CHAPTER-5

RESULTS AND DISCUSSION

5.1 Microstructure

Figure 5.1 (a) Microstructure of parent material

Figure 5.1 (b) Microstructure transition zone

Mg$_5$Si$_6$ strengthening precipitates
Microstructure details of parent material is shown in figure 5.1 (a). The fine texture of base material has been clearly preferentially oriented along rolling direction. Mg$_5$Si$_6$ strengthening precipitate shown by darker particles are randomly distributed in the base material. The parent material consists of elongated grains with average grain size of 28 $\mu$m. Microstructure of transition zone and weld nugget of friction stir welded aluminum alloy are shown in figures 5.1 (b) and (c) respectively. Specimen which was welded at 1000 rpm and 100 mm/min travel speed was selected for present investigation. From the base material to the weld centre the crystal grains become fine. There is absence of relatively large strengthening precipitates in the weld nugget (WN). WN is composed of fine equiaxed grains due to dynamic recrystalization. Grains are formed under high temperature and large deformation in the weld centre, due to stirring process [116]. The average grain size in stir zone is 10 $\mu$m. Figure 5.1 (b) represents transition zone i.e. HAZ and TMAZ, between the base material and weld nugget. In HAZ, mechanical properties are modified by the heat generated by the friction between the tool and the plates. Metallurgical modifications in this zone are similar to those occurring during traditional fusion welding processes. TMAZ corresponds to region where mechanical properties are modified by the rotation and translational motion of the tool.

Figure 5.1 (c) Microstructure of weld nugget
5.2 Micro hardness

The variation in hardness can be readily co-related with microstructure developed after the welding process. Vickers hardness profiles across the weld obtained at 1000 rpm and 50 mm/min are presented in figure 5.2 taken at the mid-section of FSW joints. In parent material work hardening is the main contributor to the high hardness of this region. The hardness decreased from the level of the parent material (111 Hv) to reduced values in the weld zone (62 Hv) [117]. Minimum hardness occurred in the TMAZ at the advancing side. In Harris and Norman’s work [118] it is suggested that the variation of the micro hardness values in the welded area and parent material is due to difference between the microstructures of the base alloy and the weld zone. T6 condition of the parent material is obtained by solutionizing and artificial ageing in which material is heated to around 530 °C followed by quenching, thereafter it is heated upto 160 °C for about 8 hours. The loss of T6 condition which occurs during welding is expected to decrease the mechanical strength, which is reflected in the drop of hardness. Only the nugget zone shows a slight increase in hardness in the weld zone due to grain refinement and formation of fine precipitates as a result of welding.

Figure 5.2 Micro hardness profile of Friction stir welded specimen of AA 6061
5.3 Tensile properties

Table 5.1 presents the tensile properties for friction stir welded specimen and the base material.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material 6061 T6</td>
<td>313.6</td>
<td>18</td>
</tr>
<tr>
<td>FSW 6061 T6</td>
<td>155.1</td>
<td>5</td>
</tr>
</tbody>
</table>

The tensile properties and elongation of FSW joint is far lower than the parent material. These results indicate that softening effect has occurred in aluminum alloy due to FSW. The tensile properties and fracture locations of the joints are to a large extent dependent on the hardness distributions of the joints [119]. Hardness degradation region composed of weld nugget, TMAZ and HAZ has occurred in the joints, thus the tensile properties of the joints are lower than the parent material. It is found that the fracture location is between weld nugget and the TMAZ on the advancing side as shown in figure.

In practice the reason for the fracture near the interface between the weld nugget and the TMAZ is the remarkable difference in the micro structure between the weld nugget and TMAZ as shown in figure (b). The weld nugget is composed of fine equiaxed grains and TMAZ is composed of coarse-bent recovered grains [120]. Therefore the interface between weld nugget and TMAZ becomes a weaker region and the joint is fractured at this interface during the tensile testing. When a tensile load is applied to the joint, the stress and strain concentration takes place in the lower strength part and consequently the joint is fractured in this region [121]. The joint is fractured on the advancing side instead of the retreating side. The reason for failure of the joint on the advancing side may be attributed to lowest hardness of the joint on the advancing side as shown in figure 5.2. This result is sufficient to indicate that the tensile strength on the advancing side is lower than on the retreating side. Figure 5.3 shows image of fractured tensile specimen.
5.4 Experimental results for heat transfer analysis

5.4.1 Introduction

To improve understanding of this new welding technique a detailed investigation of heat transfer is required. In this study, a three dimensional heat transfer model is presented and applied in analyzing the heat transfer process for 6061 alloy during FSW. The influence of process parameters such as tool rotation and weld speed on thermal history and mechanical properties of 6061 aluminum alloy was investigated. A finite element model was developed to find the transient temperature distribution using ANSYS™.

The experimental results for heat transfer analysis have been divided into two parts. The temperature distribution along the work piece and mechanical properties viz. micro hardness testing and tensile test results. The temperature distribution along the work piece gives an idea about nature of heat transfer occurring in the process and the variation of temperature at various monitoring points. The micro hardness report shows at
which location the softness has taken place and tensile test results provide the strength of various welded joints.

5.4.2 Temperature distribution along the work piece

One of the important research aspects of FSW is how to improve the weldability of materials and how to protect the tool against wear in FSW. For most alloys, coefficient of friction and the yield stress strongly depends on the temperature. Tables 5.2 and 5.3 show physical and temperature dependent mechanical properties of AA 6061 respectively. The yield stress of AA 6061 T6 is significantly decreased at higher temperatures as shown in table 5.3 [122]. The coefficient of friction also decreases at higher temperature, which means that the material is easy to be friction stir welded at a higher temperature. In order to decrease the yield stress, thus making welding easier, the following approaches can be used to obtain a higher initial temperature in the work piece in FSW: (a) applying an insulated back plate in order to reduce the heat loss, therefore reaching a higher temperature [21, 123], (b) applying a laser beam in order to assist in preheating the work piece [124].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2700</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Solidus Temperature</td>
<td>582</td>
<td>°C</td>
</tr>
<tr>
<td>Liquidus Temperature</td>
<td>650</td>
<td>°C</td>
</tr>
<tr>
<td>Specific He at 20°C</td>
<td>896</td>
<td>J/kg°C</td>
</tr>
<tr>
<td>Thermal Conductivity at 20°C</td>
<td>167</td>
<td>W/m°C</td>
</tr>
</tbody>
</table>
Table 5.3 Temperature dependent mechanical properties of AA 6061 T6 [122]

<table>
<thead>
<tr>
<th>Temperature (C)</th>
<th>-195</th>
<th>-80</th>
<th>0</th>
<th>24</th>
<th>100</th>
<th>150</th>
<th>205</th>
<th>260</th>
<th>315</th>
<th>370</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Stress (MPa)</td>
<td>415</td>
<td>338</td>
<td>325</td>
<td>310</td>
<td>290</td>
<td>235</td>
<td>130</td>
<td>52</td>
<td>32</td>
<td>21</td>
</tr>
<tr>
<td>Yield Stress, $\sigma_{\text{yield}}$ (MPa)</td>
<td>325</td>
<td>290</td>
<td>283</td>
<td>275</td>
<td>262</td>
<td>215</td>
<td>103</td>
<td>35</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>% Elongation</td>
<td>22</td>
<td>18</td>
<td>17</td>
<td>17</td>
<td>18</td>
<td>20</td>
<td>28</td>
<td>60</td>
<td>85</td>
<td>93</td>
</tr>
</tbody>
</table>

From table 5.3, it is obvious that preheat can also be helpful in obtaining a higher initial temperature in the work piece as the yield stress decreases with rise in temperature. After the tool shoulder contacts the work piece top surface, the work piece can be preheated by keeping the tool rotating for few seconds before the welding causes the tool to start moving. It can be expected that the initial temperature of the work piece in front of the tool can be increased and yield stress can be decreased, subsequently making the welding easier and protecting the tool.

