CHAPTER 4

EFFECT OF PROCESS PARAMETERS ON HIGH SPEED

FSW OF AA 2219 ALLOY

4.1 INTRODUCTION

FSW brought a radical change in metal joining processes. Since the inception of this technology, the researchers have mainly focused on consolidating the process parameters for the process feasibility and productivity. Nevertheless, studies to suggest an appropriate combination of process parameters are yet to be concluded. The process parameters apparently affect the thermal cycle and material flow, which in turn determine the weld quality. The thermal cycle brings about the microstructural changes which are to be thoroughly investigated for assessing the weld quality and feasibility of FSW process. Grain structure and the precipitates distribution are the traits of the welds which are to be focussed. In case of precipitation hardenable alloys the changes occur during FSW has more impact on the weld quality. AA 2219 is a precipitation hardenable alloy popular in aerospace applications [131]. As it offers high strength and toughness at low temperatures, AA 2219 is selected for the construction of cryogenic elements. Comparative experimental studies indicated that friction stir welded AA 2219 alloy joints exhibit superior tensile and fatigue properties compared to electron beam welding (EBM) and guided tungsten arc Welding (GTAW) processes [132]. With conventional welding process, AA 2219 exhibited superior weldability, but it recorded poor weld strength. Being a precipitation hardened alloy, the microlevel changes occur to the strengthening precipitates during FSW is crucial for the weld properties of AA 2219 alloy joints [133]. Attallah and Salem, postulated that the static properties of friction stir welded AA 2219 is dependent on the distribution of strengthening precipitates rather than the
grain size [28]. 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, but it was reported that during FSW the Al₂Cu particles show clear evidence of agglomeration [80]. These observations are significant in the investigation of effect of process parameters on the strength of FSW of precipitation hardened alloys.

In the reported studies to optimize the process parameters of FSW for AA 2219 alloy, the tool traversal speeds were found to be significantly low. In this report, the effort and results of the experimental analysis to achieve an optimum combination of process parameters of FSW for AA 2219 at higher traversal speed is elaborated.

4.2 MATERIALS AND EXPERIMENTATION:

AA 2219 is an Al - Cu - Mn tertiary alloy with remarkable cryogenic properties. The chemical composition and mechanical properties of base metal are summarized in Tables 4.1 and 4.2. AA 2219 in annealed condition was used as the base metal for the experiments.

<table>
<thead>
<tr>
<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>6.2</td>
<td>0.3</td>
<td>0.11</td>
<td>0.09</td>
<td>0.06</td>
<td>0.16</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
<td>93.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>% Elongation(On 50mm GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>151.2</td>
<td>68</td>
<td>15</td>
</tr>
</tbody>
</table>
The metallic plates of 6 mm thickness were cut into 150 mm length and 50 mm wide rectangular pieces. L9 orthogonal array of the Taguchi design method was used as the design matrix. The parameters considered were tool rotational speed, tool traversal speed, axial force and tool pin profile. The various parametric levels and the design of experiment matrix are given as Tables 4.3 and 4.4.

Table 4.3. Factors 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>Taper</td>
<td>Cylindrical</td>
<td>Threaded</td>
</tr>
</tbody>
</table>

Table 4.4. Design matrix for experiments

<table>
<thead>
<tr>
<th>Expt. No.</th>
<th>N</th>
<th>S</th>
<th>F</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200</td>
<td>125</td>
<td>11.0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>151</td>
<td>12.5</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>180</td>
<td>14.5</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>125</td>
<td>12.5</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1400</td>
<td>151</td>
<td>14.5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>1400</td>
<td>180</td>
<td>11.0</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1600</td>
<td>125</td>
<td>14.5</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>1600</td>
<td>151</td>
<td>11.0</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>1600</td>
<td>180</td>
<td>12.5</td>
<td>1</td>
</tr>
</tbody>
</table>
The effect of tool action was analysed by varying the pin of the cylindrical tools. Three types of tools with different pin profiles viz. cylindrical pin, tapered pin and threaded pin were used for the experiment as shown in Fig. 4.1.

Fig. 4.1. Tool pin profiles

Tools were fabricated from H 13 tool steel and heat treated. As a thumb rule the tool pin diameter were suggested as equal to the base metal thickness and the shoulder diameter was suggested as equal to three times that of the pin diameter. Accordingly, tool shoulder diameter was kept constant at 18 mm and pin diameter was fixed at 6 mm. Pin length was fixed as 5.8 mm 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 tests were carried out on the specimen cut perpendicular to the weld seam and prepared in accordance to ASTM E8M - 04 standards. Specimens were cut in a milling machine. Micro structural analysis was carried out using a Trinocular metallurgical microscope (TMM) and specimen were etched with Keller’s reagent.

4.3 RESULTS AND DISCUSSION

In all cases of experiments, flashes were found on the weld indicating that the shoulder was unable to trap the material beneath it (Fig. 4.2). Researchers have
reasonably explained this phenomenon as due to the excessive axial force which caused the material to extrude out and the shoulder size was not enough to trap the extruded material. Another possibility for this phenomenon is the excessive stirring of the material due to high temperature and consequently excessive softening of the material [134]. All the welds showed a smooth surface which indicated that the weld was formed in cold condition wherein the temperature is not too high [135].

The strength of the welds was assessed by measuring the ultimate tensile strength (UTS). The value of UTS for the joints fabricated at various parametric levels is given in Table 4.5. Ultimate tensile strength was found to be the maximum for the joint fabricated with a threaded pin profile at 1200 rpm, 180 mm/min, and under an axial load of 14.5 kN.

Fig. 4. 2 Flashes on the weld surface
Table. 4.5. Process parameters and ultimate tensile strength.

<table>
<thead>
<tr>
<th>Expt. No</th>
<th>N</th>
<th>S</th>
<th>F</th>
<th>D</th>
<th>UTS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1200</td>
<td>125</td>
<td>11.0</td>
<td>1</td>
<td>50.654</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>151</td>
<td>12.5</td>
<td>2</td>
<td>58.652</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>180</td>
<td>14.5</td>
<td>3</td>
<td>109.360</td>
</tr>
<tr>
<td>4</td>
<td>1400</td>
<td>125</td>
<td>12.5</td>
<td>3</td>
<td>90.644</td>
</tr>
<tr>
<td>5</td>
<td>1400</td>
<td>151</td>
<td>14.5</td>
<td>1</td>
<td>30.980</td>
</tr>
<tr>
<td>6</td>
<td>1400</td>
<td>180</td>
<td>11.0</td>
<td>2</td>
<td>66.650</td>
</tr>
<tr>
<td>7</td>
<td>1600</td>
<td>125</td>
<td>14.5</td>
<td>2</td>
<td>61.318</td>
</tr>
<tr>
<td>8</td>
<td>1600</td>
<td>151</td>
<td>11.0</td>
<td>3</td>
<td>87.000</td>
</tr>
<tr>
<td>9</td>
<td>1600</td>
<td>180</td>
<td>12.5</td>
<td>1</td>
<td>58.652</td>
</tr>
</tbody>
</table>

4.3.1 Taguchi optimization

The effect of process parameters on the strength and efficiency of the weld joints were analysed using Taguchi optimisation. The Taguchi method employs a special design of orthogonal array (OA) to analyse the output characteristics, thereby reducing the number of experimental trials. In Taguchi analysis, two types of factors are proposed which affect the functional characteristics of a product or process: control factors and noise factors. Control factors are those factors which can easily be controlled; on the other hand noise factors are those which are difficult or too expensive to control. Taguchi method uses signal to noise (S/N) ratio to assess, how the output varies relative to the target value under different noise conditions. The S/N ratio is calculated under three criteria, namely, ‘smaller the better’, ‘larger the better’ and ‘nominal the better’ depending upon the desired output. In this case, Maximum value for UTS was considered as the desired condition. Hence Taguchi analysis was carried out with a
criterion of ‘larger the better’, using equation 4.1 for deriving the process combination for maximum tensile strength.

\[
SN_L = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)
\]  

(4.1)

The analysis was carried out using MINITAB software. The effect of each factor level on the response characteristic was displayed in the response tables and main effect plots. The degree of response to the S/N ratio gave the most influential parameter. From the mean plots of S/N ratio and mean response tables the factor and factor levels which have the maximum effect on the response characteristic and the optimum levels for the parameters were identified.

The response table for S/N ratio is given in the Table 4.6 and that for means is shown as Table 4.7. Main effect plots for S/N ratio and means are shown as Figs. 4.3 and 4.4.

Table 4.6. Response table for signal to noise ratios

<table>
<thead>
<tr>
<th>Level</th>
<th>N</th>
<th>S</th>
<th>F</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.75</td>
<td>36.33</td>
<td>36.45</td>
<td>33.09</td>
</tr>
<tr>
<td>2</td>
<td>35.15</td>
<td>34.66</td>
<td>36.63</td>
<td>35.86</td>
</tr>
<tr>
<td>3</td>
<td>36.64</td>
<td>37.54</td>
<td>35.45</td>
<td>39.57</td>
</tr>
<tr>
<td>Delta</td>
<td>1.60</td>
<td>2.88</td>
<td>1.18</td>
<td>6.48</td>
</tr>
<tr>
<td>Rank</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>
The response tables for S/N ratio and means depicted the ranks of each factor based on the delta statistics, which compared the relative magnitudes of the effect on the output characteristic. From Tables 4.6, 4.7 and main effect plots (Figs. 4.3 and 4.4) it can be confirmed that the tool pin profile have the greatest effect on the tensile strength followed by feed, rpm and axial force.
4.3.2 **Optimum combination of parameters:**

Optimum combination of the parameters was identified by choosing the factor levels which have the highest effect on the S/N ratio. Then expected response corresponding to this factor setting was obtained. The value of tensile strength so obtained was compared with the result of experiment conducted with the same factor levels. Optimum values for process parameters, predicted value of corresponding weld strength in terms of UTS and the experimental result of strength for the same parametric combinations are given in Table 4.8.

