

Influence of Friction Stir Processing Parameters on Tensile properties and Microstructure of Dissimilar AA 8011-H24 and AA 6061-T6 aluminum alloy joints in Nugget Zone

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Abstract. The recently developed innovative joining process, Friction stir welding (FSW) is connected to make the best quality of strength and hardness of the welded joints. The lightweight nonferrous materials are focused on aircraft hydraulic systems, fuel tank and transportation ventures due to its high strength to weight ratio and corrosion resistance. The joining of aluminum alloys is extremely troublesome in the conventional fusion welding process because of its cementing shrinkage, hot breaking, scatter, fumes and residual stresses. The friction stir processing is connected to enhance the mechanical properties of the friction stir welded joints by the addition of Nanoparticles viz., SiC and Al₂O₃. The investigation was made on the microstructural analysis of the similar and dissimilar friction stir welded and processed AA 8011-H24 and AA 6061-T6 aluminum alloy joints by Scanning Electron Microscope and the presence of alloying elements in the welded region was found by Electron Dispersive Spectroscopy.

1. Introduction

The Welding Institute (TWI), Cambridge, UK in 1991 introduced the new material joining technique of Friction stir welding (FSW) which is very efficient, environmentally friendly, and flexible process to produce the material joining [1]. Compared to the fusion welding process, the outstanding advantage of the FSW process is that complete melting does not occur near the weld zone. This includes different process parameters like rotational speed, weld speed, plunge depth and tool parameters like tool pin diameter, shoulder diameter, pin profile etc. This process is applied to produce the good mechanical properties of the joints of the different alloy materials in a solid-state due to the formation of intermetallic compounds. The process parameters mainly affect the properties like heat dissipation, plastic flow and grain structure of the weld region, whereas the tool pin parameters affect the localized heating and material flow [2]. The requirements of lightweight materials like aluminium alloys are increasing in various fields like automation industry, aerospace, chemical and marine industrial applications due to its properties of high strength, low cost, low melting point and better metallurgical properties [3]. Welding of these aluminium alloys by Friction Stir welding process has an advantage over the fusion welding to minimize the defects such as porosity, slag formation, solidification shrinkage [4]. The characteristics of both similar and dissimilar friction stir welded aluminium alloys has shown the involvement of recrystallization phenomena as the basic cause to pave for the occurrence plastic deformation [5].



In the joining of dissimilar materials, a mixture of processes occurring in the stirred zone is expected to generate even more complex microstructure. Hence, the dissimilar welding of aluminium alloys is believed to improve the specific characteristics of weld joint viz., hardness, tensile strength [6]. The different tempered AA6013 aluminium alloys, namely T4 and T6 was successfully welded with friction stir welding process by Heinz B et al. [7] and also found the elongated needle-like structure and fine grains in the thermomechanically affected zone (TMAZ) and stir zone (SZ) due to dynamic recrystallization of the materials. The microstructural changes in dissimilar welds due to various process parameters have been widely studied to understand the behavior of AA 6061 aluminium alloy [8]. It is reported that the development of fine equiaxed grains and the occurrence of residual stress were found in the stir zone of the friction stir welding AA 6061 aluminium alloy joints Muthukumaran S et al. [9]. The material flow and plastic deformation which was controlled by the geometry of the tool via generated frictional between the FSW tool and the butt surfaces of the base materials [10]. The newly designed non-consumable tool which has more hardness than the base alloy materials [11, 12] and it consists of a different pin diameter, shoulder diameter and pin length which are used to produce butt joints. A large amount of frictional force developed by the tool shoulder which makes the recrystallization of the atoms in the nugget zone [13].