Figures 5.4 (a), (b), (c) and (d) show measured temperature-time distribution at location 8mm, 12mm, 16 mm and 25 mm respectively from the weld centre at welding speed of 50 mm/min and at 1250, 1000 and 750 rpm. Similarly Figures 5.5 (a), (b), (c) and (d) show the temperature distribution at same locations and rotational speeds but at a welding speed of 100 mm/min. The temperature-time plots are presented for the total time comprising of an initial dwell period plus the time of travel between the start and the end points of the weld joint (=90 mm). The dwell period refers to an initial time of 30 seconds during which tool rotates without any linear motion.
Figure 5.4 (a) Measured temperature-time distribution at location 8mm from the weld centre at 50 mm/min

Figure 5.4 (b) Measured temperature-time distribution at location 12 mm from the weld centre at 50 mm/min
Figure 5.4 (c) Measured temperature-time distribution at location 16 mm from the weld centre at 50 mm/min

Figure 5.4 (d) Measured temperature-time distribution at location 25 mm from the weld centre at 50 mm/min
Figure 5.5 (a) Measured temperature-time distribution at location 8mm from the weld centre at 100 mm/min

Figure 5.5 (b) Measured temperature-time distribution at location 12mm from the weld centre at 100 mm/min
Figure 5.5 (c) Measured temperature-time distribution at location 16mm from the weld centre at 100 mm/min

Figure 5.5 (d) Measured temperature-time distribution at location 25mm from the weld centre at 100 mm/min
Figures 5.4 and 5.5 depict that rise in temperature is very slow during the dwell period and increases drastically as the tool moves ahead. Furthermore, the peak temperature at a specific location occurs corresponding to a time when the tool is the nearest to the corresponding point. Maintaining a dwell period of 30 seconds the total time to cover the distance of 90 mm at welding speed of 50 mm/min and 100 mm/min are 138 and 84 seconds respectively. As shown in figure 5.4 (a) the peak temperature recorded at 8 mm from the weld centre is 420°C at 1250 rpm and it reduces to 375°C at 750 rpm. The higher value of peak temperature can be attributed to greater amount of heat generation as the tool rotational speed is increased. Similar trend is observed for thermocouple location at 12, 16 and 25 mm from the weld centre. As the tool passes through the nearest point, it is observed that the temperature does not fall significantly. This may be due to faster rate of dissipation of heat by AA 6061 T6 as it has higher thermal conductivity. Tool rpm has more dominating effect as compared to welding speed [129]. As the rotational speed of the tool increases with same weld speed, the maximum temperature at all the measured locations increase due to increase in the rate of heat generation. Figures 5.6 (a) and (b) show temperature distribution of thermocouple at a distance 8 mm away from the weld centre at the start of welding at 50 mm/min and 100 mm/min respectively at rotational speed of 1250, 1000 and 750 rpm. Less reduction in temperature has been observed in the magnitude of maximum temperature with the increase in weld speed at the same tool rotational speed.
Figure 5.6 (a) Temperature distribution of thermocouple at a distance 8 mm away from the weld centre at 50 mm/min

Figure 5.6 (b) Temperature distribution of thermocouple at a distance 8 mm away from the weld centre at 100 mm/min
Figures 5.7 (a),(b) and (c) and 5.8 (a), (b) and (c) show the numerical temperature distribution at welding speed of 50 mm/min and 100 mm/min respectively.

Figure 5.7 (a). Numerical temperature distribution at 1250 rpm and 50 mm/min

Figure 5.7 (b) Numerical temperature distribution at 1000 rpm and 50 mm/min
Figure 5.7 (c) Numerical temperature distribution at 750 rpm and 50 mm/min

Figure 5.8 (a) Numerical temperature distribution at 1250 rpm and 100 mm/min
Figure 5.8 (b) Numerical temperature distribution at 1000 rpm and 100 mm/min

Figure 5.8 (c) Numerical temperature distribution at 750 rpm and 100 mm/min
The maximum temperatures for 6061 aluminum alloy reported from the numerical results in the literature are in the range of 400 °C to 530°C [34, 125-128]. The maximum temperatures obtained from the model as shown in figures 5.7 (a), (b) and (c), corresponding to welding speed of 50 mm/min and rotational speed of 1250, 1000 and 750 rpm are respectively 512 °C, 486°C and 452°C. As shown in figure 5.8 (a), (b) and (c), corresponding to 100 mm/min and rotational speed of 1250, 1000 and 750 rpm maximum temperatures are respectively 491, 461 and 435 °C. The temperatures obtained from the model are also in the same range as reported in the literature. Hence the results obtained are validated with the results obtained from the literature.

Figure 5.9 (a) Comparison of experimental and numerical temperature distribution at 1250 rpm and 50 mm/min
Figure 5.9 (b) Comparison of experimental and numerical temperature distribution at 1000 rpm and 50 mm/min

Figure 5.9 (c) Comparison of experimental and numerical temperature distribution at 750 rpm and 50 mm/min
Figures 5.9 (a), (b) and (c) show a comparison of experimental and numerical temperature distribution at 1250 rpm, 1000 rpm and 750 rpm respectively at 50 mm/min. It can be observed that experimental and numerical temperature distribution match fairly well. It was observed that an increase in tool rotation increases the peak weld temperature of the plate in the weld zone. At higher rpm more heat is generated, so corresponding temperatures are higher as compared to lower rpm. Similar results were reported when stainless steel 304 L material was welded by FSW [47]. The fair agreement of experimental and predicted temperature distribution indicates that the developed model is reliable in predicting the temperature history.

5.5 Mechanical Properties

The higher strength of the base material is mainly attributed due to presence of alloying elements such as silicon and magnesium. These two elements combine and undergo precipitation reaction and form strengthening precipitates $\beta''$-$\text{Mg}_5\text{Si}_6$ as shown by darken particles in figure 5.1 (a). These precipitates are stable at temperatures lower than 200°C [130]. Fine and uniform distribution of these precipitates throughout the aluminum matrix provides higher strength and hardness to the joints. This precipitate exists in the unaffected base material but is absent in the weld nugget and in the HAZ. In the friction stir welds, the temperatures are over 200-250°C during heating and $\beta''$ is easily dissolved [131]. This $\beta''$ precipitate is mainly responsible for hardening. Svensson et al. [131] reported that in HAZ precipitates of $\beta'$-$\text{Mg}_2\text{Si}$ exists and $\beta'$ precipitates have less strengthening effect compared to $\beta''$, so a lower hardness is obtained. Grong [130] reported that in HAZ where the temperature are near or less than 300°C, the precipitation of $\beta'$ is very high and as a consequence, the transition from $\beta''$ to $\beta'$ by dissolution occurs. In the weld nugget, the temperature is higher; therefore $\text{Mg}_2\text{Si}$ precipitates go into the solution. On cooling, the time of precipitation is limited, therefore only a small volume fraction of $\beta'$ precipitates are formed in the weld nugget [132]. The nugget hardness recovery is due to recrystallization of very fine grain structure and by natural aging. In FSW, friction heat softens the welded material at a temperature less than its melting point. The softened material underneath the shoulder is also subjected to extrusion by the
rotating tool. It is expected that this process will inherently produce a weld with relatively few residual stress and distortion [34].