<table>
<thead>
<tr>
<th>Tool rotational speed (RPM)</th>
<th>Tool traversal speed (mm/min)</th>
<th>Axial force (kN)</th>
<th>Tool pin profile</th>
<th>UTS Predicted (MPa)</th>
<th>UTS Experimental (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>180</td>
<td>12.5</td>
<td>Threaded pin</td>
<td>111.5</td>
<td>109.8</td>
</tr>
</tbody>
</table>

Table. 4.8. Optimum parametric combination
4.3.3 Microstructure

Microstructure of the base material showed matrix of uniform eutectic grains of Cu-Al$_2$ in aluminium solid solution. Some lumps of free copper were also observed. The nature of the precipitates showed that the material is in annealed condition as shown in Fig. 4.5.

![Fig. 4.5 Optical micrograph for base metal](image1)

![Fig. 4.6 Nugget below the tapered pin; N = 1200, S = 125, F = 11](image2)

It was observed for tapered pin profile and for N = 1200, S = 125, F = 11, the nugget zone below the pin showed the three distinct zones tend to separate and giving origin for a tunnel defect as shown in Fig. 4.8. This could be due to inadequate stirring and mixing of material resulted from lower heat input as reported in some studies [156, 158, 81]. In all these cases a deviation from an optimum combination of speed and rpm of tool can be seen as a common cause for this defect.

![Fig. 4.7 Nugget zone - Tapered pin profile](image3)

![Fig. 4.8 Nugget zone - cylindrical pin](image4)
The nugget zone exhibited fine recrystallised grains (Figs. 4.7, 4.8 and 4.9). Tapered cylindrical pin caused fine fragmented particles of Al₂Cu in Al solid solution. Nugget zone for cylindrical and threaded pin profile tools showed finer and partially dissolved particles of Al₂Cu (Figs. 4.8 and 4.9). Presence of fine and undissolved precipitates has contributed to the higher tensile strength of the weldments in case of these profiles.

4.4 CONCLUSIONS

The objective of this study was to examine the feasibility of FSW of AA2219 at higher translational speeds and to determine which process parameter has the highest effect on the weld strength. Taguchi method was used to analyze the experimental results to achieve this goal. From the experimental investigation it can be concluded that:

- Friction stir welding of AA 2219 at higher translational speed is feasible by the appropriate selection of process parameters.
- The tool pin profile is the most influential process parameter in deciding the weld strength followed by tool traversal speed, tool rotational speed and axial force.
- From the experimental results an optimum combination of process parameters
has been derived as 1200 rpm for tool rotation, 180 mm/min for tool traversal speed, 12.5 kN for axial force, threaded pin profile for tool and the corresponding tensile strength has been computed as 111.5 N/mm². The results have been validated experimentally.

- The structural observations indicated that better strength of the weld while using a threaded pin profile tool was attributed to the presence of fine and undissolved particles of Al₂Cu in the nugget zone.
CHAPTER 5

EFFECT OF PROCESS PARAMETERS ON HIGH SPEED

FSW OF AA 6082 - T6 ALUMINIUM ALLOY

5.1 INTRODUCTION

Selection of the process parameters is very crucial in achieving good weld joint in the FSW. Different materials and joint configurations demand different parametric combinations. Tool rotational speed, tool traversal speed, tool shoulder geometry, pin geometry, axial force and tool tilt angle were identified as the process parameters which have effect on heat generation and material flow. In most of the analysis of the FSW, the selection of the parameters was limited to rotational speed, transversal speed, tool geometry and axial force. The role and effect of tool tilt angle were not clearly established.

It was reported that as the tool was tilted in the trailing direction, tensile strength and microhardness of the weld joint increases for dissimilar joint of aluminium and copper [78]. Researches on the FSW of dissimilar joints of aluminium and steel indicated that an increase in tool tilt angle influences the tensile strength of the welded joint [137]. Tool tilt angle of 1.5° or 2° was found to provide good results for aluminium welded joints [80, 11]. Certain studies stipulated that the surface defects can be eliminated by effective filling by tilting the tool for the FSW of aluminium alloys [138]. These reported results of the effect of tool tilt angle, were pertaining to lower welding speeds. Ana et al. [82] suggested an optimum condition for FSW of 6082 - T6 alloy with good strength at a speed of 360 mm/min. The study considered welding speed, tool rotating speed, axial force and tool tilt angle as the process parameters; nevertheless the effect of tool tilt on the weld strength was not
established. Rodrigues et al. [139] proposed that FSW at higher traverse speeds were strongly dependent on the base material characteristics and plate thickness. Good welds were up to a speed of 350 mm/min for 6 mm thick base metal. The experimental trials were performed under a wide range of process parameters including tool tilt angle. However, it was not asserted that whether the tool tilt influenced the weld quality.

Extensive researches have established the feasibility of FSW and it is commercially applied for joining aluminium alloys. However, low welding speed impedes the productivity of FSW. Hence the second phase of research in FSW needs exploring the possibility of FSW at higher welding speed.

The researches in FSW were conducted at lower or medium range of welding speeds. It is noteworthy that commercialization of FSW is retarded by lower welding speeds. The issues in high speed welding of FSW were not yet explored adequately. Efforts to identify a combination of parameters which offers welding at higher linear speeds with acceptable quality of welds are in demand by the industry. Reported efforts for the process optimization of FSW of aluminium alloys were performed at lower welding speeds [58, 70]. Table 5.1 illustrates the earlier studies focused on FSW of 6XXX series aluminium alloys to highlight the thickness, welding speed, other process parameters, weld quality and mechanical properties.

Reghubabu et al. [75] examined the effect of tool rotational speed and welding speeds on mechanical and microstructural properties of friction stir welded 6082 - T6 alloy. They carried out the experiments at the highest welding speed of 585 mm/min and suggested an optimum condition for welding with a speed of 170 mm/min.
Table 5.1 Summary of previous studies on FSW of 6XXX series alloys

<table>
<thead>
<tr>
<th>Base metal</th>
<th>Tool geometry</th>
<th>Process parameters</th>
<th>Recommended parameters</th>
<th>Tensile strength</th>
<th>Ref:</th>
</tr>
</thead>
<tbody>
<tr>
<td>6082 - T6 Thickness 1.5 mm</td>
<td>Shoulder With Scroll, Shallow cavity, Flat face. Cylindrical pin</td>
<td>N - 1810, S - 460</td>
<td>Shoulder with scroll</td>
<td>77%</td>
<td>[140]</td>
</tr>
<tr>
<td>6082 - T6 Thickness 6 mm</td>
<td>Shoulder surface with scroll and fillet, fillet and cavity, fillet. Non Threaded pin</td>
<td>N - 1810, S - 460</td>
<td>Shoulder with fillet and cavity</td>
<td>80%</td>
<td>[141]</td>
</tr>
<tr>
<td>6082 - T6 Thickness 2 mm</td>
<td>Flat shoulder Cylindrical pin</td>
<td>N - 1500, S - 400</td>
<td>-</td>
<td>80%</td>
<td>[142]</td>
</tr>
<tr>
<td>6082 - T6 Thickness 5 mm</td>
<td>Flat shoulder Threaded Pin</td>
<td>N - 215- 1700, S – 115 - 585</td>
<td>-</td>
<td>65%</td>
<td>[77]</td>
</tr>
<tr>
<td>6082 - O Thickness 5 mm</td>
<td>Flat shoulder, Taper screw thread pin, Triflute pin</td>
<td>N - 1200, S - 60, 70, 75, 85</td>
<td>Taper screw thread pin, 1200, 70</td>
<td>92%</td>
<td>[76]</td>
</tr>
<tr>
<td>6082 - T6 Thickness 6 mm, 4mm</td>
<td>Conical shoulder Cylindrical pin</td>
<td>N - 300,400, 500, S - 200,273, 350, F - 10, 15, 20, Tool tilt- 0, 1(^o),2(^o),3(^o)</td>
<td>400 rpm, 200 m/mn 500 rpm, 350 mm/mn</td>
<td>-</td>
<td>[143]</td>
</tr>
<tr>
<td>6061 - T6 Thickness 6.3 mm</td>
<td>Raised and recessed fan, Ramp shoulder Straight cylindrical pin</td>
<td>N - 1200, S - 810</td>
<td>Raised fan shoulder</td>
<td>67%</td>
<td>[144]</td>
</tr>
<tr>
<td>Base metal</td>
<td>Tool geometry</td>
<td>Process parameters</td>
<td>Recommended parameters</td>
<td>Tensile strength</td>
<td>Ref:</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------------------------------------------</td>
<td>-------------------------</td>
<td>-----------------------------------------</td>
<td>------------------</td>
<td>-----</td>
</tr>
<tr>
<td>6061 Thickness 6 mm</td>
<td>Flat shoulder Straight, Taper, Threaded, Square, and Triangular pin profiles</td>
<td>N - 1200, S - 75, F - 6, 7, 8</td>
<td>Square pin profile, 7 kN force</td>
<td>65%</td>
<td>[62]</td>
</tr>
<tr>
<td>6082- T651 thickness 6 mm</td>
<td>Flat shoulder, tapered cylindrical</td>
<td>N - 300, 400, 500, 600, 700, S - 15, 20, 25, 30, 35, F - 4, 5, 6, 7, 8</td>
<td>530 rpm, 28 mm/min, 7 kN, pin dia 7 mm</td>
<td>84.5%</td>
<td>[144]</td>
</tr>
<tr>
<td>AA 6351 Thickness 6 mm</td>
<td>Flat shoulder Square pin</td>
<td>N - 600, 782, 1050, 1317, 1500, S - 27, 51, 72, 120, 144, F - 1.2, 2</td>
<td>N - 1050 rpm, 85.2 mm/min, F 1.45</td>
<td>70%</td>
<td>[146]</td>
</tr>
</tbody>
</table>

N - Rotational speed (rpm), S - Welding speed (mm/min), F - Axial force (kN)
Patil et al. [76] investigated the effect of welding speed and tool pin profile on the weld quality of AA6082-O aluminium alloy. The study used taper screw thread and tri-flute pin profiles. They proposed a condition for high strength weld in terms of these parameters; however the maximum value of the welding speed was limited to 80 mm/min. Adamowski et al. [77] analysed the effect of welding speed and rotational speed on the FSW of 6082-T6 alloy with the highest speed of 585mm/min with a threaded pin tool. The defects associated with welds which were made at the higher range of tool linear speeds are caused by insufficient material flow. The void defect formation, widely reported in such cases was resulted from the ineffectiveness of tool action to consolidate the material flow to form a defect free joint. Material flow within the weld depends on the tool interaction with the work material which in turn depends on the tool rotational speed, welding speed and axial force exerted on the tool [147].

