Effect of Process Parameters on Microstructural and Mechanical Properties of Friction Stir Welded 2219 Aluminium Alloys

Sreenivas P1* and Sreejith P S2

1 College of Engineering Cherthala, Kerala, 688541, India.
2 Cochin University of Science & Technology, Kochi, Kerala, 682022, India.
*Corresponding author

Abstract

The effect of process parameters on the mechanical and microstructural properties of friction stir welded AA 2219 alloy is elucidated in this study. Tool rotational speed, tool traversal speed, vertical force and pin profile were considered as process parameters in the investigation. Based on the conclusion that the tool pin profile is the most influential parameter in deciding the weld strength, the microstructural changes with various pin profiles were examined. Microhardness profile was taken as the preliminary informative source for microstructural changes. Optical microscopy and scanning electron microscopy (SEM) was used for identifying the microstructural changes and behavior of strengthening precipitates. Energy dispersive spectroscopy (EDS) was conducted to identify the precipitates and their distribution. Distribution and dissolution of precipitates were distinct for different tool pin profile which is symptomatic for the variation in mechanical properties.

Keywords : Friction stir welding, AA2219 alloy, microstructure, strengthening precipitates, tool pin profile.

1. INTRODUCTION

Friction stir welding (FSW) has become a favourite choice for material joining as it eliminates the defects associated with the conventional fusion welding processes [1]. In FSW material joining is taken place much below the melting point of the base material.
Lower operating temperature avoids the chances of residual stress, corrosion and related issues in welded joints. As FSW does not associate with fumes and the use of filler material, it circumvents many environmental and safety issues.

In FSW a non consumable rotating tool with a shoulder and a specially designed pin is traversed along the faying surfaces of the base metals. The friction between the plates and tool increases the temperature and generates the metallic flow. At the joint, the base material is plastically deformed and extruded by the tool action to form the joint at elevated temperature generated by friction and heat of deformation [4]. Metallic joint is achieved through viscoplastic deformation and consequent heat dissipation occurring much below the melting point of the base metal.

AA2219 is an Al- Cu -Mn ternary alloy which can be approximated to Al- Cu binary alloy for analysis. As it offers high strength and toughness at low temperatures, AA2219 is a popular choice for the construction of cryogenic components [5]. AA 2219 belongs to the group of heat treatable alloys which increases their strength by heat treatment. It assumes higher strength on heat treatment by the presence of fine precipitates, mainly Al$_2$Cu particles [6]. It was reported that Friction stir welded AA2219 alloy joints exhibit superior tensile and fatigue properties compared to electron beam welding (EBM) and guided tungsten arc Welding (GTAW) processes [7]. AA 2219 exhibited superior weldability, but it recorded poor weld strength. Malarvizhi et al., [8] promulgated that during fusion welding, strengthening precipitates got dissolved and the material behaved like cast metal with solute segregate and columnar grains. Various studies suggested that the size and distribution of Al$_2$Cu particles play a major role in deciding the tensile properties and hardness of the heat treated alloys [9, 10]. Attallah and Salem [11] observed that the static properties of friction stir welded AA2219 is dependent on the distribution of strengthening precipitates rather than the grain size. These strengthening precipitates are formed due to the solution treatment and subsequent artificial aging. In FSW there is no melting and hence no dissolution of precipitates in the matrix, theoretically, but it was reported by Cao and Kou [12] that during FSW the Al$_2$Cu particles show clear evidence of agglomeration. Biswas et al. [13] examined the effect of varying tool geometry on the FSW of Al- Si alloy. They suggested that grain size was the maximum in the nugget zone for the joints made by the tapered cylindrical pin profile. These observations are significant in the investigation of effect of process parameters on the strength of FSW. Nevertheless, any influence of the process parameters on the alteration of strengthening precipitates has not been clearly established in these studies. These reports have not explicitly correlated the effect of process parameters on the microstructure of the welds as well.
The effect of process parameters on the weld quality and strength in FSW have been extensively studied by many researchers. These experimental studies or simulation analyses were concentrated on the optimum parametric combination for desirable results for welds, or figuring out the most influential parameter for obtaining good welds. But studies on the effect of parameters on weld quality correlated with the microstructural changes are scarce. In this paper efforts to correlate the effect of most influential parameter on the strength of friction stir welded AA 2219 alloy with the microstructural changes are elaborated.

2. MATERIALS AND METHODS
The base metal used in the experiments was AA 2219 in annealed condition. The chemical composition and mechanical properties of base metal are summarized in Table 1 and 2.