In any welding, the heat input plays an important role on the micro hardness and tensile properties of the weld. The micro hardness along the transverse section of the welded joint for specimen (1000 rpm and 50 mm/min) as shown in figure 5.2, showed softened region due to frictional heat. Localized frictional heat during FSW process produces significant micro structural changes which lead to local variation in the mechanical properties of the weld joint.

Table 5.4. Ultimate tensile strength of weld samples at 50 mm/min

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Tensile strength (MPa)</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent material</td>
<td>313.6</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>150.2</td>
<td>750</td>
</tr>
<tr>
<td>2.</td>
<td>155.6</td>
<td>1000</td>
</tr>
<tr>
<td>3.</td>
<td>147.9</td>
<td>1250</td>
</tr>
</tbody>
</table>

Figure 5.10 Micro hardness variations with temperature across the weld.

Figure 5.10 which is obtained from numerical temperature distribution at the weld zone and experimental temperature measured at distances from the centre of the
weld shows the temperature and micro hardness variation for specimen no.2 [111]. At the centre of the weld, temperature is maximum, but due to heating of the material the micro hardness reduces. The results of micro hardness and tensile test were obtained in as in weld condition. Table 5.4 shows the ultimate tensile strength of weld samples at 50 mm/min welding speed. It was observed that the tensile strength of welded joint was less than that of parent material due to dissolution of strengthening precipitates due to frictional heat. The tensile specimens failed at locations where micro hardness was minimum [111].

The fracture location of any joint is a direct reflection of the weakest part of the joint. Studying the fracture location of the joint is required to understand and improve the mechanical properties of the joint. The SEM observation of the fractured surface tensile tested specimen revealed that the fracture surfaces were populated of very fine dimples, revealing ductile behaviour of the material before failure as shown in figure 5.11.

Figure 5.11 SEM image of fractured tensile specimen no. 2
5.6 Results and discussion for stress analysis

Figure 5.12 (a) Longitudinal stress at 750 rpm and at welding speed of 50 mm/min

Figure 5.12 (b) Longitudinal stress at 1000 rpm and at welding speed of 50 mm/min
Figures 5.12 (a), (b) and (c) show the longitudinal stress at 750 rpm, 1000 rpm and 1250 rpm respectively and at welding speed of 50 mm/min. Simulated longitudinal stress are consistent with observation of Rajamanickam N et.al [133] that it is around 30\% of the yield strength of the base metal. This proves the validity of the model. The predicted stress distribution in figures 5.12 (a), (b) and (c) complies with measurements on friction stir welded Al 2024-T3 reported by Dalle Donne et. al.[134] Similar residual stress distribution was observed in friction stir weld of aluminum of 7xxx series alloys reported by Djapic.L et.al [135]. Other components of the stresses in transverse and though thickness direction are insignificant and small. It is clear that the location of the high gradient in the residual stresses in longitudinal direction is in the proximity of shoulder diameter, which is believed to be caused by high temperature gradient and high shear force by shoulder periphery edge in this region. It is observed from figure 5.13 that the magnitude of the residual stress increases with increase in tool rotational speed which is consistent with the observation of Rajamanickam N et.al [133] which further proves the validity of the model. The maximum value of final residual stress in the work piece is 121
very low compared to the corresponding value in the fusion welding in which the maximum residual stress is typically close to the yield strength of the base material. This conclusion corroborates with the general belief that FSW process creates low residual stress in the weld for heat treatable aluminum alloys. Lower residual stress is attributed to low peak temperature experienced and fixture used to clamp down the work piece during the welding process.

Figure 5.13 Comparison of longitudinal stress at 750, 1000 and 1250 rpm and at welding speed of 50 mm/min

5.7 Effect of weld parameters on performance of friction stir welded 6061 aluminum alloy

Although FSW consistently gives high quality welds, proper use of the process and control of number of parameters is needed to achieve this. Using inappropriate welding parameters can cause defects in the joint and deteriorate the mechanical properties of the FSW joints. To produce the best weld quality, these parameters have to be determined individually for each new component and alloy [136]. Only a small number of studies have involved the effects of welding parameters on the defects, microstructures and mechanical properties of the joints [64-65, 71,103]. The quality of friction stir welded joint is controlled by three welding parameters when using definite pin surface profile, these are tool’s rotational speed, welding speed and welding
force. For this relatively new method, there is still lack of optimal combinations of various welding parameters for different materials, different thickness etc. The current work was conducted to study the FSW process on 4 mm thick 6061 AA with focus on appropriate combinations of various welding parameters. In addition, the influence of these parameters on the quality and tensile properties was studied.

5.7.1 Welding force

![Force Distribution in Z direction](image)

Figure 5.14 (a) Force distribution in Z (downward) direction
Figures 5.14 (a), (b) and (c) show the forces in z, y and x direction respectively. For welding speed of 50 mm/min and rotational speed of 1000 rpm, the welding force between the tool shoulder and work piece was increased from 1000 N to 5000 N gradually. The FSW tool exerts forces on work pieces in tool feed direction ($F_x$) and tool axis direction ($F_z$). The recorded forces using three component milling tool...
dynamometer during FSW process. During the initial stage of welding, higher force
values ($F_z$) act on the material due to tool penetration, as the material temperature is
still low and consequently its yield strength is high. When the tool penetration is
completed the softening of material starts to occur. A preheating time of 30 seconds
was given. As soon as the feed starts force $F_z$ again increases and thereafter it
stabilizes. As the force $F_z$ is increased slowly, at first groove type defect appears on
the surface of the weld as shown in figure 5.15(a). When the welding forces were low,
tunnel type defect were observed near the bottom of the weld as shown in figure 5.15
(b). With increase of welding force, groove type defect disappears gradually. But
when the force exceeds one value, the welding tool would sink into the weld gradually
resulting in the depression of the weld surface and wavy burrs at the edge of the weld
region [137].

Figure 5.15 (a) Image of groove defect
5.7.2 Rotational speed and welding speed

From figure 5.7 (a), (b) and (c) it can be concluded that as the rotational speed increases, the maximum temperature attained also correspondingly increases. Comparing figure 5.8 (a), (b) and (c) with figure 5.7(a), (b) and (c) , it can be seen that with increase of welding speed the maximum temperature attained is decreased slightly. When the welding speed is increased, the surface quality becomes bad gradually and semicircle streaks appear as shown in figure 5.16, even the groove type defects was observed. For constant welding speed, when the tool rotation speed is too low, the material gets less input, causing insufficient metal flow during welding process, whereas when the rotational speed is too high, it causes severe depression of the weld surfaces and the weld has wavy burrs.
5.7.3 Tool design and heat input

During the FSW process, the main heat source is generally considered to be the friction between the rotating shoulder and surface of work piece [71]. So the size of the tool shoulder has significant influence on the surface appearance of the weld. In the present investigation, three different sizes of shoulder viz. 12, 14 and 16 mm were selected. When the tool shoulder diameter was 10 mm it resulted in poor quality of weld. The tensile strength of parent material observed was 313.6 MPa. The corresponding tensile strength for FSW joint with shoulder diameter 12, 14 and 16 mm observed were 144.2, 155.6 and 133.6 MPa respectively. When the size of shoulder is too small, the frictional heat input is extremely low. The plastic material cannot flow sufficiently. So the bonding cannot be achieved. However, when the size of tool shoulder is too large, the heat generation is too high, it can widen the weld. To a large extent, the quality of the weld depends on the heat input during the welding process. Heat input can further be increased by using fibre glass sheet between the work piece and backing plate, which reduces the heat transferred by conduction to the backing plate.
Once the parameters of FSW process are chosen, such as the material, welding pressure and size of the welding tool, the total energy input per unit time $E$ is determined by [72]

$$E = \frac{\pi \mu P N}{45 (r_1^3 + r_2^3)} \quad (5.1)$$

where $r_1$ is the radius of tool shoulder, $r_2$ is root radius of pin, $\mu$ denotes friction coefficient between the tool shoulder and the work piece. $P$ expresses the downward force on the shoulder and $N$ represents the rotational speed of the tool. Then the energy input per unit length of the weld can be expressed as

$$e = \frac{\pi \mu P N}{45 V (r_1 + r_2)} \quad (5.2)$$

where $V$ is the welding speed.

