Improving the Mechanical properties of 6061 and 5083 welded joint using Friction stir lap welding

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Abstract. Joining of metal is very important operation in every manufacturing activity. Conventional welding of Al alloys by Tungsten inert gas welding, Metal inert gas welding and Resistance spot welding was reported to produce poor quality weld joints, as the inherent characteristics of the base metal affected the weld properties. Friction stir welding, identified as one of the best alternative is employed to join Al 5083 and Al 6061 in this study. Aluminium alloys, Al 5083 and Al 6061 are welded in lap joint configuration, with SiC nano particles interlayer. The process parameters such as welding speed tool, rotational speed and volume percentage of Nano-powder were optimized by utilizing Response surface methodology, RSM. The joints welded without the SiC nano particle interlayer were observed to possess low mechanical strength at the best welding conditions determined by the RSM.

Keywords: Friction stir welding (FSW); SiC; Strength; Response Surface Methodology (RSM); lap welding;

1. Introduction
The latest trend in the automotive industry to survive in the global market, with the help of upgrading technology. Generally, lightweight materials like aluminum alloys are employed to reduce weight of a vehicle and thus correspondingly, the performance of the vehicle also is improved. Properties like higher specific strength, excellent electrical and thermal conductivity and high elastic modulus are suitable for automobile, defence and aerospace applications. 5000 series aluminum alloy and 6000 series of aluminum commonly used aluminum alloys in automobile structures [1,2]. In an automobile body, the structures are joined by the riveting method or conventional welding method and for rivet joining, holes are drilled in the parts to accommodate the rivets. The holes reduced the cross-sectional area of the member and result in stress concentration in the member [3]. For welding of aluminum alloy, it is difficult to joint by conventional welding techniques, due to the thermal conductivity and chemical composition of the aluminum alloy. Hence friction stir welding (FSW) is one of the best methods for joining aluminum alloy [1]. Friction stir welding (FSW) is a solid-state joining Technology in which a non-consumable tool is used. FSW developed by the Welding Institute (TWI) of UK in 1991 (Thomas et al.,1991) [4]. FSW is environment-friendly and energy efficient joining techniques. this technique does not require any filler material hence it is easy to welding aluminum alloy and property of base material can be improved [5]. Ramesh and Murugun, [6] obtained FSW joints of Al 7075 with mechanical strength 62% higher than that of base metal. Chandrasekhar Sannapu and Murahari kolli [7] found that that the pin profile and rotational velocity influenced the material flow in FSW joints. Fuyans Gao et al. 2020 [8] obtained fatigue strength of
336.67MPa in FSW of TA5 titanium alloy plates with a thickness of 4mm. The obtained fatigue strength was observed to be 80% of the fatigue strength of the base metal. Ayad M. Takhakh and Harith Hammody Abdulla [9] improved the joint properties in friction stir processing of Al7075-T651 using SiC particles. Yongxian Hung et al. [10] fabricated AZ31Mg composite using carbon nanotube and SiC without making groove to insert ceramic powder and found that the thickness of the composite layer is 150μm and microhardness of surface increased from 57.77HV to 115.51HV. Akash Yadava [11] studied the influence of the plate position in FSW of Al6061 and Al 5083. The authors obtained joints with high strength when Al 6061 us placed on the advancing side. Most of the studies of FSW reported in literature focused on the effects of process parameters and tool geometry on weld characteristics. Few works of literatures reported that the FSW joint properties like tensile strength, hardness was enhanced due to the addition of SiC, Al2O3 nano particles [12, 13]. The improvement of strength of weld zone is one of the possibility in FSW technique [14]. Compared to Al2O3 or Si3N4, the SiC particles were observed to possess excellent mechanical properties [15]. Also, silicon carbide particle is used as load bearing particle and the abrasive action on the counter face change the material from the counter surface to contact surface [16-18]. Therefore, in this research work, an attempt is made to study the impact of SiC particles and welding parameters on mechanical and microstructural characteristics in Friction stir lap welding of Al 6061 and Al 5083. The Al 5000 series has magnesium as the main alloying element with a weight percentage between 3-5%. The main characteristics of Al 5083 alloy are high tensile strength, high elongation, excellent corrosion resistance. In Al 6061, magnesium and silicon are the main components and it possess high strength, excellent corrosion resistance and excellent formability. The Response surface methodology, RSM is used to find the best welding conditions, as this process helps the user to find the welding parameter which has the maximum impact on the result or response and also helps the user to the information on the effects of the interaction of the welding parameters on the outcome [19-20].