Hou JC et al. [14] made an investigation on the effects of the tool rotational speed with self-reacting friction stir welding (FSW) tool of the butt joint properties of aluminium alloys. They reported that the defect-free sound welds were observed for the lower tool rotational speeds, whereas the voids at the root of the tool were found for the higher rotational speeds with an increase in grain size at the weld nugget zone. The interface of the two alloying elements has the lower hardness relate to the stir zone and base metal zone. The plasticized materials were formed due to the plunging force and rotational speed of the tool pin and these materials were allowed to move towards the axis of the tool [15]. The formation of the oxide layers in the welded joints of aluminium alloys based on the proper selection of input parameters, viz., tool rotational speed, welding speed etc., were studied and breaking of these layers were investigated in addition to Nanoparticles [16]. The material flow depends on the tool geometry, such as pin shape, tool pin diameter and tool shoulder diameter and which is decided by the transverse speed of the FSW tool. The formation of voids in the aluminium alloys minimized by the tool shoulder [17]. The authors [18] have made a joining of AA6061-T6 aluminium alloys using friction stir welding and studied the behavior of the material flow and heat transfer of the aluminium alloys with the cylindrical concave tool. The friction stir processing (FSP) improves the aluminium alloys and their combinations toughness and flexibility in the specific area of the microstructure of the aluminium alloys with the formation of fine grains [19].

It is evident that very limited work carried out earlier on the friction stir processing of different grades of aluminium alloys. In this investigation, an attempt has been done to study the influence of FSP parameters on the tensile properties and microstructure of dissimilar AA8011-H24 and AA6061-T6 aluminum alloy joints in Nugget Zone.

Table 1 Chemical compositions (wt. %) and Mechanical properties of the AA 6061-T6 and AA 8011-H24 aluminium alloys

Alloy	Mg	Mn	Cu	Fe	Si	Zn	Ti	Al	Tensile strength Mpa	Density kg/m ³
AA 6061-T6	1	0.15	0.27	0.7	0.6	0.6	0.15	Balance	310	2700
AA 8011-H24	0.1	0.1	0.1	0.75	0.7	0.1	0.05	Balance	140	2689

2. Experimentation work

2.1 Selection of Workpiece Materials

The precipitation hardened, solutionized and artificially aged AA 6061-T6 aluminium alloy containing magnesium and silicon as major alloying elements which are placed on the advancing side, whereas the AA 8011-H24 aluminium alloy (purchased from Ultimate Enterprises, Chennai) [20] is placed on the retreating side. The chemical composition of the alloy elements in (Wt. %) and mechanical properties of the aluminium alloys are given in Table 1. The aluminium plates were cut to the dimensions of 150 mm x 150 mm x 6 mm by power hacksaw and machined by grinding. Furthermore, the cut plates were cleaned in an ultrasonic sonicator bath and cleaned with acetone.

