at 1800 RPM, 30 mm min\(^{-1}\), 1.5kN and \(-2^\circ\) tilt angle which is 81.36% and 90.86% of the parent materials AA6062 and AA5052 respectively.
2. Higher heat can be generated to melt the base materials to get joined without defects by reducing weld speed and increasing tool rotational speed.
3. Increase in tensile strength of the weld is accredited to grain refinement which is formed by the lower heat input condition with lower rotational and higher traverse speeds.
4. The yield strength is increased with increase in tool rotational speed because the strength of the friction stir weld joints was sensitive to the rotational speed.
5. Rotational speeds from 1400 RPM to 1800 RPM showed good % elongation.
6. From optical microstructure, it is observed that grain size has been refined to the maximum for the samples which possess higher tensile strength.
7. Grain refinement in the weld zone during FS welding results from the dynamic recrystallisation. Grain refinement and microstructure features can improve the tensile properties of the FS welded joints. Also, welding parameters like tool rotational speed and traverse speed influence the tensile strength of the welded joints as they govern the heat generation and grain size formed.
8. Fine grains and intermetallic compounds play a major role in deciding the strength of the welded joints.
9. The EDS value of the weld conditions 11 and 23 (straight cylinder tool profile) specimens show the presence of constituents of AA6061 and AA5052 at the nugget zone.
Figure 11. Scatter diagram for yield strength.

Figure 12. Scatter diagram for tensile strength.

Figure 13. Scatter diagram for percentage of elongation.

Table 7. Results of weld run 23.

| Tensile strength (MPa) | Yield strength (MPa) | Percentage of elongation |
|------------------------|----------------------|--------------------------|
| Estimated | Predicted | Estimated | Predicted | Estimated | Predicted |
| 189.08 | 179 | 164.04 | 161 | 9.7 | 10.3 |

\[
\text{Percentage of error} = \frac{(\text{Estimated values} - \text{predicted value})}{\text{Predicted values}} \times 100
\]
10. DESIGN EXPERT 11 software package was utilized to calculate the values of coefficients for different responses and the mathematical models developed, are checked for their adequacy using ANOVA test, scatter diagrams and found to be satisfactory.

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Data availability statement

No new data were created or analysed in this study.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID iDs

Sindhuja M //https://orcid.org/0000-0001-9697-3461

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