In the current work, the size of the tool is fixed, so $r_1$, $r_2$ and $\mu$ are invariable. Thus a constant $C$ can be defined as

$$C = \frac{\pi \mu}{45 (r_1^3 + r_2^3)} \quad (5.3)$$

Then equation (5.2) can be changed to

$$e = \frac{CP N}{V} \quad (5.4)$$

Using equation (5.4) for a particular combination of the welding force, rotational speed and welding speed, values of heat inputs can be found out.

### 5.7.4 Hardness of tool

Good quality FSW joint for 6061 AA can be obtained when the hardness of the tool is between 58 to 62 R$_c$.[137] In the present investigation the hardness of the tool was kept 60 R$_c$. With repeated welding the tool gets heated up, so slowly hardness reduces. At lower hardness it was observed that the material of the work piece tends to stick to the tool and quality of the joint deteriorates [137].
5.8 Results and discussion for comparative study of FSW with TIG welding

Though research work of comparative study of FSW with other welding techniques have been reported, it appears that systematic study and comparison between FSW and TIG welding for 6061 T6 aluminum alloy has not been reported yet. An experimental investigation has been carried out, in present study, on microstructure, micro hardness distribution, tensile properties and fracture surface morphology of weld butt joints of 6061 T6 aluminum alloy. Two different welding processes have been considered: a conventional tungsten inert gas (TIG) process and friction stir welding (FSW) process.

The influence of two joining methods, i.e. fusion (TIG) and solid-state (FSW) welding processes, on both microstructure and mechanical properties of AA 6061 T6 was investigated.

5.8.1 Microstructure

![Figure 5.17 Macrostructure of TIG joint](image)

Figure 5.17 Macrostructure of TIG joint
Figures 5.17 and 5.18 show the macrostructure of TIG and FSW joints respectively. Figure 5.19 shows the optical micrographs of the TIG joint. The base metal contains coarse and elongated grains with uniformly distributed very fine Mg\textsubscript{5}Si\textsubscript{6} strengthening precipitates. The weld region of FSW joint contains very fine, equiaxed grains and this may be due to dynamic recrystallisation that occurred during FSW process. The fusion zone of TIG welded joints contains dendritic structure and this may be due to fast heating of base metal and fast cooling of molten metal due to welding [138].
When aluminum alloys are welded using non-heat treatable AlSi₅ filler metal to avoid solidification cracking problem, the weld material is composed of fewer strengthening precipitates compared to base metal. In fusion welding even though, large amount of silicon is available in base and filler metal, (the available magnesium which is present in base metal alone), for precipitation reaction in the weld pool its content is very low. Hence, the weld region of AA 6061, when welded with AlSi₅ filler metal usually contains lower amount of strengthening precipitates compared to the base metal region. Therefore the precipitates strengthening of Mg₂Si precipitates is weak in TIG joints. On the other hand, the weld region of FSW joint contains the alloying elements similar to the base metal. In FSW, there is no filler metal addition and no melting of base metal [138]. The base metal is plastically stirred under the action of the rotating tool. Due to this severe plastic deformation, the coarse elongated grains are fragmented into fine, equiaxed grains, and coarse strengthening precipitates are fractured into very fine uniformly distributed particles in friction stir processed zone [139]. Ying Chun Chen et al. [140], opined that during higher rotation speeds, particles would suffer more fragmentation. The metastable precipitates will be dissolved and solutionized in the aluminum matrix during FSW, but the stable precipitates remained and are prone to segregate in the high-strain region. Fonda et al. [27], reported that as rotation speed increased, and the temperature within the nugget becomes higher and more uniform, the volume fraction of coarse second phase particles decreased at different positions within the nugget zone region. The fracture location therefore corresponds to the region with least precipitate strengthening. As the peak temperature during FSW was about 450°C for this alloy and was not sufficient to force stable precipitates to dissolve and solutionize into aluminum matrix. In the weld region of FSW joints, there is no possibility of depletion of strengthening precipitates as in case of TIG joints. In friction stir processed (FSP) AA 7075 alloy, Ma and Mishra [141] made three important observations using TEM micrographs : (i) the fine precipitates were uniformly distributed within the interior of grains and at the grain boundaries, (ii) while the grain boundary particles usually exhibited a needle or disc type morphology, the precipitates inside the grains generally had equiaxed shape, (iii) the precipitates in the FSW zone were fine and generally had size of <0.5 μm. This may be
one of the reasons for superior tensile properties of FSW joints compared to TIG welded joints.

5.8.2 Micro hardness

Figure 5.20 shows the micro hardness distribution for TIG and FSW joint. The micro hardness of the base metal was 111 Hv. The micro hardness of TIG joint in the weld metal region was 55 Hv. This shows that the hardness is reduced in TIG joint due to higher heat input and use of lower hardness AlSi3 filler metal. The micro hardness of FSW joint in the weld region is 70 Hv. In FSW joint lowest hardness is observed on the advancing side which 62 Hv. The hardness is lower than the base metal due to dissolution of strengthening precipitates during the weld thermal cycle. However, FSW showed higher micro hardness compared to TIG joint due to shear stresses induced by tool motion which lead to generation of very fine grain structure, which allows a partial recovery of hardness. In case of TIG welding, very high arc temperature increases the peak temperature of the molten weld pool causing a slow cooling rate. This slow cooling rate, in turn, causes relatively wider dendritic spacing in the fusion zone. These
microstructures generally offer lower resistance to indentation and this may be one of the reasons for lower hardness and inferior tensile properties compared to FSW Joints.

5.8.3 Tensile properties

The ultimate tensile strength of base and welded metals are shown in table 5.5. It indicates that FSW joints are exhibiting superior tensile properties compared to TIG joints. Figure 5.21 shows image of fractured tensile specimen which shows that during tensile test all the specimens invariably failed in the weld region. This indicates that the weld region is comparatively weaker than other regions and hence joint properties are controlled by weld region chemical composition and microstructure.

Table 5.5 Ultimate tensile strength of base and welded (FSW & TIG) metals

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>% Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material 6061 T6</td>
<td>313.6</td>
<td>18</td>
</tr>
<tr>
<td>FSW 6061T6</td>
<td>159.9</td>
<td>5.5</td>
</tr>
<tr>
<td>TIG 6061 T6</td>
<td>139.6</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Figure 5.21 Image of fractured tensile specimen for base, FSW and TIG joint
The tensile properties and elongation of both TIG and FSW joint is far lower than the parent material. These results are consistent with the observations reported by Ericsson M, and Sandstrom R [57] and Cabello Munoz A et al. [55]. These results indicate that softening effect has occurred in aluminum alloy. The tensile properties and fracture locations of the joints are to a large extent dependent on the hardness distributions of the joints. Hardness degradation region composed of weld nugget, TMAZ and HAZ has occurred in the joints, thus the tensile properties of the joints are lower than the parent material. It is found that, in FSW the fracture location is between weld nugget and the thermo mechanically affected zone (TMAZ) on the advancing side. The percentage elongation of FSW joint is higher than TIG joint which shows FSW exhibited higher ductility values compared to TIG joint. Joint efficiency is the ratio between ultimate tensile strength of welded joint to that of base metal. FSW joint exhibited higher efficiency (51%) compared to TIG joint (44.5 %).