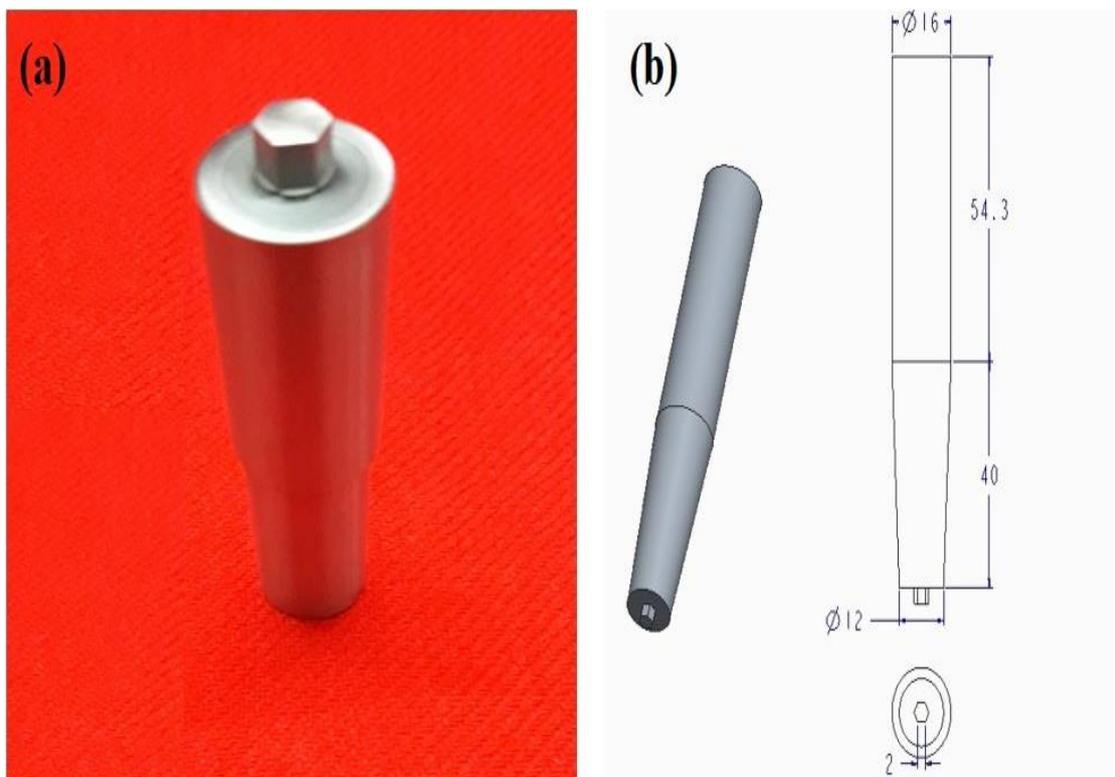


Figure 1 FSW Hexagon pin tool

2.2 Selection of Tool materials

The tool material, D2 grade steel (High Carbon-High Chromium steel) tool (Procured from SRK Diamond tools, Chennai) was selected for friction stir welding process to join the AA 8011-H24 and AA 6061-T6 aluminium alloys. The non-consumable FSW tool was designed based on the requirements with the dimensions of shoulder diameter 18 mm, shank diameter 16 mm, pin length of 54.3 mm, pin diameter of 12 mm and pin side length of 2 mm with hexagonal pin profile shown in Figure 1 which is used for joining of these alloys.

Table 2 Different combinations of aluminium alloys

Sl.No.	Material Combinations of Aluminium alloys	Status of Nano particles used
1	AA 8011 - AA 8011	Without Nano Particles
2	AA 8011 - AA 6061	Without Nano Particles
3	AA 6061 - AA 6061	Without Nano Particles
4	AA 8011 - AA 8011	With Al ₂ O ₃ Nano Particles
5	AA 8011 - AA 6061	With Al ₂ O ₃ Nano Particles
6	AA 6061 - AA 6061	With Al ₂ O ₃ Nano Particles
7	AA 8011 - AA 8011	With SiC Nano Particles
8	AA 8011 - AA 6061	With SiC Nano Particles
9	AA 6061 - AA 6061	With SiC Nano Particles

In this investigation, the nine different aluminium alloy material combinations shown in Table 2 was friction stir welding and processing in addition to two different nanoparticles, such as SiC and Al₂O₃. The process parameters are the key factors in deciding the quality of the welded joints which is obtained in a similar way [21]. The FSW parameters were considered, such as 1200 RPM tool rotational speed, 50 mm/min welding speed and plunge depth of 2 mm in joining of two different grades of aluminium alloy in butt joint configuration. The microstructure of the friction stir welded joints were examined by preparing the specimens based on the ASTM E340-15 standard after dipped into the Keller's reagent for 20 seconds and immediately washed through water [22] and it reveals the good microstructure at the welded region. The Optical microscope, Scanning Electron Microscope (SEM) with Electron Dispersive Spectroscopy (EDS) respectively were used to find the macrostructure, microstructure analysis of the dissimilar welded joints. The tensile test was conducted on the welded specimen which was prepared as per ASME Sec IX standards.

3. Results and Discussions

The following results have been observed from the testing done for the weld specimens with different specifications.