2 Experimental Methodology
Aluminium 6061 and 5083 of dimensions (100×50×3) mm are rigidly clamped on the 10 mm thickness mild steel backing plate as observed in Figure 1.

Figure 1. FSW of Al 6061-Al 5083
The FSW machine, with 11 kW capacity and 30 KN axial force is used to join the Al alloys with the help of the threaded profile tool, Figure.2 of H-13 steel material with a hardness of 60 HRC.

![Threaded tool](image)

**Figure 2.** Threaded 8 mm diameter Pin tool with 25 mm shoulder diameter.

The Chemical Composition of the base metals and the tool material, H13 steel are presented in Table 1 and Table 2, respectively.

**Table 1:** The Chemical Composition

| 6061 Aluminum Alloy Composition by Mass % | Al   | Mg   | Fe   | Si   | Cu   | Cr   | Zn   | Ti   | Mn   |
|-----------------------------------------|------|------|------|------|------|------|------|------|------|
| Mass %                                  | 95.85 - 98.56 | 0.8 - 1.2 | 0.7  | 0.40 - 0.8 | 0.15 - 0.40 | 0.04 - 0.35 | 0.25 | 0.15 | 0.15 |

| 5083 Aluminum Alloy Composition by Mass % | Al   | Mg   | Fe   | Si   | Cu   | Cr   | Zn   | Ti   | Mn   |
|-----------------------------------------|------|------|------|------|------|------|------|------|------|
| Mass %                                  | 92.4 - 95.6 | 4 - 4.9 | 0.4  | 0.4  | 0.1  | 0.05 - 0.25 | 0.25 | 0.15 | 0.4 - 1 |

**Table 2:** The Chemical Composition of H13

| Element         | Content (%) |
|-----------------|-------------|
| Chromium, Cr    | 4.75-5.50   |
| Molybdenum, Mo  | 1.10-1.75   |
| Silicon, Si     | 0.80-1.20   |
| Vanadium, V     | 0.80-1.20   |
| Carbon, C       | 0.32-0.45   |
| Nickel, Ni      | 0.3         |
| Copper, Cu      | 0.25        |
| Manganese, Mn   | 0.20-0.50   |
| Phosphorus, P   | 0.03        |
| Sulphur, S      | 0.03        |
2.1 Silicon Carbide (SiC)
Silicon carbide is the third hardest material. It is a ceramic material with known mechanical, abrasive chemical, thermal, electrical, and refractory properties being commonly used in the production of refractory parts. SiC has excellent mechanical property when compared to Al₂O₃. The addition of SiC Nanoparticle of 3.5 μm size in weld zone significantly improves strength and decrease elongation of the composites as compared to base metal alloy [18]. The specification of the SiC nanopowder is presented in Table 3.

| Table 3: SiC Powder Specifications |
|-----------------------------------|
| Purity                           | 99 %          |
| Median grain size ds(μm)         | 3.5+-0.5      |
| Designated grit                  | 1200          |
| Silicon Content                  | 70 %          |
| Carbon Content                   | 29.94 %       |
| Density                          | 3.22 g/cm³    |

The SiC nano particles were securely arranged in between two clamped sheets in order to avoid the scattering of the particles at the weld area.

2.2 Arrangement Sheets
The AA 6061 and AA 5083 are cut to the dimensions of 100x50x3 mm using a power axe-saw. The AA 6061 is placed on top of Al 5083 (Figure 3) because AA 6061 is reported to possess, excellent flowability at high welding temperatures achieved during FSW and help in enhancing the joint properties due to better material mixing between the two alloys.

