CHAPTER 5

EFFECT OF PROCESS PARAMETERS ON THERMAL HISTORY, RESIDUAL STRESSES AND MECHANICAL PROPERTIES

5.1 INTRODUCTION

In friction stir welding process, a rotating cylindrical tool with shoulder and pin is traversed along the interface between the two plates to be joined. The frictional heat generated is used to heat the material which is extruded around the tool pin before being forged by the large shoulder pressure. The weld is formed by the forging action at high temperature below the melting point. The simultaneous translation and rotation of the tool during FSW creates a characteristic asymmetry between the adjoining sides. The microstructural changes in various zones have significant effect on post weld mechanical properties. These microstructural changes are influenced by the heat input which, in turn, are influenced by process parameters such as tool rotation, weld speed and axial load on the tool etc (Peel et al 2003, Su et al 2003)

This chapter briefs the investigation on the effect of process parameters such as tool rotation (TR) and weld speed (WS) on thermal cycles, residual stresses, mechanical properties and microstructure of the welded aluminum alloy AA2014-T6 by FSW process. A finite element thermo-mechanical model was developed to generate the temperature and residual stress data for various welding conditions considered. Nine samples were
welded using various combinations of TR and WS within the capacity of the modified FSW machine. Weld samples were characterised by conducting tensile test, hardness test and microstructural examinations. Residual stress measurements were carried out for a limited number of samples. The temperature, residual stress, tensile strength and hardness data were related to process parameters. The statistical tool ANOVA was also employed to study the statistical significance of process parameters on thermal cycles and tensile properties.

5.2 INFLUENCE OF PROCESS PARAMETERS ON THERMAL CYCLES

The effect of the key weld parameters TR and WS on thermal cycles of the weld plate is discussed in this section. Simulated temperature distribution of the workpiece for various input parameters is given in Appendix 3. Simulated and experimental temperature data are used to find out the significance of these two parameters.

5.2.1 Effect of Tool Rotation

Figures 5.1 (a) and (b) show temperature distribution across the plate perpendicular to the weld direction. It is observed that the increase in tool rotation increases the temperature distribution of the weld sample due to increased heat input. Similar findings were reported by Zhu et al (2004) and Reynolds et al (2003) while welding stainless steel 304L material by FSW. Moreover it is observed from the temperature profiles that the peak temperature at weld zone is more influenced by the tool rotation.
Figure 5.1  a) Simulated b) measured temperature profile across the weld sample (WS = 60 mm/min)

5.2.2 Effect of Welding Speed

From the temperature distribution across the weld samples shown in Figure 5.2, it is seen that the peak temperature at the weld zone decreases with increase in weld speed. Moreover, the uniform difference between the temperature profiles for various weld speeds indicates that the influence of weld speed on temperature across the plate including weld zone is uniform.
5.2.3 Effect of Tool Rotation and Weld Speed

The heat input for a friction stir weld is obtained from the quotient of the spindle power and the weld speed (Reynolds et al 2003). The spindle power is a function of tool rotation. So the combined effect of tool rotation and weld speed determines the heat input into the weld samples. The simulated peak temperature at weld zone for different TR and WS is shown in Figure 5.3.
Figure 5.3 Simulated peak temperature at weld zone

The temperature in the weld centre under the tool varies between 710 K (lowest value) for the weld trial E1 and 880 K (highest value) for the weld trial E9. The weld produced with the higher tool rotation (1120 rpm) corresponding to trial E3 has higher temperature than the lower tool rotation corresponding to trial E7 (355 rpm) and is slightly cooler than the weld trial E9 which was produced using the same tool rotation (1120 rpm). The same situation is observed for the welds produced at 355 rpm (E1, E4 and E7) where the changes in the weld speed has little effect on the peak temperature at weld zone. It is seen from the plot that the peak temperature at weld zone is more influenced by tool rotation than weld speed.

5.3 STATISTICAL ANALYSIS

The influence of weld parameters TR and WS on peak temperature at weld zone has been studied by the statistical technique ANOVA (Davim and Padro 2003). The result of the ANOVA is tabulated in Table 5.1.
Table 5.1 ANOVA table for the peak temperature under tool shoulder

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>Sum of squares( (S) )</th>
<th>Df( (f) )</th>
<th>Variance ( (S/f) )</th>
<th>Variance ratio (Test F)</th>
<th>( F_{\alpha=5%} )</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld speed (WS) (mm/min)</td>
<td>8325.33</td>
<td>2</td>
<td>4162.67</td>
<td>82.35</td>
<td>4.26</td>
<td>15.05</td>
</tr>
<tr>
<td>Tool rotation (TR) (rpm)</td>
<td>45285.33</td>
<td>2</td>
<td>22642.67</td>
<td>452.85</td>
<td>4.26</td>
<td>82.67</td>
</tr>
<tr>
<td>Interactions (I = WS \times TR)</td>
<td>597.33</td>
<td>4</td>
<td>149.33</td>
<td>2.99</td>
<td>3.63</td>
<td>0.73</td>
</tr>
<tr>
<td>Error</td>
<td>450.00</td>
<td>9</td>
<td>50.00</td>
<td>1.00</td>
<td>-</td>
<td>1.55</td>
</tr>
<tr>
<td>Total</td>
<td>54657.99</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Df : Degree of freedom, \( F_{\alpha=5\%} \) : F-table, P: Percentage of contribution