3.1 Macrostructure of the FSW/FSPed Joints in the Nugget Zone

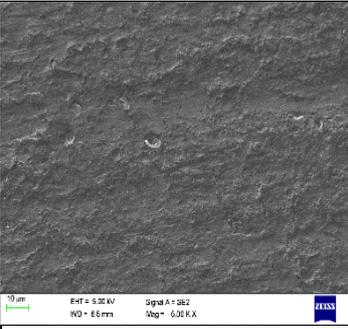
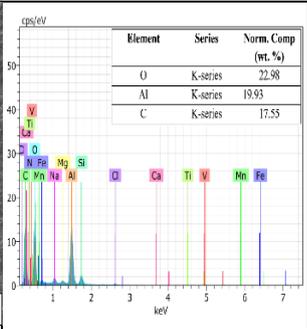
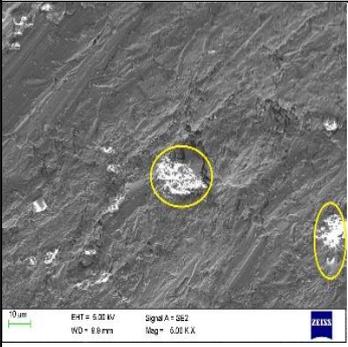
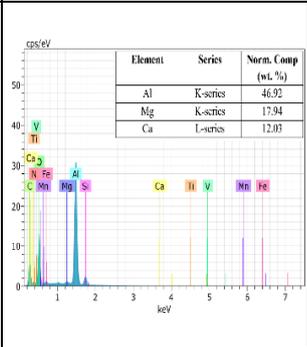
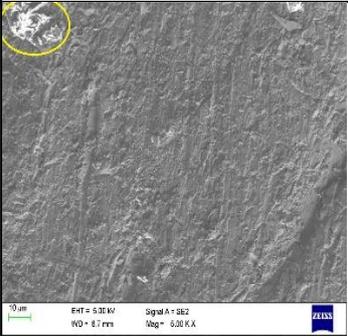
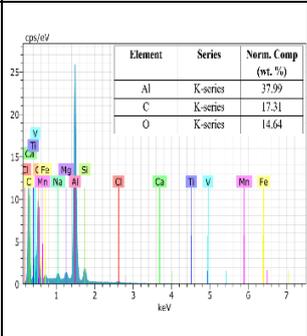
The defect-free sound weld was found to improve the joint strength by the macrostructure examination of the welded joints. Table 3 shows the macrostructure of the friction stir welding and processing joints of the different grades of aluminium alloys in the weld nugget zone. The appearance of tunnel defects was observed in the both similar and dissimilar AA 8011 and AA 6061 aluminium alloys without nanoparticles due to lack of material mixing in the root of the tool inside the aluminium alloys in the stir zone. The defect-free friction stir processed joints were observed on the dissimilar aluminium alloys due to the proper mixing of material and plastic deformation in the stir zone of both FSW/FSP welded joints and similar to Threadgill PL et al. [23].

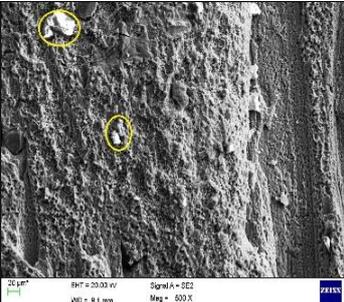
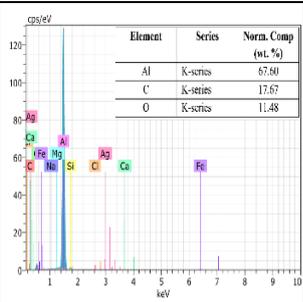
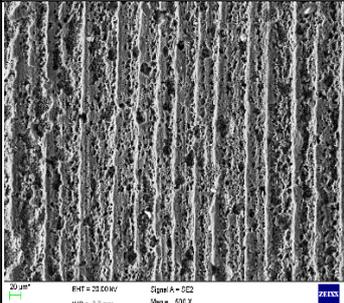
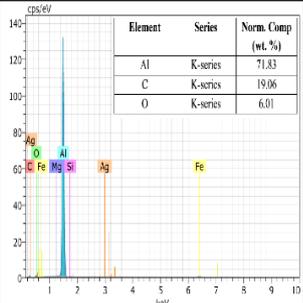
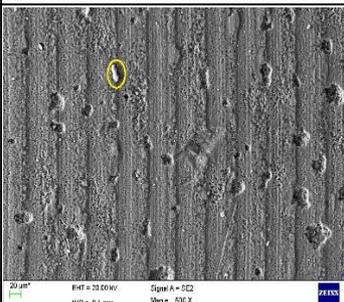
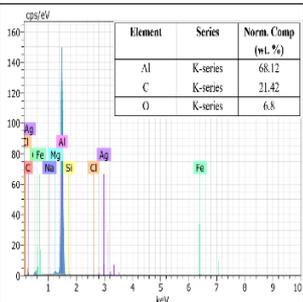
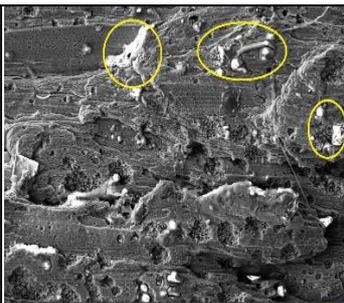
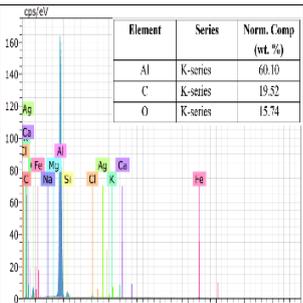
Table 3 Macrostructure of the FSW/FSPed Joints in the Nugget Zone