5.8.4 Fractography

![Fractograph for FSW joint](image)

Figure 5.22 Fractograph for FSW joint
A better comprehension and understanding of the mechanical fracture and defect nucleation properties are strongly dependent on analyses of the rupture surfaces. With the rapid increasing of FSW technology in various applications fractography studies such as scanning electron microscope has been extremely useful to detect the rupture mechanism. The fracture location of any joint is direct reflection of the weakest part of the joint. Studying the fracture location of the joint is quite important to understand and improve the mechanical properties of the joint.

For both FSW and TIG joint the fracture location was in weld region. The fractured surface of tensile specimens of welded joints was analyzed using scanning electron microscope to reveal the fracture surface morphology. Figures 5.22 and 5.23 show fractography for FSW and TIG joints respectively. The fractography consists of dimples, which is indication that the tensile specimen failed in a ductile manner under the action of tensile loading. An appreciable difference exists in the size of the dimples with respect to welding processes. Coarse dimples are seen in TIG joint and fine dimples in FSW joint. Since fine dimples are characteristic feature of ductile failure, FSW joints have shown higher ductility compared to TIG joint. The dimple size has direct proportional relationship with strength and ductility, i.e. if the dimple size is finer, then the strength and ductility of the respective joint is higher and vice versa [142].
5.9 Copper joining by FSW

In this study, the feasibility of FSW for joining copper is explored. The microstructure of copper base material and FSW zones were studied using optical metallography. Micro hardness profiles at the weld zone and corresponding tensile strength test data were also correlated. The results presented in this investigation represent an evaluation of the FSW capability to produce 2 mm thick copper joint.

Experiments were performed at various tool rotation and welding speed using left hand threaded pin. It was found that when the tool was rotated in counterclockwise direction, sound joints were obtained but when it was rotated in clockwise direction with same welding parameters groove type defects were obtained due to the insufficient stirring of the metal as shown in figure 5.24 and figure 5.25 respectively. Similar observations were reported by Cemal Meran [63] for friction stir welded joint of brass.

![Photo image of defect free FSW copper joint](image)

Figure 5.24 Photo image of defect free FSW copper joint
The main reasons for welding defects in FSW are improper selection of welding parameters like rotational speed, welding speed, direction of rotation and downward force of the tool. Perfect weld can be obtained by proper design of the tool and proper selection of welding parameters.

5.9.1. Microstructure

Figure 5.25 Photo image of copper joint with welding defect
The butt joining of copper was successfully conducted by FSW. The microstructure of FSW copper joint consists of different zones such as stir zone (SZ), Thermo mechanically affected zone (TMAZ), heat affected zone (HAZ) and parent metal. Figures 5.26 (a), (b) and (c) show the typical microstructure of the parent metal, transition zone (TMAZ and HAZ) and stir zone (SZ) respectively. The parent material
showed elongated grains due to cold rolling as seen in figure 5.26 (a). The mean grain diameter was 28 μm. Optical microscopy revealed the presence of fine equiaxed recrystallized grains in the SZ which are formed under high temperature and high rate of plastic deformation due to pin’s stirring. In stir zone mean grain size diameter of 10 μm was measured. TMAZ which consisted of coarse bent grains, is the region subjected to both plastic deformation and relatively low peak temperature compared to SZ. HAZ is the region separated between TMAZ and parent metal which experiences a thermal cycle but no plastic deformation occurs in this area. TMAZ is characterized by rotation of the elongated grains at both sides of the joint [143]. Adjacent to the TMAZ a few coarse grains were observed in the heat affected zone as shown in figure 5.26 (b), this results in hardness variation as shown in figure 5.27.

5.9.2. Micro hardness

Micro hardness measurements were performed on copper butt joint for specimen welded at 1000 rpm and 25 mm/min at the mid thickness. Figure 5.27 shows the Vickers hardness profile for the joint and parent material. The hardness variation along the weld zone was highly correlated with microstructure. The hardness of the parent material was
varying between 105 to 110 Hv. Significant variation in hardness was observed in the weld region varying between 98 and 77 Hv due to thermo-mechanical conditions. Nugget zone has slightly higher hardness than TMAZ due to presence of extremely fine recrystallized equiaxed grains [144]. TMAZ and HAZ showed lower hardness than the parent material because of annealing softening effect [61]. Minimum hardness was observed in the TMAZ region towards the advancing side. Similarly Okamoto et al [145], Lee & Jung [60], Hautala & Tiainen [146] and Xie et al [61] noted that the hardness in the weld region was lower than the parent copper after FSW.

5.9.3 Tensile properties

Ultimate Tensile strength and percentage of elongation of the copper base material was 272 MPa and 6.2 % respectively. For Friction stir weld copper, ultimate strength and percentage of elongation observed was 247 MPa. and 3.2 % respectively. Hence the tensile strength of the FSW copper weld was 89 % (strength of weld/strength of the parent metal x 100) of the base plate. The percentage elongation of FSW weld was less than the parent material. The region of the weld is softened due to frictional heat hence the tensile properties of the joints are lower than that of the base material. It is found that the fracture location of the joints is on the TMAZ on the advancing side. Figure 5.28 shows the photo image of parent metal and FSW copper joint after fracture.
In practice, the reason for the fracture near the interface between the SZ and TMAZ is the remarkable difference in the microstructure between the SZ and TMAZ. The SZ is composed of fine equiaxed recrystallized grains as shown in figure 5.26 (c), while TMAZ is composed of coarse bent elongated grains. Also in the weld region as shown in figure 5.27, the advancing side has lower hardness than the retreating side hence the joint is fractured in advancing side. As the micro hardness is correlated with tensile strength, hence the tensile strength on the advancing side is lower than on the retreating side.

5.10 Friction stir welded 1100 to 6061 dissimilar aluminum alloy

Joining of dissimilar aluminum alloys can be of particular interest in some industrial applications. Some works can be found in the literature, but data is still scarce on the characterization of this joint type. Recently, the aspect of industrial structures has become more complicated, making the joining of dissimilar materials an indispensable technique. The objective of the present investigation is to evaluate the microstructure.
hardness distribution and tensile properties of dissimilar pure 1100 aluminum and 6061 T6 aluminum alloy joints produced by FSW.

In this study the ability to join dissimilar alloys by FSW was studied using pure aluminum 1100 and 6061 aluminum alloy. Dissimilar welds formed by AA 6061 T6 and Al 1100 have been joined by FSW and no visible superficial porosity or cracks or any defects have been observed on both top and rear welded surfaces.