The material properties of the parent metal control the tool interaction during the welding process. However, for a given material the tool action is optimized by adjusting the various process parameters. The good weld condition - with sufficient strength and without defect depends on adequate softening and the flow of material during the process. The velocity of the tool traversal plays a crucial role in determining the good weld condition. Certain studies reported the feasibility of FSW at higher welding speeds by providing different shapes for the tool shoulder [148]. But such approaches enhanced the operational cost and complexity of tool fabrication. Hence, it may be appreciable if welds can be made at higher traverse speeds by adjusting the process parameters.

Higher tool travel speeds lessen the heating of base material and hence retard the material flow. The failure to make weld joint is attributed to deceleration of plastic flow of weld metal. A tool tilt accelerates the material stirring and hence the metal
flow. Moreover the pressing of tool shoulder resulting from the tool tilt may enhance the friction and therefore increase the frictional heat.

In this chapter, the results of the experiments to investigate the effect of tool tilt angle on the quality of weld joint and to achieve an optimum combination of process parameters including tool tilt angle for the FSW of AA 6082 T - 6 at highest possible traversal speeds is discussed. Simple tool shapes were adopted with a view of better productivity and reliability. Experimental design and analysis were carried out based on Taguchi method.

5.2 MATERIALS AND EXPERIMENTATION

The base metal used in the experiments was AA 6082 T - 6 aluminum alloy. The mechanical properties of the base metal are summarized in Table. 5.2. The base metal was in rolled condition and in the form of metallic plates of 6 mm thickness. The plates were cut in to 100 mm length and 50 mm wide rectangular pieces to make the butt joints. The faying surfaces were prepared by milling.

<table>
<thead>
<tr>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>% Elongation</th>
<th>Hardness, Hv,</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>245</td>
<td>9</td>
<td>110</td>
</tr>
</tbody>
</table>

The following process parameters were considered for the FSW; tool rotational speed (N), tool traversal speed (S), axial force (F) and tool tilt angle. The various parameters and levels are given in the Table 5.3
Table 5.3. Process parameters and levels

<table>
<thead>
<tr>
<th>Factors</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotational speed,N (rpm)</td>
<td>1080</td>
<td>1260</td>
</tr>
<tr>
<td>Tool traversal speed, S (mm/min)</td>
<td>600</td>
<td>700</td>
</tr>
<tr>
<td>Vertical force F (kN)</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Tool tilt angle, D (Degree)</td>
<td>0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The FSW tool was fabricated from H13 tool steel and was oil hardened. The cylindrical pin was provided with right hand threads (Fig. 5.1). Simple tool shoulder with a flat face was provided. Other tool parameters viz. shoulder and pin diameters were kept constant to focus the effect of tool tilt on weld formation. As a thumb rule, the tool pin diameter was suggested as equal to the thickness of the parent metal and the shoulder diameter as three times as that of the pin diameter. Accordingly shoulder diameter and pin diameter were fixed at 18 mm and 6 mm respectively.

![Fig. 5.1. FSW tool.](image)

The experimental matrix was prepared according to the Taguchi L8 orthogonal array. FSW was carried out on a 11kV/440 V (AC) direct FSW machine.
Table 5.4. displays the experimental design matrix which is an orthogonal array with two levels of parameters. The weld samples were subjected to 100% destructive post weld examination. Three specimens were cut transverse to the weld seam from each sample, in a milling machine. Specimens were prepared in conformance with American Society for Testing and Materials (ASTM) standard E8M-04 for the tensile tests. The average value of the tensile strength was considered for each sample. For micro structural analysis samples were cut thwart wise to the weld line. The specimens were grounded, polished and etched with Keller’s reagent. A Trinocular metallurgical microscope (TMM) was used to examine the microstructure of the weld.

![Fig. 5.2. Tensile test specimen.](image)

The disparateness in mechanical properties of the weld joints was examined through hardness measurements across the transverse cross section of the weld. Measurements were taken by a Vicker’s hardness tester at 0.5 kgf load with a dwell time of 10 Sec. Readings were taken 1.5 mm below from nugget zone and at an interval of 1 mm.
Table 5.4 Experimental matrix with parameters and levels.

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Tool tilt angle(°)</th>
<th>S (mm/min)</th>
<th>N (rpm)</th>
<th>F (kN)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>600</td>
<td>1080</td>
<td>10</td>
</tr>
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<td>1.5</td>
<td>700</td>
<td>1260</td>
<td>15</td>
</tr>
</tbody>
</table>

5.3 RESULTS AND DISCUSSION

5.3.1 Visual inspection

All welds were visually checked to verify the presence of possible external defects such as flashes and surface tunnel. Welded joints were visibly free of defects and showed smooth surfaces. In the case of weld joints formed at higher temperatures, the weld surface was characterised by the roughness and the presence of small aluminium particles giving an abrasive paper like appearance. On the other hand, cold welds were seen to have smooth surfaces on visual examination. Fig. 5.3 indicated that, in this case the welds were formed at cold weld condition.

![Fig. 5.3. FSW joint.](image.png)
5.3.2 Tensile strength

The variation of ultimate tensile strength (UTS) for the joints fabricated at various parametric levels is displayed in Fig. 5.4. The results show that tensile strength registered a significant descent as the tool was tilted by an angle of 1.5\(^\circ\). Maximum tensile strength was reported for a tool tilt of 0\(^\circ\) even at a higher tool travel speed of 600 mm/min. This travel speed is one of the highest values ever reported for AA6082-T6 alloy for the thickness of 6 mm.

![Variation of UTS](image)

Fig. 5.4 Variation of ultimate tensile strength.

The effect of process parameters on the strength of the weld joints were analysed based on the criterion of ‘larger the better’ for predicting the process combination for maximum tensile strength. The response tables for ‘signal to noise’ (S/N) ratio and means illustrated the ranks of each factor based on the delta statistics, which compared the relative magnitudes of the effect on the output characteristic.

Optimum combination of the parameters was identified by choosing the factor levels which have the highest effect on the S/N ratio. Afterwards expected response corresponding to this factor setting was obtained. The effect of process parameters on the strength and of the weld joints were summarised as response tables. From the mean plots of S/N ratio and the mean responses the optimum parametric levels were identified. The response tables for S/N ratio are given in the Tables 5.5 and 5.6.
Table 5.5. Response table for signal to noise ratios

<table>
<thead>
<tr>
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<th>S</th>
<th>N</th>
<th>F</th>
</tr>
</thead>
<tbody>
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<td>40.19</td>
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<td>0.36</td>
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<tr>
<td>Rank</td>
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<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.6. Response table for means

<table>
<thead>
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<th>S</th>
<th>N</th>
<th>F</th>
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<td>99.73</td>
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<td>2</td>
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<td>107.95</td>
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</tr>
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<td>Delta</td>
<td>24.80</td>
<td>1.66</td>
<td>5.16</td>
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<tr>
<td>Rank</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

From Tables 5.5 and 5.6, it can be inferred that the tool tilt angle has the highest effect on the tensile strength followed by force, tool rotational speed and welding speed. The effect of parameters is illustrated by the main effect plots as shown in Fig. 5.5.

Based on the response tables optimum values for process parameters were suggested as 0° tool tilt angle, 600 mm/min travel speed, 1260 rpm and a vertical force of 15 kN.

Fig. 5.5. Main effect plots for SN ratio and means
5.3.3 Microhardness

The variation in microhardness for two cases; one with a tilt angle of $0^0$, 700 mm/min, 1080 rpm and other with $1.5^0$, 600 mm/min, 1080 rpm are shown in Fig. 5.6 as a representative example. The microhardness distribution exemplified the effect of tool tilt angle distinctively. Welds obtained with $1.5^0$ tilt angles showed lower values for hardness. Hardness shows a higher value in the advancing side as reported in various studies [149, 150]. It is observed that micro hardness of the welds is about 70 leading to a softening up to 63% relative to the base-material hardness in case of $0^0$ tool tilt angle, whereas the microstructure hardness value is reduced to 45 in case of $1.5^0$ tool tilt angle.

![Microhardness distribution](image)

Fig. 5.6 Variation in microhardness

Variation in ultimate tensile strength and micro hardness characterizes the change in mechanical properties of the welds with variation in process parameters. Tensile strength recorded a notable descent for welds produced with tool tilted at an angle of $1.5^0$. Similar result was reported for the FSW of polyethylene [151]. However the general observation is that a tool tilt favors higher strength for FSW joints of aluminium alloys. Micro structural characterization of friction stir welded steel joints concluded that tool tilt is the most influential parameter for the tensile strength of the weld joints and a tool tilt enhances the tensile strength of the welds [152].
Experimental analyses have been reported endorsing the postulate that a tool tilt favors mixing and periodical filling of material in the weld joint and the confinement of extruded material in the weld line by the tool shoulder [153]. But the fall in the weld strength registered in this experiment indicated that a tilted tool at higher speeds may not be effective in achieving confinement and mixing of extruded material. The variation in UTS and microhardness is examined based on the microstructure, in the later part of this chapter.