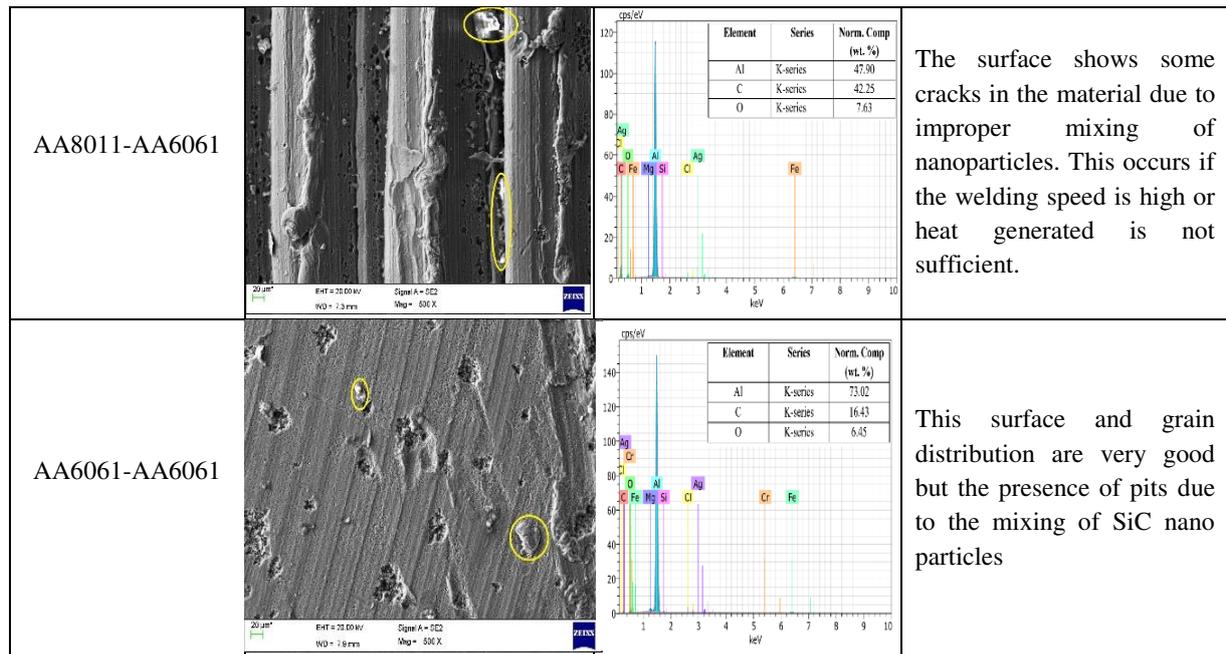
Material Combinations	Macrostructure	Name of the Defects	Probable reason
(Without Nano Particles)			
AA8011 - AA 8011		Tunnel Defect	Tunnel defect is identified due to improper heat generation.
AA6061 - AA6061		Tunnel defect	Cavities were observed in this joint due to uneven mixing of nano particles.
AA8011 - AA6061		Tunnel defect	Tunnel defect is observed because of less hardness material at retreating side.
(With Al₂O₃ Nano Particles)			
AA8011 - AA 8011		No defects	No defects are appeared due to proper mixing of materials.
AA6061 - AA6061		No defects	Mixing is done properly and no defects are found.
AA8011 - AA6061		No defects	Good structure is observed due to proper mixing of nanoparticles at the stir zone.
(With SiC Nano Particles)			
AA8011 - AA 8011		No defects	No defects are observed due to sufficient amount of heat generation.