5.10.1 Microstructure

![Figure 5.29 (a) Microstructure of parent 1100](image)

![Figure 5.29 (b) Microstructure of transition zone (HAZ and TMAZ) and stir zone](image)
The microstructure of pure 1100 aluminum is shown in figure 5.29 (a). The pure 1100 is characterized by Si particles dispersed in a finer matrix. Figure 5.29 (c) shows weld nugget (or stir zone) at higher magnification, which experiences high strain and it consists of fine grains formed due to dynamic recrystallization. The optical microscope showed distribution of strengthening precipitates in the weld zone. By moving away from the weld centre the grains begin are less equiaxed than those closer to weld centre. Figure 5.29 (b) represents transition zone i.e. thermo mechanical affected zone (TMAZ) and heat affected zone (HAZ). Adjacent to weld nugget is the thermo mechanical affected zone (TMAZ) which ends at the tool shoulder. TMAZ corresponds to region where mechanical properties are modified by the rotation and translational motion of the tool. In HAZ, mechanical properties are modified by the heat generated by the friction between the tool and the plates. Metallurgical modifications in this zone are similar to those occurring during traditional fusion welding processes.
5.10.2. Micro hardness distribution

Vickers hardness profiles across the weld are presented in figure 5.30 taken at the mid-section of FSW joint. The hardness decreased from the level of the parent material (111 Hv) for 6061 alloy to reduced values in the weld zone (62 Hv) for similar joint (6061-6061). For dissimilar joint, the micro hardness for TMAZ and stir zone is considerably lower than base materials. Minimum hardness occurred in the TMAZ at the retreating side (40 Hv) for dissimilar joint [147]. The loss of T6 condition which is obtained by solutionizing and artificial ageing for 6061 aluminum alloy, occurs during welding and is expected to decrease the mechanical strength, which is reflected in the drop of hardness.

5.10.3 Tensile properties

Table 5.6 presents the tensile properties for friction stir welded specimen and the base material.
The tensile properties and elongation of FSW joint is far lower than the parent material. These results indicate that softening effect has occurred in welding zone due to FSW. The tensile properties and fracture locations of the joints are to a large extent dependent on the hardness distributions of the joints. Hardness degradation region composed of weld nugget and TMAZ, has occurred in the joints, thus the tensile properties of the joints are lower than the parent material. It is found that the fracture location is between weld nugget and the TMAZ on the retreating side for dissimilar joint as shown in figure 5.31. This study has shown that in a dissimilar friction stir weld, the weaker component dictates the performance of the joint, where failure happens in the region of the greatest strength reduction related to annealing phenomena. Microscopic investigation as well as the evaluation of local mechanical properties has suggested that mechanical mixing is the major material flow mechanism in the formation of the stirred zone [147].
5.11 FSW of dissimilar 6061 T6 AA to copper

Application of FSW method for joining of copper to aluminum causes considerable difficulties. When pin was penetrated at the centre line of the two plates with offset = 0 mm, it created poor weld. Also when aluminum was kept on advancing side and Cu on retreating side, it resulted in poor weld quality as aluminum material is plasticized but copper plate is not sufficiently heated. A pin penetrating in between the surfaces of the two plates, when there are considerable differences of their physical properties, hardness, tensile strength, melting point, leads to asymmetrical heating and plasticizing of the plate. Most frequently such a process leads to heating and plasticizing only the material of one plate and does not lead to sufficient plasticizing of the second material in the contact area. This is the case of welding aluminum to copper.

As heating and plasticizing of the faying areas of the materials gradually increase, when using a tool running alongside the line of the contact of the materials, the process gets more and more difficult. This is because of physical properties of these materials in
the range of temperature between 300-600°C, in which aluminum gets plasticized, copper shows significant decrease of its plasticity and at temperatures when copper gets plasticized, it causes aluminum to melt. In case of butt welding of aluminum to copper with pin at the centre with zero offset, the welds become very fragile of poor quality and low tensile strength as a result of overheating of aluminum in the contact area and under heating of copper in the faying area. As copper in the faying area is not sufficiently heated, right welds cannot develop in the solid state. This way of welding can only create bonds of adhesion or diffusion with very limited range of penetration of atoms diffusing into other metal. This may be reason for poor quality of the welds. Sound welds were obtained for specimen no.3 (Table 3.5, 1000 rpm and 20 mm/min) and 4 (Table 3.5, 1250 rpm and 20 mm/min), when the centre line of pin was shifted by 1 mm towards copper with copper plate on advancing side [148]. Similar results were obtained by Chen and Kovacevic by shifting the tool centre line towards steel for FSW of 6061 AA and AISI 1018 steel [149].

5.11.1 Microstructure of joints

![Figure 5.32 (a) Microstructure of stir zone for Cu-Al FSW joint](image)
The microstructure of the stir zone was characterized by equiaxed fine grains. Several authors suggested that recrystallized grains in the stir zone are formed by continuous dynamic recrystallization. As shown in figures 5.32 (a) and (b), particles of copper are spread in aluminum which shows the movement of material during heating the area with the pin of the tool. The high temperatures associated with strong stirring action of tool pin cause heterogeneous mixing of Al and Cu resulting in the formation of intermetallic compounds $\text{CuAl}_2$, $\text{CuAl}$ and $\text{Cu}_9\text{Al}_4$ [90]. Similar results were also found by Aritoshi et.al [150] in the friction welding of oxygen free copper to pure aluminum.
5.11.2 Mechanical properties of joints

The hardness distribution across the cross-section is shown in figure 5.33. The average hardness of 6061 AA (on retreating side) and copper (on advancing side) are 110 Hv and 105 Hv respectively. The hardness observed in stir zone is slightly higher than base materials mainly due to formation of hard, brittle intermetallic compounds. Similarly higher hardness in the stir zone was also reported by Elrefaey A et al [87]. Figure 5.34 (a) and (b) shows top and bottom images respectively of friction stir welded tensile specimen of copper with AA 6061 T6.
Figure 5.34 (a) Top image of friction stir welded tensile specimen of Cu-Al joint

Figure 5.34 (b) Bottom image of friction stir welded tensile specimen of Cu-Al joint
The tensile strength of parent material of 6061 AA and copper was 313.2 MPa and 272 MPa respectively. Tensile strength of Cu/Al joint at 1000 rpm, welding speed 20mm/min and at 1250 rpm, welding speed 20 mm/min observed were 62.2 MPa and 56.3 MPa respectively. Low tensile strength is mainly due to formation of intermetallic compounds due to heterogeneous mixing of copper with aluminum. The fracture in the tensile specimen occurred on the advancing side. More formation of intermetallic compounds is likely to occur in advancing side because of higher amount of temperature and strain at this side [87]. The intermetallic compounds of CuAl₂, CuAl and Cu₉Al₄ are responsible for preferential development of the crack in the tensile test. Increasing the rotational speed of the tool to 1250 rpm results in higher temperature, which produce higher amount of intermetallic compounds at the interface between aluminum and copper. By increasing the temperature, the nucleation and growth of these compounds are accelerated. When the rotational speed was below 800 rpm, the joints produced were of incompletely welded surfaces.

5.12 Optimization of process parameters for FSW using Taguchi L9 orthogonal design

During the welding process, frictional heat associated with the thermal cycle varies in the transverse direction of the weld. The maximum temperature is observed in the FSW zone, which causes an alteration in the precipitate distribution present in the base material and also due to stirring of the plasticized material. These changes in the heat and temperature distribution in the welding process alter the strength and ductility of the joints [22]. Though FSW joints yield better joint efficiency compared to fusion welding processes, the gap between strength values of the base metal and weld metal is considerably large.

The tensile strength of the FSW joint mainly depends on the welding parameters such as pin rotation, traverse speed, axial force and tool geometry. The effect of some important parameters such as rotational speed, welding speed and axial force on weld properties has been major topics for researchers [66,68,151-153]. In order to study the effect of FSW process parameters, most researchers follow the traditional experimental techniques i.e. varying one parameter at a time while keeping others constant. This
conventional parametric design of experiment approach is time consuming and calls for enormous resources. The major disadvantage of this strategy is that it fails to consider any possible interactions between the parameters. An interaction is the failure of one factor to produce the same effect on the response at different levels of another factor. It is also impossible to study all the factors and determine their main effects (i.e. individual effects) in a single experiment. Taguchi techniques overcome all these drawbacks. There have been plenty of recent applications of Taguchi techniques [96-101,154-159].