5.3.4 Microstructure

![Macrostructure of weld generated at 0° tool tilt angle, 600 mm/min, 1260 rpm](image1)

*Fig. 5.7. Macrostructure of weld generated at 0° tool tilt angle, 600 mm/min, 1260 rpm*

![Macrostructure of weld generated at 1.5° tool tilt angle, 700 mm/min, 1260 rpm](image2)

*Fig. 5.8. Macrostructure of weld generated at 1.5° tool tilt angle, 700 mm/min, 1260 rpm*

![Macrostructure of weld generated at 1.5° tool tilt angle, 700 mm/min, 1080 rpm](image3)

*Fig. 5.9: Macrostructure of weld generated at 1.5° tool tilt angle, 700 mm/min, 1080 rpm*
The microstructure indicated that the base metal was in solution treated and precipitation hardened condition. Presence of fine uniform precipitated \( \text{Mg}_2\text{Si} \) eutectic particles in primary aluminium solid solution, were evident as seen in Fig. 5.10. The Grain orientation shows that the material was subjected to rolling process. The grains orientation could be seen along the direction with parallel lines. The micrograph also shows some insoluble inter metallic compound \( \text{Al}_6(\text{Fe Mn}) \) in base metal matrix.

As a representative example the microstructure of the different zones of the weld generated with \( 0^0 \) and \( 1.5^0 \) tool tilt are illustrated.

![Microstructure of the base metal.](image)

**Fig. 5.10** Microstructure of the base metal.

![Shoulder zone: (a) 0° tilt angle (b) 1.5° tilt angle.](image)

**Fig. 5.11.** Shoulder zone: (a) 0° tilt angle (b) 1.5° tilt angle.

In both the cases fragmentation of the eutectic particles occurred at the shoulder zone (SZ) due to the pressure of the rotating shoulder. The insoluble inter metallic compounds have formed a cluster at the shoulder zone as seen in Fig. 5.11. (a) & (b).
The nugget zones (NZ) of both cases show no difference in optical micrograph. The nugget zones show fragmented particles of eutectic Mg2Si which have undergone dynamic recrystallization as can be seen in Fig. 5.12. (a) & (b). The evidence of recrystallization is seen as due to the absence of grain orientation, which was present in the parent metal. The stirring stress and the thermal effect would have caused the dissolution and rapid re-precipitation of the eutectic particles.

The microstructure reveals no significant difference for various welds generated under various parameters. Hence it is logical to assume that heat input was comparable for all the welds. The defect formation in certain welds may therefore be attributed to the insufficiency in material flow. The macrostructure of the welds under various parameters supports this observation.

Joining mechanism in FSW can be comprehended to extrusion and forging of materials. As the pin rotates the material got softened due to frictional heating and extruded around the pin and subsequently forged by the shoulder action. The appropriate combination of the rotational and transversal speed is to be achieved for the effectiveness of this action. Heat input is critical to soften the material to facilitate proper mixing of the extruded material. Low heat input was reported to be the main cause of tunnel defect or kissing bond [154].

Fig. 5.12. Microstructure of the NZ (a) 0 tilt angle (b) 1.5 tilt angle
A steady and continuous FW is performed under partial sticky and sliding, interface contact conditions except for the tool plunge phase [155]. Nevertheless, at higher speed, sticky contact conditions dominate the process. Hence at higher speeds tool torque will be high. Various studies have suggested that, except in the cases of overheating, tool torque has a strong inverse linear relation with nugget hardness, yield strength and ultimate tensile strength [156]. As the welding speed increases, heat input decreases, power consumed increases, because of the reduced time for material deformation and processing. Moreover, at higher welding speeds, the material ahead of the pin gets little time to preheat the material in the surrounding and this retards the material softening for the welding process, which requires higher tool torque. In such a condition, the heat input relies largely on the plastic deformation of the surrounding bulk material. In FSW, the input power is converted into plastic deformation energy, which is partially stored in the microstructure and partially converted into heat. The results of numerical simulations reveal that the heat energy so obtained from plastic deformation varies from 2 to 20% [157]. These observations substantiate low heat input at higher welding speeds. The general trend of low UTS in all welds was indicative of low heat input in the selected range of welding speed.

Macrostructure of the weld generated at $0^\circ$ tilt angle is shown in Fig. 5.7. The macrostructure indicates that the weld obtained was free from major defects. The NZ is relatively larger than other types of welds. It was reported that in FSW, the rotating pin deforms the material immediately in the vicinity of the tool surface and is referred as the rotating shear material (RSM). When a threaded pin profile is provided with the tool, the heavily deformed material from the tool pin thread surface drags the surrounding material by the pin action, and this surrounding flow, RSM and the shoulder driven material periodically fills the cavity formed by the tool advancement.
to avoid the formation of volumetric defects [158]. Larger NZ indicates sufficient rounding flow and shoulder driven flow. Hence the size of the NZ is emblematic of better material flow and corresponding mechanical properties. The material flow in the macrostructure indicated onion ring formation. The better mechanical properties of this weld may be attributed to the better material transfer and consolidation when compared to other welds.

Macrostructure of the welds generated at 1.5° tool tilt angle shows insufficient material flow leading to defects of inadequate filling seen as in Figs. 5.8 & 5.9. Shoulder driven material must be adequately merged with the pin driven material to avoid defect formation [159]. Temperature and axial force play a significant role in this mechanism of material flow. Since the tool tilt influences the shoulder driven material flow and hydrostatic pressure, it may be logical to conclude that tilt angle of the tool, at the higher traversal speed adversely affects the material flow and merging of layered material during welding and causes defect formation. FSW of AA 6082 is reportedly sensitive to the shoulder driven material flow [160]. When tool is tilted, the vertical force acting on the weld line is altered. This may affect the material drawn by the shoulder and heat generated. This effect may assume relevance at higher speeds. This may be a possible reason for the generation of defects when the tool is tilted as shown in the macrograph in Fig. 5.8.

The shoulder action generates most of the heat in FSW and the axial pressure exerted by the shoulder on plasticized material influences the material flow as well. The pin action controls the material consolidation and periodic filling of the joint by transferring material. In the advancing side the material is pushed downwards and in the retreating side the material is moved upwards [161]. Material ahead of the pin is moved upwards and the tool threads pulls the material downwards [162]. The tool tilt
favours the upward movement of the material ahead of the pin. However the consolidation through periodic transfer of the material is influenced by other parameters viz. axial force, rotational speed and welding speed. Even if the modes of shoulder driven flow and pin driven flow are unaffected, the individual flow volume and hence the total stir zone is a function of welding speed [163]. Hence the material flow can presumably be affected more, by the welding speed.

Material flow of the tool action in FSW is complex. Guerra et al. [164] suggested a division of the material processing zone in to rotation zone and transition zone. Rotation zone is located immediately in the tool pin surface where the material flow is a combination of transverse, longitudinal and angular with respect to the tool axis. The shear layer of material located between the rotational zone and material matrix was identified as the transition zone. The overall friction stir volume is a function of heat input.

In FSW the weld formation proceeds through a time delay in material filling. Effective combination of parameters overshadows this time delay by filling the material cavities periodically to ensure a defect free weld. The formation of tunnel defects has resulted from this time delay when the cavities are not compensated by the effective material flow. Based on the material flow, weld zone can be divided into shoulder affected zone (SAZ), pin affected zone (PAZ), and weld bottom zone (WBZ) (Fig. 5.13). Time delay for material filling in the PAZ is viewed as the source of tunnel defect. If the material flow from retreating side to the advancing side is not sufficient, and, or the axial force is not sufficient, then the downward material flow in the SAZ is reduced and as a result, defects are generated. It was reported that in the SAZ, the material flow is continuous because the material in contact with the shoulder rotates with the same velocity as that of the tool. In the PAZ, the material flows in the
direction of tool rotation and also in the vertically downward direction. Hence, in the PAZ the material flow is non-continuous. The flow velocity of material in the WBZ which is located between the tool tip and the bottom surface of the parent metal is relatively small. The filling of material in the WBZ occurs during the linear movement of the tool. At any instant, at any point on the weld line, WBZ is filled when tool passes that point. Therefore in the WBZ, the weld formation required more time [165].

![Fig. 5.13. Weld zones based on material flow.](image)

The time delay in material flow forms different deposition patterns in the weld nugget zone. In PAZ material is driven by the pin rotation to the trailing side and the cavities are filled periodically. At higher welding speeds, the material in the PAZ will not get enough time to rotate with the pin for one whole round. So the material flow may be terminated at some point leaving a gap between the PAZ and shearing edge in the material matrix. This delay in material flow leads to the volumetric defects [166].

Macrostructure of the weld shown in Fig. 5.9 indicates a considerably large area of void at the bottom of the pin. Insufficient heat input leading to a cold weld condition has resulted in such defects [167]. Higher welding speed might have stimulated this condition and conversion of the void in to a tunnel or worm hole defect. In FSW pin slithers the material around it and in addition the material flows vertically in almost circular pattern in layers [168]. Fig. 5.8 indicates ineffective mixing of material in different tiers of the process. Ineffective material flow around the pin and lack of
sufficient forging action by the shoulder may be the reason behind it. The tool tilt at higher speeds might not be able to use the geometrical features of the threaded pin in achieving the appropriate material flow. It might have lead to the internal folding defects as shown in Fig. 5.8.

The macrostructure of the welds prepared with a tool tilt explain the possible effect of tool tilt on defect formation. Zhang et al. [169] proposed a criterion for the formation of defect free welds in FSW, which was represented as follows.

\[
\frac{P \cdot \omega}{v} \geq \frac{V}{k(r_{sh} - r_{p})}
\]  

(5.1)

where \( P \) is the pressure, \( \omega \), and \( v \) are the rotary and linear speeds of the tool respectively, \( V \) is the volume of the defect, \( r_{sh}, r_{p} \) are the radii of the tool and \( k \) is the constant of proportionality. According to this criterion, they suggested that the pressure should be larger than a limiting value. It can be observed that tool tilt reduces the pressure vertically applied on the weld surface. From the relation 5.1, According to the above relation it can be seen that the low pressure increases the volume of defect, especially at the higher range of the welding speeds. Hence, it can be concluded that tool tilt at higher welding speeds adversely affect the weld quality, which substantiates the experimental results of this work.