![Figure 3: Arrangement sheets for lap welding](image)

2.3 Friction Stir Lap Welding of Al 6061-Al 5083 with SiC Nano particles
Response surface methodology (RSM) employs mathematical and statistical techniques to determine the best processing condition in a system, where the response is influenced by several variables. In this study, the processing conditions like rotational speed, welding speed and weight % were considered, which are presented in Table 4.
Table 4: Process parameters

| Tool rotation speed (RPM) | Welding Speed, (mm/s) | Weight % |
|---------------------------|-----------------------|----------|
| 650                       | 0.25                  | 1.4      |
| 850                       | 0.5                   | 2.0      |
| 1050                      | 0.75                  | 2.6      |

Overall, 15 experiments were done based on the Box-Behnken experimental design, which is presented in Table 5.
The tensile test for shear specimens cut perpendicular across weld direction, the cross section of plate is 20mm as width and 3mm thickness.

Table 5: Experiment sequence by RSM method.

| Standard Order | Run Order | Rotational Speed (rpm) | Welding Speed (mm/s) | Weight % | Tensile shear force (kN) |
|----------------|-----------|------------------------|----------------------|----------|--------------------------|
| 14             | 1         | 850                    | 0.5                  | 2        | 8.70                     |
| 4              | 2         | 1050                   | 0.75                 | 2        | 7.49                     |
| 7              | 3         | 650                    | 0.5                  | 2.6      | 8.56                     |
| 12             | 4         | 850                    | 0.75                 | 2.6      | 4.06                     |
| 15             | 5         | 850                    | 0.5                  | 2        | 6.20                     |
| 11             | 6         | 850                    | 0.25                 | 2.6      | 6.39                     |
| 3              | 7         | 650                    | 0.75                 | 2        | 8.19                     |
| 1              | 8         | 650                    | 0.25                 | 2        | 8.15                     |
| 8              | 9         | 1050                   | 0.5                  | 2.6      | 10.20                    |
| 6              | 10        | 1050                   | 0.5                  | 1.4      | 9.66                     |
| 10             | 11        | 850                    | 0.75                 | 1.4      | 9.67                     |
| 2              | 12        | 1050                   | 0.25                 | 2        | 7.11                     |
| 9              | 13        | 850                    | 0.25                 | 1.4      | 6.32                     |
| 13             | 14        | 850                    | 0.5                  | 2        | 8.25                     |
| 5              | 15        | 650                    | 0.5                  | 1.4      | 9.24                     |

The maximum joint strength of 10.20 kN was obtained at 1050 RPM, 0.5 mm/s and 2.6 %.
3 Result and discussion:

3.1 Tensile Test of the Friction stir lap welded Al 6061-Al 5083 joints

Tensile strength, Fig. 4 of the FSW joints was evaluated at a cross-head speed of 1 mm/min. The tensile strength of the joints was observed to be severely influenced by the rotational speed, welding speed and weight %.

![Figure 4: Tensile testing of Friction stir lap welded Al 6061-Al 5083](image)

3.1.1 Influence of Welding conditions on Weld strength. The 3D Response surface plots were used to study the influence of the welding parameters on the weld strength. The influence of the rotational speed, the welding speed and the weight percentage on the weld strength presented in Figure 5 with the help of the Optimization plot. The Figure 5 shows that the joint strength was observed to decrease with the increase in the rotational speed initially and soared after 800 RPM. Such a trend in fall and rise of the weld strength, indicates the influence of the material mixing. At higher welding speeds, the joint strength was observed to be due to the poor material mixing. The use of the higher weight % SiC resulted in denting the load-carrying capacity of the weld joint, which is credited to the poor agglomeration of the SiC particles in the Al matrix.

![Figure 5: Optimization plot](image)
The maximum strength of 10.9452 kN was predicted by the RSM at 650 RPM, 0.6894 mm/s and 1.40 %. With the maximum strength obtained for the joint with the SiC nano particle, the joint strength of the weldment welded without the SiC nano particle was verified. The joint strength for this configuration was observed as 7.24 kN in Table 6. From it is confirmed that the addition of the SiC particle into the weld zone enhanced the joint strength of the Al 6061-Al 5083 joint.