It seems that most of the published papers are focusing on the effect of FSW parameters and tool profiles on tensile properties and microstructure formation. A systematic investigation of optimization of FSW process parameters for 6061 T6 aluminum alloy is rather lacking. In the present investigation, Taguchi L9 method is adopted to analyze the effect of rotational speed, welding speed and axial force for optimum tensile strength of FSW joints using commercial software MINITAB [160]. ANOVA was used to investigate optimum levels and effect of process parameters on tensile strength.

5.12.1 Selection of orthogonal array (OA)

Orthogonal arrays are a simplified method of putting together an experiment when compared to traditional methods such as one factor at a time experiments. It gives more reliable estimate of factor effects with less number of experiments. Before selecting a particular OA to be used as a matrix for conducting the experiments, the following two points must be considered: 1) The number of parameters and interactions of interest; 2) The number of levels for the parameters of interest. The non-linear behavior, if exists among the process parameters, can only be studied if more than two levels of the parameters are used. Therefore, each parameter was analysed at three levels. To limit the study, it was decided not to study the second order interaction among the parameters. In this approach, the total degree of freedom required \((\text{DOF})_R\) for process input parameters each at level is given by [161]

\[
(\text{DOF})_R = P \times (L-1) \tag{5.5}
\]

where,

\(P\) = number of factors of parameters, \\
\(L\) = number of levels.
In the present work, $P = 3$, $L = 3$, therefore, the total DOF required for 3 parameters each at three levels is $6 (=3 \times (3-1))$. As per Taguchi’s method, the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So an L9 OA having $8(=9-1)$ degrees of freedom were selected for the present analysis.

Table 5.7 Orthogonal Array for L9 with experimental values of tensile strength (mean)

<table>
<thead>
<tr>
<th>Test</th>
<th>Rotational speed (rpm)</th>
<th>Welding speed (mm/min)</th>
<th>Axial force (N)</th>
<th>Tensile Strength (MPa)</th>
<th>S/N ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>750</td>
<td>50</td>
<td>1700</td>
<td>150.2</td>
<td>43.5339865</td>
</tr>
<tr>
<td>2</td>
<td>750</td>
<td>80</td>
<td>2000</td>
<td>154.1</td>
<td>43.75605277</td>
</tr>
<tr>
<td>3</td>
<td>750</td>
<td>100</td>
<td>2400</td>
<td>146.8</td>
<td>43.33452111</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
<td>50</td>
<td>2000</td>
<td>155.6</td>
<td>43.84019185</td>
</tr>
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<td>1000</td>
<td>80</td>
<td>2400</td>
<td>160.8</td>
<td>44.12572089</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>100</td>
<td>1700</td>
<td>150.6</td>
<td>43.55649944</td>
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<tr>
<td>7</td>
<td>1250</td>
<td>50</td>
<td>2400</td>
<td>147.9</td>
<td>43.39936348</td>
</tr>
<tr>
<td>8</td>
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<td>80</td>
<td>1700</td>
<td>140.4</td>
<td>42.94734216</td>
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<td>9</td>
<td>1250</td>
<td>100</td>
<td>2000</td>
<td>137.4</td>
<td>42.75973465</td>
</tr>
</tbody>
</table>

Table 5.8 Main effects of tensile strength (means and S/N ratio)

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Mean</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>N</td>
<td>150.4</td>
<td>155.7</td>
</tr>
<tr>
<td>WS</td>
<td>151.2</td>
<td>151.8</td>
</tr>
<tr>
<td>AF</td>
<td>147.1</td>
<td>149.0</td>
</tr>
</tbody>
</table>
Figure 5.35 Response graph (means) of tensile strength

Figure 5.36 Response graph (S/N ratio) of tensile strength
In the present study, the tensile strength data was analyzed to determine the effect of FSW process parameters. The experimental results were then transferred into S/N ratio. Analysis of mean for each of the experiments will give better combination of parameters levels that ensures a high level of tensile strength according to the experimental set of data. The mean response refers to the average value of performance characteristic for each parameter at different levels. The mean for one level was calculated as the average of all responses that were obtained with that level. The response of raw data and S/N ratio of tensile strength for each parameter at level 1, 2 and 3 were calculated and are given in Table 5.7. The mean and S/N ratio of the various process parameters when they changed from lower to higher levels are given in Table 5.8. It is clear that a larger S/N ratio corresponds to better quality characteristics. Therefore, the optimal level of process parameter is the level of higher S/N ratio [162]. The mean effect (Figure 5.35 ) and S/N ratio (Figure 5.36) for tensile strength which were calculated by MINITAB statistical software , indicates that the tensile strength was maximum when rotational speed (level 2), welding speed (level 2) and axial force (level 3) are 1000 rpm , 80 mm/min and 2400 N respectively [163]. The tensile strength of the base material was 313.6 MPa.

5.12.2 Discussion on welding parameters for optimum tensile strength

The response graph of tensile strength(means) can be effectively used to understand the effect of FSW parameters such as tool rotational speed, welding speed, axial force, and tool profile on tensile strength of friction stir welded AA 6061aluminum alloy joints.

5.12.2.1 Effect of tool rotational speed

The yield strength and tensile strength of all the joints are lower than that of the base material, irrespective of the tool rotational speeds used to fabricate the joints. Of the three tool rotational speeds used to fabricate AA 6061 joints, the joint fabricated at a rotational speed of 1000 rpm yielded superior tensile properties. Figure 5.35 reveals the effect of tool rotational speed on tensile strength of friction stir welded AA 6061 joints. At lower rotational speed (750 rpm), the tensile strength of FSW joints is lower. When the rotational speed is increased from 750 rpm, correspondingly the tensile strength also increased and reaches a maximum at 1000 rpm. If the rotational speed is increased to
1250 rpm, the tensile strength of the joint decreased. The tensile properties and fracture locations of the joints are to a large extent, dependent on the rotational speed, and other parameters. As rotational speed increased, the heat input per unit length of the joint increased, resulting in inferior tensile properties due to rise in temperature, which increases grain growth. Considerable increase in turbulence, which destroys the regular flow behaviour available at lower speed, is also observed. Moreover a higher-rotational speed causes excessive release of stirred materials to the upper surface, which resultantly leaves voids in the weld zone. On the other side, the area of the weld zone decreases with decreasing the tool rotation speed and affect the temperature distribution in the weld zone. This lower heat input condition results in lack of stirring and yields lower joint strength.

5.12.2.2 Effect of tool welding speed

The welding speed has a strong impact on productivity in streamlined production of friction stir welding of aluminum alloy sections. A significant increase in welding speed is achieved with high weld quality and excellent joint properties. The softened area is narrower for the higher welding speed than that for the lower welding speed. Thus, the tensile strength of as welded aluminum alloy has a proportional relationship with welding speed. Higher welding speeds are associated with low heat inputs, which result in faster cooling rates of the welded joint. This can significantly reduce the extent of metallurgical transformations taking place during welding (such as solubilisation, re-precipitation and coarsening of precipitates) and hence the local strength of individual regions across the weld zone [164]. When the welding speed is slower than a certain critical value, the FSW can produce defect-free joints. When the welding speed is faster than the critical value, welding defects can be produced in the joints. The defects act as a crack initiation site during tensile test. Therefore, the tensile properties and fracture locations of the joints are determined by the welding speed [165]. Fig. 5.35 reveals the effect of welding speed on tensile strength of friction stir welded AA6061 aluminum alloy. At lower welding speed (50 mm/min) tensile strength of the FSW joints is lower. When the welding speed is increased from 50 mm/min, correspondingly the tensile strength also increased and reaches a maximum at 80 mm/min. If the welding speed is increased above 80 mm/min, the tensile strength of the joint is decreased. The joints fabricated at lower welding speeds contain defects like pinhole or crack in FSW region and results in lower tensile
properties. On the other hand, joints fabricated at higher welding speeds contain large size defects and it appears like tunnel. In general friction stir welding at higher welding speeds, results in short exposure time in the weld area with insufficient heat and poor plastic flow of the metal and causes some voids like defects in the joints. It seems that these voids are formed due to poor consolidation of the metal interface when the tool travels at higher welding speeds. The reduced plasticity and rates of diffusion in the material may have resulted in a weak interface.