The microhardness values show a clear distinction with the change in tool tilt as shown in Fig. 5.6. But NZs in these cases appear with little difference, even though the distribution of hardening precipitates is not clear. In FSW, dissolution of hardening precipitates lessens the microhardness. The variation in microhardness for the weld with zero tool tilt angle submitted in the present study is comparable with the available results in various studies. The microhardness behavior is underlined by the presence of dynamically recrystallised precipitates as shown in the NZ microstructure as in the Fig. 5.12. But for the weld produced by tilting the tool to 1.5° the micro
hardness values were dramatically reduced even though the rotational speed remained the same. The tool tilt angle is reported to be an influential parameter along with rotational speed, for the heat input. Hence it can be concluded that at higher tilt angle the heat input may not be optimum to ensure the re precipitation of the strengthening particles, which causes the fall in hardness.

5.4. CONCLUSIONS

The effect of tool tilt angle on the high speed FSW of 6082 - T6 aluminium alloy was studied along with other process parameters and an optimum combination of process parameters were suggested. The experimental results indicated that:

- Tool tilt angle is the most influential parameter which affects the weld strength and it was found that tool tilt angle adversely affects the weld strength at higher speeds of tool travel.
- The welds performed at higher speeds are visually defect free, but it was observed that the weld strength is relatively low, especially, with a tool tilt.
- Microhardness of the welds was found to be lowered with the tool tilt.
- The UTS values and macrostructure hints higher tool torque conditions for the weld. The macrostructure of the weld formed with a tool tilt indicates that the material flow was not synchronized and periodic in nature.
- With a tool tilt, weld pressure is reduced and the reduced pressure is possibly below the limiting value which is required to avoid volumetric defects. The reduced pressure at higher welding speed might have affected the material flow and caused the defect formation.
6.1 INTRODUCTION

In FSW, the friction between the plates and tool increases the temperature and generates the metal flow. The frictional heat together with the heat of plastic deformation softens the material at the joint. The plasticized material is extruded by the tool action to form the joint [170]. Metallic joint is achieved through viscoplastic deformation and consequent heat dissipation occurring much below the melting point of the base metal. The heating cycle below the melting point results in complex microstructural changes in the base metal and reportedly affects the grain refinement and orientation [28]. For precipitation hardened alloys, the dissolution, re precipitation and/or agglomeration of the strengthening particles during hot working dominates the properties of the base metal. However, studies in this direction are scarcely reported in the case of FSW.

Malarvizhi et al. [171] promulgated that during fusion welding, strengthening precipitates dissolved in the metal matrix and the material behaved like cast metal with solute segregate and columnar grains. Various studies suggested that the size and distribution of $\text{Al}_2\text{Cu}$ particles play a major role in deciding the tensile properties and hardness of the heat treated alloys [172, 173]. Attallah and Salem [28] observed that the static properties of friction stir welded AA 2219 is dependent on the distribution of strengthening precipitates rather than the grain size. These strengthening precipitates were formed due to the solution treatment and subsequent artificial aging. In FSW there is no melting and hence, theoretically no dissolution of precipitates
occurs in the matrix, but it was reported by Cao and Kou [80] that during FSW the Al₂Cu particles showed clear evidence of agglomeration. Biswal et al. [174] examined the effect of varying tool geometry on the FSW of Al - Si alloy. They reported that the grain size was found to be maximum in the nugget zone for the joints made by tapered cylindrical pin profile. These observations were significant in the investigation of effect of process parameters on the strength of FSW. Nonetheless, any influence of the process parameters on the alteration of strengthening precipitates has not been clearly established in these studies. Moreover, 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 [175 - 177]. 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 correlating the weld quality with the microstructural changes were very little. Age hardened or precipitation hardened alloys are highly sensitive to the heating cycle in case of FSW. Perhaps, the behavior or changes in the strengthening precipitates is the most crucial factor in determining the weld strength, in case of FSW of these alloys. In this context it can be assumed that the change in micro structural characteristics and thereby the mechanical properties in FSW, under varying process parameters needs further study.

In this chapter efforts to correlate the effect of most influential parameter on the strength of friction stir welds, with the microstructural changes is discussed. Experiments and analysis were conducted with AA 2219 as a representative alloy, for precipitation hardened or age hardened group of aluminium alloys.
6.2 MATERIALS AND METHODS

AA 2219 is an Al - Cu - Mn ternary alloy which can be approximated to Al - Cu binary alloy for analysis (Fig. 6.4). 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, consisting mainly of Al₂Cu particles [178].

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 Tables 6.1 and 6.2.

Table 6.1. Chemical composition (wt. %) of base metal

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<th>Cu</th>
<th>Mn</th>
<th>Zr</th>
<th>V</th>
<th>Ti</th>
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<td>0.01</td>
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</table>

Table 6.2. Mechanical properties of base metal

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

The metallic plates of 6 mm thickness were cut into 150 mm x 50 mm rectangular pieces. The parameters considered were tool rotational speed, tool traversal speed, axial force and tool pin profile. The various parametric levels and the experimental matrix are given in Tables 6.3 and 6.4.
Table 6.3. Parameters and levels used in the experiments

<table>
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<th>Factors</th>
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<th>Level 3</th>
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</tr>
<tr>
<td>Tool traversal speed, S (mm/min)</td>
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<td>151</td>
<td>180</td>
</tr>
<tr>
<td>Vertical force, F (kN)</td>
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<td>12.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Tool pin profile, D</td>
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<td>THC</td>
</tr>
</tbody>
</table>

Table 6.4 Experimental matrix

<table>
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<th>D</th>
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</tbody>
</table>

Three types of pin profiles viz. straight cylindrical (SC), tapered cylindrical (TC) and threaded cylindrical (THC) were used for the experiments. The three types of tools used for the experiments are shown in Fig. 6.1.
Tools were fabricated from H13 tool steel and subjected to heat treatment. They were flame hardened. As per the thumb rule available from the literatures tool pin diameter was selected as equal to the base plate thickness and the shoulder diameter was fixed as three times as that of the pin diameter. Accordingly, tool shoulder diameters were kept constant at 18 mm and pin diameters were fixed at 6 mm. Pin length was fixed at 5.8 mm to ensure sufficient plunge depth and for preventing any damage occurring to the pin by striking on the backing plate. The experiments were carried out on a 11kV/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 with ASTM E8M - 04 standards.

Microhardness values were measured employing a 402 - MVD 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 (TMM) 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). SU 6600 variable
Table 6.5 Technical features of SEM

<table>
<thead>
<tr>
<th>Make</th>
<th>Hitachi SU 6600 FESEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron gun</td>
<td>Tungsten schottky emission electron source</td>
</tr>
<tr>
<td>Resolution</td>
<td>1.2 nm/30 kV, 3.0 nm/1 kV.</td>
</tr>
<tr>
<td>Probe current</td>
<td>1 pA – 200 nA</td>
</tr>
<tr>
<td>Specimen size</td>
<td>150 mm x 40 mm</td>
</tr>
<tr>
<td>Magnification</td>
<td>500,000 x</td>
</tr>
</tbody>
</table>

6.3 RESULTS AND DISCUSSION

The thermomechanical process in FSW results in different microstructure in various parts of the weld. Typical macroscopic zones pertaining to the friction stir weld are shown in Fig. 6.2.

As the rotating tool traverses along the weld line forging action of the tool shoulder triggers softened material flow in the shoulder zone (SZ) continuously in downward direction. The pin initiates the material movement in the pin driven zone (PZ), from retreating side (RS) to advancing side (AS). Accordingly, the material in the PZ will
be subjected to the maximum strain. The strain rate depends upon the process parameters and pin geometry [179].

![Al - Cu phase diagram](image)

Aluminium rich portion of the phase diagram is shown in Fig. 6.3. 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 which are identified as Al$_2$Cu [180]. The chemical composition of the constituent elements in the alloy AA2219 allows approximating 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 intermetallic particles in aluminium solid solution. Some lumps of free copper were also observed (Fig. 6.4.a). Nature of the precipitates indicated that the material was in annealed condition.
Fig. 6.4: Optical micrograph of different weld zones. 
(a) Base metal (b) SZ- Taper pin profile. (c) Interface zone, Taper pin profile. (d) Interface zone, Threaded pin profile. (e) Interface zone, cylindrical pin profile. (f) Nugget below the tapered pin

In general, the SZ depicted presence of fragmented particles of Al$_2$Cu with some presence of free copper as shown in Fig. 6.4 (b). This is indicative of the fact that the heat input was low; 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 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 $N = 1200$ rpm, $S = 125$ mm/min, $F = 11$ kN, the nugget zone below the pin showed the three
 distint zones which tend to separate and giving origin for a tunnel defect as shown in Fig. 6.4(f). This is due to inadequate stirring and mixing of material resulted from lower heat input. Adamowski and Szkodo, Lakshminarayanan et al., and Reghubabu et al. [135, 181, 75] have reported similar cases for different pin profiles and for different alloys. In all these cases a deviation from an optimum combination of speed and rpm of tool was the reason for this defect.

FSW of high strength aluminium alloys showed soluble and insoluble second phase particles [182]. In case of AA 2219 alloys, Al$_2$Cu precipitates were identified as the second phase particles in the nugget zone [183]. 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 [184].

The types of pin profiles have influenced the nugget microstructure significantly. It was reported that the presence of undissolved strengthening precipitates contribute significantly to the ultimate tensile strength of friction stir welded joints of precipitation hardened aluminium alloys [185]. In case of AA 2219 alloy, as the temperature increases, the strengthening precipitates may re-enter the solid solution lowering the hardness. But during the cooling part of the welding thermal cycle, some of them may re precipitate, favouring the total hardness of the weld [186].

In the experiments, 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 disorientation of grains and finer grains compared to other pin profiles as shown by the optical micrograph in Fig. 6.5 and SEM images in Fig. 6.6.
EDS analysis indicated that Cu and Al are the major components of the intermetallic compounds. The inter-metallic particles were identified as Al₂Cu by EDS spectra as shown in Fig. 6.7. For the straight cylindrical and threaded pin profiles the microstructure indicated that some re precipitation could be expected.
The EDS spectra indicated that presence of θ particles were more for threaded pin profiles, according to Fig. 6.7 and Table. 6.6.