AA8011 - AA6061		No defects	Due to sufficient material flow and plastic deformation by the generated heat, there is no defects are observed
AA6061 - AA6061		No defects	Due to the proper selection of nanoparticles and process parameters good structure is obtained.

Table 4 SEM and EDS Images of the FSW/FSPed Joints in the Nugget Zone

Material Combinations	SEM Microstructure	EDS Image	Inferences												
(Without Nano Particles)															
AA8011-AA 8011		 <table border="1" data-bbox="877 918 1069 1030"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>O</td> <td>K-series</td> <td>22.98</td> </tr> <tr> <td>Al</td> <td>K-series</td> <td>19.93</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>17.55</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	O	K-series	22.98	Al	K-series	19.93	C	K-series	17.55	Proper mixing has been done and intermetallic components were not found.
Element	Series	Norm. Comp (wt. %)													
O	K-series	22.98													
Al	K-series	19.93													
C	K-series	17.55													
AA8011-AA6061		 <table border="1" data-bbox="877 1265 1069 1377"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>46.92</td> </tr> <tr> <td>Mg</td> <td>K-series</td> <td>17.94</td> </tr> <tr> <td>Ca</td> <td>L-series</td> <td>12.03</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	46.92	Mg	K-series	17.94	Ca	L-series	12.03	The surface seems to be clear with evenly distributed grains but with the presence undissolved intermetallic components.
Element	Series	Norm. Comp (wt. %)													
Al	K-series	46.92													
Mg	K-series	17.94													
Ca	L-series	12.03													
AA6061 - AA6061		 <table border="1" data-bbox="877 1612 1069 1724"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>37.99</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>17.31</td> </tr> <tr> <td>O</td> <td>K-series</td> <td>14.64</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	37.99	C	K-series	17.31	O	K-series	14.64	The surface seems to be clear with evenly distributed grains but with the presence of little amount unprocessed intermetallic components here and there.
Element	Series	Norm. Comp (wt. %)													
Al	K-series	37.99													
C	K-series	17.31													
O	K-series	14.64													

(With Al₂O₃ Nano Particles)															
AA8011-AA 8011	 <p>30.0µm EHT = 20.00 kV Signal A = SE2 WD = 8.1 mm Mag = 500 X</p>	 <table border="1"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>67.60</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>17.67</td> </tr> <tr> <td>O</td> <td>K-series</td> <td>11.48</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	67.60	C	K-series	17.67	O	K-series	11.48	<p>The surface is rough and intermetallic compounds are found due to improper mixing.</p>
Element	Series	Norm. Comp (wt. %)													
Al	K-series	67.60													
C	K-series	17.67													
O	K-series	11.48													
AA8011-AA6061	 <p>20.0µm EHT = 20.00 kV Signal A = SE2 WD = 7.7 mm Mag = 500 X</p>	 <table border="1"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>71.83</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>19.06</td> </tr> <tr> <td>O</td> <td>K-series</td> <td>6.01</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	71.83	C	K-series	19.06	O	K-series	6.01	<p>The surface is very clear with no presence of intermetallic components. But we can observe voids due to improper mixing or insufficient rotational speed.</p>
Element	Series	Norm. Comp (wt. %)													
Al	K-series	71.83													
C	K-series	19.06													
O	K-series	6.01													
AA6061-AA6061	 <p>20.0µm EHT = 20.00 kV Signal A = SE2 WD = 8.1 mm Mag = 500 X</p>	 <table border="1"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>68.12</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>21.42</td> </tr> <tr> <td>O</td> <td>K-series</td> <td>6.8</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	68.12	C	K-series	21.42	O	K-series	6.8	<p>Grain distribution is properly done but the presence of Pits due to the mixing of Al₂O₃ nanoparticles has been improperly done which lead to the formation of intermetallic components.</p>
Element	Series	Norm. Comp (wt. %)													
Al	K-series	68.12													
C	K-series	21.42													
O	K-series	6.8													
(With SiC Nano Particles)															
AA8011-AA 8011	 <p>20.0µm EHT = 20.00 kV Signal A = SE2 WD = 14.9 mm Mag = 500 X</p>	 <table border="1"> <thead> <tr> <th>Element</th> <th>Series</th> <th>Norm. Comp (wt. %)</th> </tr> </thead> <tbody> <tr> <td>Al</td> <td>K-series</td> <td>60.10</td> </tr> <tr> <td>C</td> <td>K-series</td> <td>19.52</td> </tr> <tr> <td>O</td> <td>K-series</td> <td>15.74</td> </tr> </tbody> </table>	Element	Series	Norm. Comp (wt. %)	Al	K-series	60.10	C	K-series	19.52	O	K-series	15.74	<p>The surface seems to be rough and with the presence of intermetallic components which were not melted by insufficient heat generation.</p>
Element	Series	Norm. Comp (wt. %)													
Al	K-series	60.10													
C	K-series	19.52													
O	K-series	15.74													