5.12.2.3 Effect of axial force

Fig. 5.35 reveals the effect of axial force on tensile strength of friction stir welded AA6061 aluminum alloy. At lower axial force (1700 N) tensile strength of the FSW joints is lower. When the axial force is increased from 1700 N, correspondingly the tensile strength also increased and reaches a maximum at 2400 N. The heat input and temperature distribution during friction stir welding is due to frictional heat generation between the rotating tool shoulder and surface of the plate to be welded and in turn depends on co-efficient of friction. Apart from the properties of tool and plate material, the axial force decides the coefficient of friction. Hence axial force plays a significant role in friction stir welding process. The degree of material mixing and inter diffusion, the thickness of deformed aluminum lamellae, the material flow patterns highly depends on welding temperature, flow stress and axial force [166]. Oyuang and Kovacevic [167] observed that the axial force is directly responsible for the plunge depth of the tool pin in to the work piece and load characteristics associated with linear friction stir weld. When the axial force is relatively low, there is a tunnel found at the bottom. While with higher axial force, the weld is sound with full penetration. It shows that sufficient axial force is required to form good weld. This is because the temperature during friction stir welding defining the amount of plasticized metal and the temperature is greatly dependent on the axial force.
5.12.3 Analysis of variance (ANOVA)

Table 5.9 ANOVA for tensile strength (means)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>V</th>
<th>F</th>
<th>P</th>
<th>SS’</th>
<th>% contribution</th>
</tr>
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<tbody>
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<td>0.157</td>
<td>70.553</td>
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<td>0.319</td>
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<td></td>
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<td>100</td>
</tr>
</tbody>
</table>

DF = Degree of freedom, SS = Sum of squares, V = Variance, F = Fisher ratio, P = Probability that exceeds the 95% confidence level, SS’ = Pure sum of squares

SS, V, F and P are calculated by MINITAB software. The last two terms in table 5.9 and 5.10 cannot be generated by ANOVA. The formula for finding these terms is given below [168]:

\[ SS' = \text{Seq SS} - \text{DF} \times \text{(Error)} \]

Percentage contribution = (SS’/ Total Seq SS) * 100

Analysis of variance test was performed to identify the process parameters that are statistically significant. ANOVA is a technique for determining whether there are significant differences between more than two sample averages. It is the most commonly used technique for comparing the means of groups of measurement data. The purpose of ANOVA is to find the significance of the process parameters which affects the tensile strength of FSW joints. ANOVA results for tensile strength of means and S/N ratio are given in Table 5.9 & 5.10 respectively. In addition, the F-test named after Fisher can also

Table 5.10 ANOVA for tensile strength (S/N ratio)

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>V</th>
<th>F</th>
<th>P</th>
<th>SS’</th>
<th>% contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>2</td>
<td>0.99411</td>
<td>0.49706</td>
<td>17.14</td>
<td>0.055</td>
<td>0.93611</td>
<td>64.06</td>
</tr>
<tr>
<td>WS</td>
<td>2</td>
<td>0.29456</td>
<td>0.14728</td>
<td>5.08</td>
<td>0.164</td>
<td>0.23656</td>
<td>16.19</td>
</tr>
<tr>
<td>AF</td>
<td>2</td>
<td>0.11461</td>
<td>0.05731</td>
<td>1.98</td>
<td>0.336</td>
<td>0.05661</td>
<td>3.87</td>
</tr>
<tr>
<td>Error</td>
<td>2</td>
<td>0.05799</td>
<td>0.02900</td>
<td></td>
<td></td>
<td></td>
<td>15.88</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>1.46127</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>
be used to determine which process has a significant effect on tensile strength. Usually, the change of the process parameter has a significant effect on the quality characteristics, when $F$ is large. Results of ANOVA indicate that the considered process parameters are highly significant factors affecting the tensile strength of FSW joints in order of rotational speed, welding speed and axial force.

Percentage contribution indicates the relative power of a factor to reduce variation. Percentage contribution is the portion of the total variation observed in the experiment attributed to each significant factor. For a factor with a high percent contribution, a small variation will have a great influence on the performance. Percentage contribution is a function of sum of squares for each significant item; it indicates the relative power of a factor to reduce the variation. If the factor levels were controlled precisely, then the total variation could be reduced by the amount indicated by the percentage contribution. The percentage contribution of rotational speed, welding speed and axial force is shown in the form of pie chart (figure 5.37).

Figure 5.37 Pie chart showing percentage contribution of factors (means)
Once the experiments are conducted and optimum process parameters are determined, one of two possibilities exists:

1. The prescribed combination of factor level is included in the experiment.
2. The prescribed combination of factor level was not included in the experiment.

This is expected because here only 9 combinations are selected out of $3^3 = 27$ possible combinations.

In this work, the first situation exists. The significant process parameters and their optimum levels have already been selected as $N_2$, $S_2$ and $F_3$ (Table 5.8). The estimated mean of the response characteristics can be computed as [97, 169]

$$TS = N_2 + S_2 + F_3 - 2T$$

where,

- $TS = $ tensile strength
- $T = $ overall mean of tensile strength
- $N_2 = $ average tensile strength at second level of rotational speed, 1000 rpm
- $S_2 = $ average tensile strength at second level of welding speed, 80 mm/min
- $F_3 = $ average tensile strength at third level of axial force, 2400 N.

$$TS = 155.7 + 151.8 + 151.8 - 2 \times 149.31$$

$$= 160.68 \text{ MPa}$$

### 5.12.4 Confirmation test

The confirmation experiment is the final step of design of experiment process. The purpose of the confirmation experiment is to validate the conclusions drawn during the analysis phase. The confirmation experiment is performed by conducting a test with specific combination of the factors and levels previously evaluated. In this study, after determining the optimum conditions, a new experiment was designed and conducted with optimum levels of the FSW parameters.

A confirmation experiment is needed to determine the optimum condition and to compare the results with the expected conditions [170]. Two confirmation experiments were conducted at the optimum setting of process parameters. The rotational speed at second level, welding speed at second level and axial force were set at level 3 and...
average tensile strength of friction stir welded 6061 AA was found to be 160.42 MPa which was within the confidence interval of the predicted optimal tensile strength. The improvement of tensile strength at optimum parameters is attributed to sufficient heat generation due to optimum stirring of the plasticized material.

5.12.5 Fractography

![Fractography of FSW joint for optimum condition](image)

The fracture surface of sample for optimum condition was studied by scanning electron microscope (SEM) to reveal the fracture surface morphology. Figure 5.38 shows fractography for FSW joint, which shows broad population of microscopic voids of different dimensions and shapes. The fractography consists of dimples, which is indication that the tensile specimen failed in a ductile manner under the action of tensile loading.