Table 6.6. EDS results: Elemental analysis

<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. 6.8 illustrates the variation in ultimate tensile strength (UTS) for various pin profiles. The analysis of results showed that the pin profile is the 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. 6.9. The NZ recorded highest hardness for threaded and cylindrical pin profiles. Weld produced using the threaded pin profile exhibited maximum hardness. Hardness variation registered higher values for the advancing side as reported elsewhere [187]. 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 [188]. But due to the higher strain rate, re-precipitation of the strengthening particles may occur in the case of AA2219 alloy [189]. The higher values of microhardness in the stir zone are attributed to the re-precipitation of the strengthening particles.
Microhardness variation shows that hardness assumes the highest value for the threaded pin profile. Both grain size and presence of θ 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 undissolved precipitates would have contributed to the higher strength and hardness, in case of the welds produced using threaded pin profiles.

6.4 CONCLUSIONS

AA 2219 alloy is a precipitation hardened alloy. Hence the mechanical properties of AA 2219 alloys depend on the distribution and concentration of the strengthening particles. The material phase conditions of AA 2219 result in the presence of α, aluminium matrix and θ particles which are identified as Al₂Cu. Being a thermo-mechanical process FSW brings about significant changes in the presence of Al₂Cu particles. Therefore the effect of process parameters on the mechanical properties of welds in FSW of AA 2219 alloy needs to be studied based on the microstructural
changes containing the dissolution and the precipitation of the θ particles. In FSW tool pin profile takes the major part in heat generation and material flow.

The effect of tool pin profile on the mechanical properties of FSW in relation with the microstructural changes were studied by using three types of simple tool pin profiles. The weld NZs were closely examined, distribution and behavior of strengthening precipitates were identified.

Tensile properties were evaluated and microstructural changes were examined for the behavioral characteristics of the strengthening precipitates. 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 reprecipitation of the Al$_2$Cu particles occurred on cooling of the welds.
- SEM and EDS analysis indicated that the precipitation of the Al$_2$Cu particles was more for the welds generated by the threaded pin profile.
- Presence of fine and undissolved precipitates has contributed to the higher strength and hardness of the welds produced using threaded pin profiles.
CHAPTER 7

ANALYTICAL MODEL FOR MAXIMUM TEMPERATURE

7.1 INTRODUCTION

In FSW, a rotating tool of complex geometry is inserted at the faying edges of the base metal and traversed to accomplish the joining. The metal joint is accomplished from the thermo mechanical mixing of the base metal below its melting point. As the process temperature is much below the melting point of the base metal, FSW is devoid of the inherent defects of fusion welding. However, the solid state metal joining in FSW is associated with complex thermal cycle and material flow, which makes the analysis of FSW joints clumsy.

FSW technique has been adopted by the industry for joining aluminium alloys. Nevertheless, a considerable part of the basic problems are yet to be solved reliably. Since its inception and development, FSW has been analysed experimentally and by using mathematical models. A generic material theory for understanding the process mechanism is needed to be evolved for joining a variety of alloys. Tool design, selection of parameters is to be optimized based on such a theory, to expand the applications of FSW in the industry. Selection of process parameters to achieve non defective joints with appreciable quality is a critical issue in the FSW process design. Different metal alloys demand different parametric combinations. So far, efforts for parameter optimization, elimination of defects and characterization are mostly confined to experimental analysis. Experimental analyses are met with high cost and are time consuming. Numerical and analytical models can solve these issues conveniently, to certain extent. To ease the efforts for experiments and streamline the process design, various numerical models have been introduced. Most of these models were thermo flow and thermomechanical models [190 - 193].
The FSW process consists of three phases; plunging and dwell, traverse and retraction. During the plunge phase the rotating tool is plunged vertically into the joint line between the mating faces of the work piece. The plunge phase is followed by the dwell period where the rotating tool is held stationary with respect to the base plates. The prerequisite heating for the joining of the base metal is achieved by the friction between the tool and work piece during the dwell period. The mechanical interaction between tool and work piece generates heat by frictional work and material deformation. The heat, thus generated dissipates to the surrounding and the material in the vicinity of the tool softens due to the rise in temperature. During traverse phase the tool moves along the joint line and initiates the actual joint. After covering the weld distance, the tool is retracted which leaves behind a hole in the welded piece. The friction generated between the surfaces of the rotating tool and the base metal is responsible for the metallic joint formation. The heat generation to build up the metallic joint is attributed to mainly the friction and the plastic deformation. Qian et al. [194] proposed an analytical model for optimising the welding speed and tool rotational speed to produce defect free welds. The model is based on a balanced material flow at an optimum temperature. In their model, the optimum temperature range was selected based on a regression analysis of selected data from the previously reported experimental studies. Khandkar et al [195] introduced a torque based model for FSW in which the torque values reported in the previous studies were used to evaluate the heat input. The contact interface interaction is an important aspect of the
FSW process in case of heat input and material flow. The interface contact conditions for tool and material interaction is specified in terms of slip factor. The effectiveness of the metallic joint is governed by the heat generated and the material flow. Hence, any mathematical model of FSW is incomplete if it ignores any of these key components. The material flow and heat generation depend on the tool and material interface contact conditions which are specified as sliding and sticking conditions. Further, the heat generated through friction is governed by the sliding conditions of friction and heat build up by plastic deformation dominates under sticking conditions \[196\]. Most of the heat generation models suggested by researchers assume ‘perfect sliding’ as the conditions for tool and work faces interaction \[197, 198\]. Schmidt et al. \[199\] proposed an analytical model for heat generation considering various contact conditions for tool and matrix interface viz. slipping and sticking conditions. However, the actual interface contact conditions are determined by the heat generation and proceed through sticking condition and partial sticking and sliding conditions. As the welding speed is a key factor in the heat generation, the interface contact conditions are apparently influenced by the welding speed. In FSW the contact conditions follow a partial sticking and sliding behaviour \[200, 201\]. However, analytical models based on partial sliding and sticking conditions are scarce. In this study partial sticking and sliding condition for material contact is considered.

An analytical model for tool torque and maximum temperature attained during FSW, based on the contact conditions of tool- material surfaces is elaborated in this study. The model is used to estimate the maximum temperature attained in a realistic contact condition between the tool and matrix interface. The model is assumed to be useful in considering the different interface contact conditions at higher tool speeds. The model proposed is to suggest the process parameters at higher tool linear speeds.
7.2 THEORY AND CALCULATION

Nandan et al. [202] proposed a numerical model for FSW considering the material flow as non-Newtonian, incompressible and viscoplastic. In general, the frictional contact between metals can be described by Coulomb friction, and then the shear stress can be calculated as

\[ \tau_{\text{contact}} = \tau_{\text{friction}} = \mu_p \cdot P \]  

(7.1)

Schmidt et al. and Hasan et al. [203, 204] suggested that the contact conditions are determined by the contact and shear yield stress defined as

\[ \tau_{\text{yield}} = \frac{\sigma_y}{\sqrt{3}} \]  

(7.2)

They suggested three conditions for material interface contact in FSW, designated by the slip factor ‘\( \delta \)’

I. Sliding condition: This condition occurs when the material velocity at the interface is zero and \( \delta = 0 \)

II. Sticking condition: In this condition the material velocity is equal to the tool velocity and \( \delta = 1 \)

III. Partial sticking and sliding condition: Where material velocity is less than the tool velocity and the value of \( \delta \) varies between 0 and 1.

The coefficient of friction is, in fact, a function of material welded and varies with temperature and the shear stress. With a proposition that shear stress is independent of pressure, a constant shear model is widely accepted for FSW [205]. The mathematical modelling proposed in this study for the torque and, consequently the maximum temperature attained is based on the assumption that coefficient of friction and the shear stress are constants.
7.3 TOTAL TORQUE DEVELOPED

In this model, for the calculation of torque, the coefficient of friction and the shear stress are assumed to be constants.

Measured values of total tool torque recorded a hike at the starting phase of FSW, then a dip and continue to be steady for the rest of the process [206, 207]. It indicates that at the plunge phase sticking friction conditions dominate and then the process goes through partial sticking and sliding conditions.

Geometry of a typical, cylindrical tool is shown in Fig. 7.2. ‘rₕ’ is the shoulder radius, ‘rₖ’ is the pin radius and ‘h’ is the height of the pin.

Total torque generated can be considered as equal to the sum of sticking torque and sliding torque [208].

The tool torque is expressed as

\[ T_r = r.F \]  \hspace{1cm} (7.3)

Or

\[ dT_r = r.\tau.dA \]  \hspace{1cm} (7.4)

Considering the contact conditions [209]

For sliding condition where \( \delta = 0 \)
\[ \tau = \mu, p \]  
(7.5)

Where

\[ p = F/A \]  
(7.6)

For sticking condition where \( \delta = 1 \)

\[ \tau = r \]  
(7.7)

Based on the tool action, total torque can be split into torque generated at the shoulder surface, torque generated at the pin bottom surface and the torque generated at the pin side surface.

a. Torque generated at the shoulder surface:

To calculate the torque generated at the shoulder surface an infinitesimal segment of area \( dA \), at a distance of \( 'r' \) from the axis of rotation is considered.

\[ dA = r \cdot dr \]  
(7.8)

Then, torque:

\[ dT_r = r \cdot \tau \cdot dA \]  
(7.9)

From the Fig. 7.2, the shoulder surface \( r \) varies from \( r_i \) to \( r_o \).

Hence the total shoulder torque,

\[ T_{\phi} = \int_0^{2\pi} \int_{r_i}^{r_o} r \cdot \tau \cdot r \cdot dr \cdot d\theta \]

\[ = \frac{2}{3} \pi \tau (r^3 - r_i^3) \]  
(7.10)

b. Torque generated at the pin bottom surface:

With the same approach as above torque generated at the pin bottom surface is given by the equation;

\[ T_{\beta} = \int_0^{2\pi} \int_0^{r_b} r \cdot \tau \cdot r \cdot dr \cdot d\theta \]

\[ = \frac{2}{3} \pi \tau r_b^3 \]  
(7.11)

c. Torque generated at the pin side surface:
Torque is calculated by considering the pin side surface area:

\[ T_p = r_i \tau \cdot 2 \pi r_i h \]

\[ = 2 \pi r_i^2 \tau h \quad (7.12) \]

Total tool torque is equal to the sum of the torque generated at the shoulder surface, tool bottom surface and pin side surface.