Table 1. Chemical composition (Wt. %) of base metal

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mn</th>
<th>Zr</th>
<th>V</th>
<th>Ti</th>
<th>Fe</th>
<th>Si</th>
<th>Zn</th>
<th>Mg</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.2</td>
<td>0.3</td>
<td>0.11</td>
<td>0.09</td>
<td>0.16</td>
<td>0.05</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of base metal

<table>
<thead>
<tr>
<th>Property</th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>% Elongation (On 50mm GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>151.2</td>
<td>68</td>
<td>15</td>
</tr>
</tbody>
</table>

The metallic plates of 6 mm thickness were cut in to 150 mm length and 50 mm wide rectangular pieces. The parameters considered were tool rotational speed, tool traversal speed, axial force and tool pin profile. The various parametric levels and the experiment matrix are given as Table 3 and 4.

Table 3. Parameters and levels used in the experiments

<table>
<thead>
<tr>
<th>Factors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotational speed, N (rpm)</td>
<td>1200</td>
<td>1400</td>
<td>1600</td>
</tr>
<tr>
<td>Tool traversal speed, S (mm/min)</td>
<td>125</td>
<td>151</td>
<td>180</td>
</tr>
<tr>
<td>Vertical force, F (kN)</td>
<td>11</td>
<td>12.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Tool pin profile, D</td>
<td>TC</td>
<td>SC</td>
<td>THC</td>
</tr>
</tbody>
</table>
Three types of pin profiles; straight cylindrical pin (SC), tapered cylindrical (TC) pin and threaded cylindrical (THC) pin were used for the experiment as shown in Fig.1.

![Fig. 1 Tool pin profiles](image1)

Tool was fabricated from H13 tool steel and heat treated. Tool shoulder diameter was kept constant at 18mm and pin diameter was fixed at 6mm. Pin length was fixed as 5.8mm to ensure sufficient plunge depth and the prevention of any damage to the pin by striking on the backing plate. The experiments were carried out on a 11KV/1440 RPM/440 V (AC) direct FSW machine.

Tensile test specimens were cut perpendicular to the weld seam from the welded pieces in a milling machine, and prepared in accordance to ASTM E8M-04 standards.

![Fig. 2 Tensile test specimen](image2)

Microhardness values were measured employing a Vickers hardness testing machine across the weld with a load of 0.5 Kg. Micro structural analysis was carried out using a Trinocular metallurgical microscope and specimen were etched with Keller’s
reagent. The combinations of specific precipitates were identified by scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS).

3. RESULTS AND DISCUSSION
Typical macroscopic zones pertaining to the friction stir weld is shown in Fig.2

![Fig.2 Typical macroscopic zones associated with FSW](image)

BM- Base metal; RS- Retreating side; SZ- Shoulder zone; TMAZ- Thermo mechanically affected zone; PZ- Pin driven zone; NZ- Nugget zone; AS- Advancing side.

As the rotating tool traverses along the weld line forging action of the tool shoulder triggers softened material flow in the shoulder zone (SZ) down ward and continuously. Whereas the pin initiates the material movement in the pin driven zone (PZ), from retreating side (RS) to advancing side (AS) [14]. Accordingly the material in the PZ may be subjected to the maximum strain and strain rate depending upon the process parameters and pin geometry.

The concentration of Cu in AA 2219 alloy is 6.2%, which exceeds the maximum solubility of Cu in aluminium; therefore the base material can be considered to have \(\alpha\), aluminium matrix and additional \(\theta\) particles identified as Al\(_2\)Cu [15]. The chemical composition of the constituent elements in the alloy AA2219 allows us to approximate it as a binary alloy of 6.2 weight percent of Cu. Optical micrograph of the base material showed matrix of uniform eutectic grains of inter metallic particles in aluminium solid solution. Some lumps of free copper were also observed (Fig.3.a). Nature of the precipitates indicates that the material is in annealed condition.
In general, the SZ depicted presence of fragmented particles of Al$_2$Cu with some large presence of free copper as shown in Fig. 3, which indicated that the heat input was low and otherwise more amount of copper would have been dissolved. The interface zone of TMAZ and NZ showed grains oriented by the effect of stress and heat. Grains were appeared to be finer due to fragmentation. In contrast to taper pin profile, interface region of TMAZ and NZ of the welds, generated by threaded and straight cylindrical profile showed disoriented grains even when grains appeared to be finer due to fragmentation. It was observed for tapered pin profile and for $N=1200$, $S=125$, $F=11$, the nugget zone below the pin showed the three districts zones tend to separate and giving origin for a tunnel defect as shown in Fig. 3.f. This could be due to inadequate stirring and mixing of material resulted from lower heat input. Adamowski and Szkodo, Lakshminarayanan et al., and Reghubabu et al. [16-18] have reported similar cases for different pin profiles and for different alloys. In all these cases a deviation from an optimum cobination of speed and rpm of tool can be seen as a common cause for this defect.

FSW of high strength aluminium alloys shows soluble and insoluble second phase particles [19]. In case of AA2219 alloys Al$_2$Cu precipitates were identified as the second phase particles in the nugget zone [20]. It was observed that FSW of aluminium alloys with low heat input resulted in refinement of grain structure along with the dissolution of the precipitates [21].