In both similar and dissimilar AA8011-H24 and AA6061-T6 aluminium alloys, the surface appearance is clear and there is proper distribution of grains without intermetallic components is presented in Table 4. The usage of Al₂O₃ nanoparticles in similar welding, especially in AA6061-AA6061-T6 aluminium alloys, has led to defect-free joints and clear surface without any intermetallic components and in the dissimilar welding joint was formed without any defects but the surface showed some voids and intermetallic components in the specimen. In the specimens where SiC was used as nanoparticles in similar welding the specimen (AA6061-AA6061-T6) gave better weld surface and joint when compared to (AA8011-AA8011-H24) and in dissimilar welding the intermetallic components were formed which leads to improper mixing of base metals and formation of tiny cracks in the weld region and similar discussion was made on the dissimilar aluminium alloys by Rodrigues DM et al. [24].

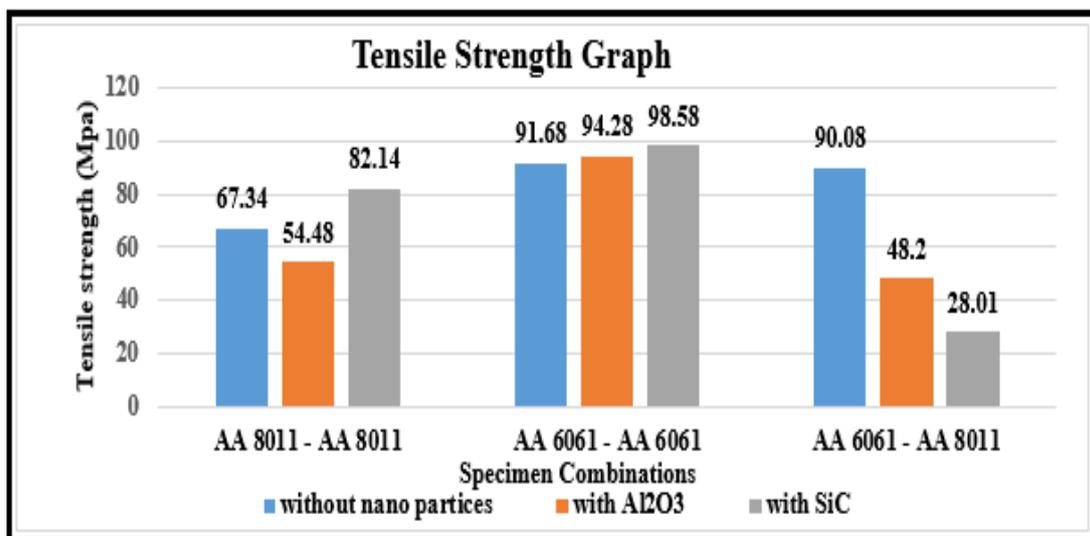


Figure 2 Tensile strength graph for different combinations

3.2 Analysis of the Tensile Strength of the FSW/FSP joints in Nugget zone

The tensile strength analysis of a specimen gives the value of axial pull up to which the material or substance can withstand without breaking. In this work, the Friction Stir Welded specimens were cut as per the ASME standard dimensions and tensile strength analysis has been made. The results are plotted on a graph for different combinations and is presented in Figure 2. The tensile strength graph is drawn based on the values obtained from the tensile test on the welded joints. From the graph, the similar AA 6061 with AA6061 aluminium alloys with and without nanoparticles showed the maximum tensile strength compared to the other material combinations of the welded joints. Furthermore, the similar AA6061 aluminium alloys combinations in addition to SiC nanoparticles gave better tensile strength, viz., 98.58 Mpa in the welded region when compared to other combinations of the welded joints due to the proper diffusion of the SiC nanoparticles in the stir zone of the similar friction stir welded AA 6061 aluminium alloys.