Total torque,

\[ T_f = \frac{2}{3} \pi \tau \left( r^3 - r_i^3 \right) + \frac{2}{3} \pi \tau r_3^3 + 2 \pi r_3^2 \tau h \]

\[ = 2 \pi \tau r_3^2 \left( \frac{r_o}{3} + \frac{r_i^2}{r_o} h \right) \quad (7.13) \]

Equation (7.13) is a general expression for tool torque. Following the equations (7.5) (7.6) and (7.7), for different contact conditions, equations for \( T_f \), can be revised as follows;

For sliding contact conditions, when \( \delta = 0 \)

\[ T_\mu = 2 \pi \mu p r_o^2 \left( \frac{r_o}{3} + \frac{r_i^2}{r_o} h \right) \quad (7.14) \]

But \( p = \frac{F}{A} = \frac{F_o}{\pi r_o^2} \)

Hence

\[ T_\mu = 2 \mu F_o \left( \frac{r_o}{3} + \frac{r_i^2}{r_o} h \right) \quad (7.15) \]

For sticking contact conditions, when \( \delta = 1 \)

\[ T_\nu = 2 \pi \tau \cdot r_o^2 \left( \frac{r_o}{3} + \frac{r_i^2}{r_o} h \right) \quad (7.16) \]

Hence for two extreme contact conditions tool torque can be expressed as
\[ T_\mu = \mu F_N \cdot k ; \quad \text{for } \delta = 0 \]  \hspace{1cm} (7.17)

\[ T_\nu = \pi \cdot \pi \cdot r_o^2 \cdot k ; \quad \text{for } \delta = 1 \]  \hspace{1cm} (7.18)

From equations (7.17) and (7.18), value of tool torque for partial sticking and sliding condition can be written as follows

\[ T_\tau = \delta \cdot \pi \cdot \pi \cdot r_o^2 \cdot k + (1 - \delta) \cdot \mu F_N \cdot k \]  \hspace{1cm} (7.19)

where \( \delta = 0 \) to 1; and

\[ k = 2 \left( \frac{r_o}{3} + \frac{r_o^2}{r_i^2} \cdot \rho \right) \]

### 7.4 VARIATION OF SLIP

At the commencement of FSW, during the insertion and dwell phase, tool surface is in close contact with the material. The material layer at the interface gets heated up by the friction and stick to the tool. The material layer rotates with the same velocity as that of the tool. During the traverse phase material softens and slips. Then the material velocity is less than the tool velocity and as an extreme case it can be assumed that the material velocity becomes zero. These contact conditions determine the weld quality and they can be specified by the slip factor. Slip is a spatially varying factor. It depends on the heat input and temperature. It varies along the tool radius. Many researchers have proposed many models and functions for the value for the slip. Certain models calculated slip based on a reference welding condition [209, 210]. But these parameters of reference may vary with alloys. Hamilton et al. [211] expressed slip factor as efficiency of frictional heat transfer based on a concept; maximum effective energy. They have postulated that variation of slip is primarily influenced by the welding energy and zero slip condition is reached when the temperature approaches the solidous temperature of the base metal.
Dependence of process temperature on force and torque is more reasonable, further more; tool action softens the material which in turn dictates the interface contact conditions. As the torque varies from sticking torque $T_{tr}$ to slipping torque $T_{ts}$, slip factor $\delta$ varies from 1 to 0. This variation is gradual and continuous. In this scenario a possible expression for the extend of slip is proposed as follows;

$$\delta = \exp \left( -\frac{T_{sl}}{T_{tr}} \right)$$  \hspace{1cm} (7.20)

where $T_{sl}$ is the total torque corresponding to sliding condition and $T_{tr}$ is the torque corresponding to the sticky friction condition.

The equation (7.20) represents slip as a partition of frictional work and work of plastic deformation. For the sliding conditions, where slip factor $\delta = 0$, plastic deformation alone generates heat. On the other hand, for the sticking conditions where the slip factor is unity friction generates heat. Hence, slip factor has been referred as the partition of heat generated by plastic deformation and heat generated by friction [212]. In equation (7.20), slip is expressed in terms of torque developed under varying contact conditions and it represents the heat transfer effectiveness. Slip has been established as a spatially varying factor. Equation (7.20) retains the spatial dependency of slip. Based on this slip factor total torque is computed.

**7.5 MAXIMUM TEMPERATURE**

The average power $P_a$ is calculated by multiplying total torque with rotational speed. Then energy per unit length is expressed as the ratio of $P_a$ to the welding velocity.

$$P_a = T_f \omega$$ \hspace{1cm} (7.21)

Energy per unit length,

$$E_i = \frac{P_a}{v} = T_f \frac{\omega}{v}$$ \hspace{1cm} (7.22)
In order to account the influence of pin length on the welding temperature, the transfer efficiency $\eta$ is introduced as follows;

$$\eta = \frac{h}{t}$$

Then the effective energy per unit length is

$$\left(E_l\right)_{\text{eff}} = E_l \cdot \frac{h}{t} \quad (7.23)$$

Hamilton et al. [211] introduced an empirical relation for the ratio of maximum temperature to the solidus temperature $T_s$ and the energy per unit length as given below;

$$\frac{T_{\text{max}}}{T_s} = 1.5610^{-4}\left(E_l\right)_{\text{eff}} + 0.54 \quad (7.24)$$

From equations (7.19) – (7.24) maximum temperature can be calculated.

7.6 RESULTS AND DISCUSSION

The analytical model proposed in the previous section accounts for the variation in contact conditions with the tool and material interfaces. This aspect is crucial in FSW as the contact conditions in terms of the slip factor dominate the material flow and bonding. The proposed model was tested for validity against the experimental values of peak temperature attained during FSW with the same parameters, for various aluminium alloys. Table 7.1 lists out the aluminium alloys and the tool parameters considered for validation. Table 7.2 displays the welding parameters and maximum temperature reached in accordance with the model against the experimental values.
Table 7.1. Material properties and tool geometry [210]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ts (K)</th>
<th>r_o (mm)</th>
<th>r_i (mm)</th>
<th>t (mm)</th>
<th>h (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 6082 - T6</td>
<td>879</td>
<td>7.5</td>
<td>2.5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>AA 6061 -T651</td>
<td>855</td>
<td>12.7</td>
<td>5</td>
<td>8.13</td>
<td>8</td>
</tr>
<tr>
<td>AA 6061 -T6</td>
<td>855</td>
<td>12</td>
<td>9.5</td>
<td>6.4</td>
<td>6</td>
</tr>
<tr>
<td>AA 7050 - T7451</td>
<td>761</td>
<td>10.2</td>
<td>3.6</td>
<td>6.4</td>
<td>6.1</td>
</tr>
<tr>
<td>AA 7050 - T7451</td>
<td>761</td>
<td>9.5</td>
<td>3.2</td>
<td>19.1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 7.2: Comparison of experimental values and the calculated values of $T_{max}$

<table>
<thead>
<tr>
<th>Alloy</th>
<th>$\omega$ (rpm)</th>
<th>v (mm/s)</th>
<th>F (kN)</th>
<th>$T_{max}$ Expt. (K) [197]</th>
<th>$T_{max}$ (proposed model)</th>
<th>% age error</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 6082- T6</td>
<td>1500</td>
<td>5</td>
<td>7</td>
<td>594</td>
<td>604</td>
<td>1.6</td>
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<tr>
<td></td>
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<td>8</td>
<td></td>
<td>548</td>
<td>555.7</td>
<td>1.4</td>
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<td></td>
<td></td>
<td>12</td>
<td></td>
<td>523</td>
<td>528.7</td>
<td>0.9</td>
</tr>
<tr>
<td>AA 6061-T6</td>
<td>344</td>
<td>2.2</td>
<td>13</td>
<td>698</td>
<td>724</td>
<td>3.7</td>
</tr>
<tr>
<td>AA 6061-T6651</td>
<td>390</td>
<td>2.4</td>
<td>22</td>
<td>739</td>
<td>737.4</td>
<td>0.02</td>
</tr>
<tr>
<td>AA 7050-T7451 (1)</td>
<td>360</td>
<td>1.7</td>
<td>24</td>
<td>673</td>
<td>664.06</td>
<td>1.32</td>
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<tr>
<td></td>
<td>540</td>
<td>2.5</td>
<td>34</td>
<td>663</td>
<td>659.86</td>
<td>0.47</td>
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<tr>
<td></td>
<td>810</td>
<td>3.8</td>
<td>39</td>
<td>703</td>
<td>652.86</td>
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</tr>
<tr>
<td>AA 7050-T7451 (2)</td>
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<td>24</td>
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<td></td>
<td>700</td>
<td>2.6</td>
<td>18</td>
<td>483</td>
<td>504.06</td>
<td>4.36</td>
</tr>
</tbody>
</table>
Variation of maximum temperature attained in the FSW of various aluminium alloys, recorded through various experiments and those obtained from the mathematical model suggested in this study is shown in Fig. 7.3.

![Variation of peak temperature in FSW for various alloys](image)

**Fig. 7.3**  Variation of peak temperature in FSW for various alloys - Experimental value and the proposed model

From the results it can be concluded that the proposed model yields better results which are close to the experimental results for various aluminium alloys. The error percentage of the computed results is minimum, except for alloys with higher thickness. The peak temperature obtained for higher thickness recorded maximum variation. The model may not predict the slip factor values appreciably for higher thickness.