The type of pin profile was appeared to have influenced the nugget microstructure significantly. It was reported that the presence of un dissolved strengthening precipitates contribute significantly to the ultimate tensile strength of friction stir
welded joints of precipitation hardened aluminium alloys [22]. In case of AA2219 alloy, as the temperature increases, the strengthening precipitates may re-enter to the solid solution lowering the hardness. But on cooling part of the welding thermal cycle some of them may re-precipitate, favouring the total hardness of the weld [23].

**Fig. 4.** Optical micrograph of NZ for different pin profiles a. Tapered pin b. Cylindrical pin c. Threaded pin.

In our case, the NZs exhibited fine recrystallised grains. Tapered cylindrical pin caused fine fragmented particles of Al\(_2\)Cu in Al solid solution. NZ for tapered and threaded pin profile tools showed finer and partially dissolved particles of Al\(_2\)Cu. The NZ of the threaded pin profile was characterised by boundary mis orientation of grains and finer grains compared to other pin profiles as shown by the optical micrograph in Fig. 4 and SEM images in fig. 5. EDS analysis indicated that Cu and Al make the major components of the intermetallic compounds. The intermetallic particles were identified as Al\(_2\)Cu by EDS spectra shown in Fig. 6. For the straight cylindrical and threaded pin profiles the microstructure indicated that some re precipitation could be expected.

**Fig. 5.** SEM images of NZ for different pin profiles: a. Cylindrical. b. Taper. c. Threaded. d. Base metal
Fig. 6. EDS element spectrum in the weld nugget. a. Base Metal. b. Taper pin. c. Cylindrical.

d. Threaded pin
The EDS spectra indicated that presence of θ particles may be more for threaded pin profiles, according to Fig. 6 and table. 4.

<table>
<thead>
<tr>
<th>Pin Profile</th>
<th>Element</th>
<th>Weight%</th>
<th>Atomic%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical pin</td>
<td>Al</td>
<td>86.92</td>
<td>86.53</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>6.34</td>
<td>2.68</td>
</tr>
<tr>
<td>Taper pin</td>
<td>Al</td>
<td>87.63</td>
<td>87.91</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>6.49</td>
<td>2.77</td>
</tr>
<tr>
<td>Threaded</td>
<td>Al</td>
<td>84.35</td>
<td>87.06</td>
</tr>
<tr>
<td></td>
<td>Cu</td>
<td>10.47</td>
<td>4.59</td>
</tr>
</tbody>
</table>

Fig. 7 illustrate the variation in ultimate tensile strength (UTS) for various pin profiles. The analysis of results showed that the pin profile is most influential parameter determining the tensile strength. The maximum tensile strength was recorded for the welds generated by the threaded pin profile.
The microhardness variations across the various regions of the welded plates are shown in Fig. 8. The NZ recorded highest hardness for threaded and cylindrical pin profiles. Weld produced using the threaded pin profile exhibited the maximum hardness. Hardness variation registered higher values for the advancing side as reported elsewhere [24]. The variation in the microhardness values is expressive of the microstructural changes. For various pin profiles higher values were registered for hardness in the stir zone than that of TMAZ. Generally in case of FSW of aluminium alloys strengthening particles were reported to be dissolved by the stirring effect of pin and the frictional heat [25]. But due to the higher strain rate re precipitation of the strengthening particles may occur in the case of AA2219 alloy [26]. The higher values of microhardness in the stir zone may be attributed to the re precipitation of the strengthening particles. Microhardness variation in this case shows that hardness assumes the highest value for the threaded pin profile. Both grain size and presence of \(\theta\) particles contributed to the strength of the weld joints. Grain size is determined by the frictional heat generated and the cooling rate. But here tool pin profiles did not have any flat faces and hence the frictional heat generated was not much influenced by the pin profile. The microstructures of the shoulder zones were almost identical as shown in the optical micrographs which indicated nearly identical heat generation. Presence of fine and un dissolved precipitates might have contributed to the higher strength and hardness of the weldments in case of the welds produced using threaded pin profiles.
4. CONCLUSION
Effect of the tool pin profiles on the microstructure and mechanical properties of the weld nuggets for the FSW of AA2219 alloy were examined. Distribution and behavior of strengthening precipitates were identified. Tensile properties and microhardness distribution were evaluated. The results of the study can be summarized as follows.

- Welds generated by the threaded pin profile exhibited maximum tensile strength and microhardness.
- Distribution of strengthening precipitates indicated that re precipitation of the Al2Cu particles occurred on cooling of the welds.
- SEM and EDS analysis indicated that the precipitation of the Al2Cu particles was more for the welds generated by the threaded pin profile.
- Presence of fine and undissolved precipitates might have contributed to the higher strength and hardness of the welds produced using threaded pin profiles.

REFERENCE
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