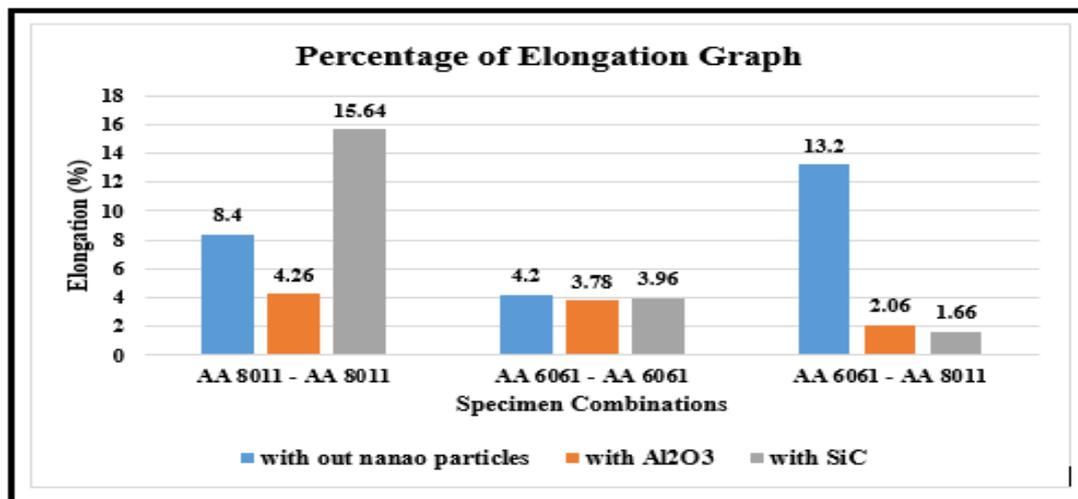


Figure 3 Percentage of Elongation of different specimens

The proper dynamic recrystallization of the materials was appeared in the weld nugget zone by the developed heat in the joints compared to other combinations of the materials with and without nanoparticles [25]. The tensile strength of 90.08 Mpa was found in dissimilar friction stir welding of AA 8011 with AA 6061 aluminium alloys without nano additions whereas the lower strength was observed with nanoparticles due to the improper material flow and the formation of the intermetallic compounds.

3.3 Analysis of the Percentage of Elongation of the FSW/FSP joints in Nugget zone

The percentage elongation showed the strength properties of the dissimilar friction stir welded different grades of aluminium alloys. Figure 3 shows the percentage of elongation of both the similar and dissimilar AA 6061 and AA 8011 aluminium alloys with and without the addition of the nanoparticles. The elongation of 8.4 % was achieved for the similar AA 8011 aluminium alloys in the stir zone, whereas these alloys with the SiC nanoparticles addition increases the elongation properties and showed 15.64 % compared to other combination of the welded joints. Furthermore, the minimum elongation was obtained in the hot worked aluminium alloy combinations with and without nanoparticles, while the dissimilar AA6061 and AA 8011 alloys without nanoparticles have the maximum hardness of 13.2 % compared to the addition of the nanoparticles.

4. Conclusion

The study was done successfully on the influence of FSP parameters on the tensile properties and microstructure of dissimilar AA8011-H24 and AA6061-T6 aluminum alloy butt joints in Nugget Zone and the following conclusions can be drawn:

- The microstructure analysis showed that both similar and dissimilar FSP joints in addition to Al₂O₃ revealed the better microstructure in the stir zone relate to the SiC nanoparticles in stir zone, whereas the SiC nanoparticles processed welded joints gave the better results than the others in the thermomechanically affected zone at Advancing side.
- The tensile strength of 98.58 % and 90.08 % was found at the weld nugget zone of the similar AA6061 aluminium alloys in addition to SiC nanoparticles and dissimilar friction stir welding of AA 8011 with AA 6061 aluminium alloys without nano additions respectively.
- The similar friction stir welded AA 8011 aluminium alloys in addition to SiC nanoparticles showed the better percentage of elongation compared to other combinations of the welded joints.

5. References

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