The proposed model is an extension of the existing analytical models for computing the maximum temperature. The maximum temperature attained during the FSW is crucial, as it influences the properties and quality of the weld generated, extensively. The material flow by the tool action is another factor decisive for the weld quality. The proposed analytical model acknowledges the heat input and the material flow in terms of torque and tool matrix interactions.
Table 7.3. Comparison the calculated values of $T_{\text{max}}$ in various models

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Experi - mental Trials</th>
<th>t (mm)</th>
<th>$\omega$ (rpm)</th>
<th>v (mm/s)</th>
<th>F (kN)</th>
<th>$T_{\text{max}}$ (K) Sameer [198]</th>
<th>$T_{\text{max}}$ (K) Gaddak [197]</th>
<th>$T_{\text{max}}$ (K) (Proposed model)</th>
<th>% age error</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 6082- T6</td>
<td>1</td>
<td>6</td>
<td>1500</td>
<td>5</td>
<td>7</td>
<td>683</td>
<td>668</td>
<td>604</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td></td>
<td>8</td>
<td>7</td>
<td>731</td>
<td>731</td>
<td>555.7</td>
<td>1.4</td>
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<tr>
<td></td>
<td>3</td>
<td>6</td>
<td></td>
<td>12</td>
<td>5</td>
<td>583</td>
<td>570</td>
<td>528.7</td>
<td>0.9</td>
</tr>
<tr>
<td>AA 6061-T6</td>
<td>4</td>
<td>6.4</td>
<td>344</td>
<td>2.2</td>
<td>13</td>
<td>547</td>
<td>534</td>
<td>724</td>
<td>3.7</td>
</tr>
<tr>
<td>AA 6061-T651</td>
<td>5</td>
<td>8.13</td>
<td>390</td>
<td>2.4</td>
<td>22</td>
<td>527</td>
<td>514</td>
<td>737.4</td>
<td>0.02</td>
</tr>
<tr>
<td>AA 7050- T7451</td>
<td>6</td>
<td>6.4</td>
<td>360</td>
<td>1.7</td>
<td>24</td>
<td>636</td>
<td>661</td>
<td>664.06</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>6.4</td>
<td>540</td>
<td>2.5</td>
<td>34</td>
<td>701</td>
<td>773</td>
<td>659.86</td>
<td>0.47</td>
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<tr>
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<td>8</td>
<td>6.4</td>
<td>810</td>
<td>3.8</td>
<td>39</td>
<td>739</td>
<td>821</td>
<td>652.86</td>
<td>7.1</td>
</tr>
<tr>
<td>AA 7050- T7451</td>
<td>9</td>
<td>19.1</td>
<td>520</td>
<td>1.9</td>
<td>24</td>
<td>507</td>
<td>517</td>
<td>503</td>
<td>12.3</td>
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<tr>
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<td>19.1</td>
<td>700</td>
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<td>18</td>
<td>490</td>
<td>490</td>
<td>504.06</td>
<td>4.36</td>
</tr>
</tbody>
</table>
Table 7.3 and Fig. 7.4 display a comparison of the peak temperature values attained during experiments, various models, and proposed model.

Fig. 7.4 Variation of peak temperature for the proposed model, experimental results and other analytical models

These results indicate that the proposed model provides better results which are more close to the experimental values compared to other models, except for the last four cases. These situations are characterised by lower welding speeds (Tables 7.2 and 7.3). Hence it may be observed that the proposed model furnishes better results at higher speeds. The previous analytical models assume ‘perfect sliding’ as the contact conditions which may not be appropriate for higher welding speeds. At higher welding speeds sticking or partial sticking and sliding condition may dominate the material contact conditions during welding. The proposed model is based on the slip factor which designates the material contact conditions and is therefore able to forecast the maximum temperature more realistically at higher welding speeds.
7.7 CONCLUSIONS

A simple analytical model for FSW of aluminium alloys is suggested in this study. The model calculates the total tool torque taking the slip factor into account. The model is based on an expression derived for the slip factor in terms of the tool torque. Welding energy per unit length is calculated with reference to the previous research work. An empirical relation already reported is used to calculate the peak temperature attained as a measure of weld efficacy. The calculated results of the model are compared to that of the experimental results available in order to validate the model for a variety of aluminium alloys under different parametric conditions. The results match best with the experimental data, especially at higher welding speeds underlying the relevance of the model.

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CHAPTER 8

CONCLUSIONS

FSW is a formidable development in material joining process. It is considered as a better option for joining aluminium alloys. In this scenario, two extreme cases can be considered; precipitation hardened alloys and solid solution hardened alloys. Both these are weldable by conventional fusion welding processes. However, precipitation hardened alloy welds were found to be more defective under fusion welding. Hence FSW is a promising technology for these types of aluminium alloys. In this work FSW of precipitation hardened alloys were dealt with by considering AA 2219 O and AA 6082 T6 alloys as representative examples. The effect of various parameters on the strength and microstructure were analysed. The parameters were so chosen that they can be easily adjusted in the dedicated machines presently available. Simple tool geometries with tapered, cylindrical and threaded pin profiles were selected so as to minimize the initial cost. The welding is performed at higher linear speeds to enhance the productivity. Hence the experimental analysis focused on the commercialization and popularisation of the technology.

Effect of axial force on the FSW was explored taking AA 6082 – T6 as the base metal. Experiments were conducted by varying the axial force when other parameters were kept constant. Process parameters considered were tool rotational speed and tool translational or linear speed with a threaded pin profile.

Even for these parameters selected form a ‘process window’ for good weld conditions as recommended by previous studies, axial force was found to influence the weld properties significantly.
UTS vary with axial force and this variation was attributed to the defect formation. This effect is justifiable as the axial force influences the material flow during welding. The macrographs showed onion ring formation and with surface defects in case of some welds. However 4 kN axial force produced welds with adequate material flow depicted by good onion ring structure and with no defects. This fact was substantiated by the mode and location of the tensile fracture. Welds with low tensile strength due to defects were having a brittle fracture with no neck formation and the fracture occurred at the NZ. In the case of welds formed with 4 kN and 5 kN axial force, the axial force was found to have strong influence in material flow for a given shoulder diameter.

Microhardness of the welds was significantly higher than the base metal. The microstructural characterization revealed that NZ underwent dynamic recrystallization and showed presence of fine fragmented particles of Mg$_2$Si. This was the possible reason for the enhancement in hardness for all weld specimens. However, the axial force appeared to have no effect on the re-precipitation of the strengthening particles which indicated that the heat flow is least influenced by the variation in axial force. All these factors along with the microstructure of the shoulder zone, pointed out that the axial force was ineffectual to bring about any substantial change in the weld microstructure.

Effect of process parameters on the FSW of AA 2219 - O were analyzed by varying tool rotational speed, tool linear speed, axial force and tool pin profile. The welding was performed at speeds in a range (100 - 150 mm/min.) higher than the generally reported studies. Three types of simple tool pin profiles were used in the experimental campaign namely; tapered, cylindrical and threaded pin profiles.
The selected range of parameters set a hot weld conditions as indicated by the weld appearance and the axial force values were high so that the shoulder couldn’t confine the weld material along the weld line as indicated by the flashes associated with most of the welds. But it is noteworthy that the base material AA 2219 - O is a soft alloy in annealed condition.

Taguchi analysis of the experimental results showed that tool pin profile is the most influential process parameter. Threaded pin profile and tapered pin profile provided the best results for the UTS. The microhardness for threaded pin profile and tapered pin profile registered higher values than that of the base metal. Microstructural analysis indicated that threaded pin profile resulted in grain reorientation and re precipitation of Al₂Cu as fine and undissolved particles. For the precipitation hardened alloys, the distribution of strengthening particles determine the strength, rather than the grain size. EDS analysis showed that precipitation of Al₂Cu particles was more for the threaded pin profile. This is the reason for the better strength for the welds produced using threaded pin profile. Higher values of microhardness values welds also substantiated the presence of more precipitates in case of these welds. As the rotational speed and linear speed determine the heat flow and the pin profile influences the material stirring, the impact of pin profile on the degree of precipitation of strengthening particles can be considered as a general characteristic for the precipitation hardened alloys.

FSW of AA 6082 – T6 was performed at the highest linear speed ever reported (600 mm/min, 700 mm/min.) for the considered thickness (6 mm) with a common tool with threaded pin profile to check the feasibility of the process. Apart from the tool rotational speed and linear speed, effect of tool tilt was inquired. A tilt for the tool was recommended for producing good weld was reported in the previous studies. Strength
of the welds were analysed in terms of UTS. Since, welding defects were expected at higher speeds, macrostructure of the weld cross sections were studied. Microstructure evaluation was carried out using microhardness tests and optical micrography.

It was observed that FSW at higher welding speeds was feasible for the given parameters; however the tilted tool produced defective welds. Taguchi analysis of the experimental results proved that the tool tilt was the most influential parameter deciding the weld strength. The weld pressure at higher welding speed was possibly low and the tool tilt caused further depletion in welding pressure. In these cases, the pressure was reduced below a limiting value which was required to avoid volumetric defects. The macrostructure vindicated this fact as it showed that weld material flow for the welds with a tool tilt was not synchronised and periodic. Microhardness of the welds was found to be lower for welds produced with a tool tilt. Hence it can be concluded that tool tilt is detrimental at higher welding speeds or causing a reverse effect at higher welding speeds.

An analytical model was suggested for the FSW of aluminium alloys based on the slip factor with simple tool having cylindrical pin. An expression for slip factor is suggested which represented slip as a partition of frictional work and work of plastic deformation. The slip factor is expressed in terms of the tool torque. It is noticeable that tool torque increases at higher welding speeds. The model enabled computation of maximum temperature in the FSW process. The proposed model has taken partial slipping and partial sticking tool contact conditions in to consideration. That could be the reason that the model displayed errors in the computation of maximum temperature for lower welding speeds. At lower welding speeds slipping contact conditions dominated during welding process. However, at higher welding speeds the model displayed better results for maximum temperature with minimum error when it
is compared with experimental results. The maximum temperature value will be useful in deciding the process parameters if the variation in flow stress of the alloys with temperature is known.

The present experimental work sought the effect of process parameters on FSW of aluminium alloys at higher welding speeds along with the microstructural analysis. Further study is needed to suggest a process window helps to suggest various process parameters with simple tool geometry at higher speeds. This will support the commercialisation of the FSW technology.

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REFERENCE:


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LIST OF PAPERS

SUBMITTED ON THE BASIS OF THIS THESIS

I  REFEREED JOURNALS


II  PRESENTATIONS IN CONFERENCES


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