**Table 6**: Shows the process parameters of without nano powder experiment and tensile shear force of both experiments are compared.

| Standard Order | Run Order | Rotational Speed (rpm) | Welding Speed (mm/s) | Without Nano particles Tensile shear force (kN) | With Nano particles Tensile shear force (kN) |
|----------------|-----------|------------------------|----------------------|-----------------------------------------------|---------------------------------------------|
| 8              | 2         | 1050                   | 0.5                  | 7.24                                          | 10.20                                       |

The improvement in the tensile shear force was observed to be 29%, when compared to that of the conventional FSW. The comparison for the joint strength at different welding conditions is presented with the help of the stress-strain curves.

**Figure 6**: Stress strain curves for Run Order 9, Graph (a) and (b) shows the stress strain relationship for the joint with the tensile shear force of 10.20 kN with nano powder and 7.24 kN without nano powder.

**Figure 7**: Stress strain curves for Run Order 10, Graph (c) and (d) shows the stress strain relationship curve, for the joint with 9.662 kN welded with SiC particle and for the joint without SiC nano particle possessing 8.700 kN.
Figure 8: stress strain curves for Run Order 11, Graph (e) and (f) also shows the similar stress strain relationship curve with respect to presence and absence of the SiC nano particle.

3.2 Microstructure studies
Microstructural investigation reveals that the friction stir weldment is composed of four different regions namely Nugget Zone (NZ) or stirred zone, Thermo-Mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ) and base metal (BM).

The genesis of the above regions is plagued by the material flow deportment under the action carry outed by rotating non-consumable tool. This refinement is the outcome of dynamic recrystallization that is coaction of a significant rate of strain and elevated temperature. Such a recrystallized structure is characterized by inferior level of residual stresses and mechanical properties superior to the HAZ. The lap welded nugget is a part of the significantly bigger zone, the thermomechanical affected zone, in which grains are elongated, deformed and rotated on account of strain to which they were subjected. getting away in the direction of base metal, the consequent zone is HAZ. The microstructure here is identical to the one of base metal. The grains are sprightly and immensely expanded as a consequence of exposure to welding heat.

The strength of the stir zone is significantly highly advance than of the parent metal. They distinguish among weld nugget zone and heat affected zone is attributable to the grain refinement in weld nugget, triggered by intensive stirring. Tunnel defect at the crisscrossing intersection of nugget zone and thermomechanically affected zone is a result of high rotational speed and travel speed. Optimizing travel speed and rotational can be prevent this type of defect.

Figure 9: Optical microstructure of Weld and base metal region
The optical micrograph clearly shows the base metal and the weld regions in Fig.10. The optical micrographs were obtained by etching the polished samples with sodium hydroxide solution. The optical microstructure shows the presence of the SiC particles pushed into the Al matrix, by the threaded tool.

![300μm]

**Figure 10**: Optical microstructure at TMAZ

Nugget zone of FSW joints comprises very fine, equiaxed grain and this may be due to the dynamic recrystallization that occurred during the FSW process. The deformed and elongated grains were noticed in the TMAZ region. This could be due to insufficient deformation strain and thermal exposure of this region. This region is located 3-4 mm away from the weld centre, where the strength is low compared to the nugget zone.

4 Conclusion:

Based on the result, In the current study, it can be concluded.

- Friction Stir Welding can be effectively used to joining and improving the strength of AA 5083 H111 and AA 6061 T6 sheet with SiC Nano-powder.
- The maximum load-carrying capacity of 10.2013 kN was observed at the rotational speed 1050 RPM with 0.5 mm/s welding speed, 2.6% of nano powder weight percent and for the same welding conditions without SiC nano powder, tensile shear force of 7.240 kN is observed.
- Thus, comparing the normal FSW of lap welding with FSW plus nano powder, FSW plus nano powder result 9% to 31% higher as compared to normal FSW.
- In microstructural study weld zone of AA 5083 H111 and AA 6061 T6 sheet, it’s found that the residual stresses and mechanical properties superior to the HAZ and some inclusions near the HAZ due to change in material composition in the weld zone.
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