From the Table 5.1, it is observed that the WS, TR and their interactions I (WS and TRS) have the statistical significance of 15.05 %, 82.67 % and 0.73 % on peak temperature. It is observed from the percentage contribution that the peak temperature under the tool is more influenced by TR than weld speed. Similar findings were reported by Peel et al (2006a) when two dissimilar aluminium alloys were friction stir welded. The factors such as WS and TR present a statistical significance Test F> \( F_{\alpha=5\%} \). But the interaction does not have statistical significance on peak temperature because Test F < \( F_{\alpha=5\%} \). It is noticed that the error associated to the ANOVA for peak temperature is 1.55 %.
5.4 INFLUENCE OF PROCESS PARAMETERS ON RESIDUAL STRESSES

Figures 5.4 and 5.5 show the variation of longitudinal residual stress across the plate for various tool rotations. It is observed from the experimental work and simulation studies that the magnitude of residual stress in the weld increases with increase in tool rotation.

**Figure 5.4** Simulated longitudinal stress along the transverse direction (WS = 60 mm/min)

**Figure 5.5** Measured longitudinal stress along the transverse direction (WS = 60 mm/min)
Here both simulated and measured longitudinal residual stresses for the various input parameters take the W-form with tensile stress along the weld line.

5.5 INFLUENCE OF PROCESS PARAMETERS ON TENSILE PROPERTIES

In any welding process, heat input plays an important role on mechanical properties of the weldments. In FSW heat input is mainly influenced by tool rotation and welding speed. So the weld properties of fiction stir weld are greatly influenced by tool rotation and welding speed.

Welded samples were characterized by means of tensile strength, hardness and microstructure examination to study the influence of process parameters. The welded specimens were radiographically examined using the machine ANDREX at DRDL, Hyderabad. Defect free samples were chosen and used for further characterisation. The radiograph of the weld sample (trial E4) is shown in Figure 5.6.

Figure 5.6 Radiograph of the welded sample
5.5.1 Tensile Testing

Standard test specimens were made for transverse tension by wire-cut EDM process. The configuration and size of the transverse tensile specimens were prepared as per ASTM E8, and marked length and width of the specimen were 25.4 mm and 6.3 mm respectively. In this study, a total of nine tensile tests were carried out to relate input parameters with tensile behaviour of the weld.

5.5.2 Effect of Welding Speed

The tensile strength of the joints is less than that of the base metal irrespective of the welding speeds used to fabricate the joints. Figure 5.7 reveals the effect of welding speed on tensile strength of weld joint produced by FSW. From the experimental results plotted, it is observed that the ultimate tensile strength increases with increase in welding speed in the tested range. In FSW, it is observed that increasing the welding speed for a given TR, reduces the heat input required for joining. Similar findings were reported by Liu et al (2003a), Lee (2004) and Hasan et al (2007) when aluminum alloys were welded by FSW.

![Figure 5.7 Tensile strength of the weld joint for various TR](image)

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5.5.3 Effect of Tool Rotation

Figure 5.8 shows the effect of tool rotation on tensile strength of the joint fabricated by FSW. From the experimental results plotted in Figure 5.8, it is observed that the ultimate tensile strength increases with increase in tool rotation up to 710 rpm for the welding speeds 30 mm/min and 60 mm/min. Of the three tool rotations used to fabricate aluminum alloy AA2014 joints, the joint fabricated at a rotation speed of 1120 rpm and 120 mm/min yielded higher tensile strength.

![Figure 5.8 Tensile strength of the weld joint for various WS](image)

5.5.4 Effect of Revolutionary Pitch

To study the combined effect of TR and WS on tensile properties, the parameter revolutionary pitch proposed by Lie et al (2003a) and Fujii et al (2005) was considered. Revolutionary pitch is the ratio of weld speed to tool rotation. Figure 5.9 shows the tensile properties of the joint welded at different revolutionary pitches. The ultimate tensile strength increases with increase in revolutionary pitch when the revolutionary pitch is less than 0.11 mm/rev. The maximum ultimate strength is obtained at the revolutionary pitch of 0.11 mm/rev which is equivalent to 78% that of the base material.
Ceschini et al (2007) reported that the tensile strength of friction stir weld was 80% of the base material. When the revolutionary pitch is greater than 0.11 mm/rev the revolutionary pitch decreases gradually.

Figure 5.9  Tensile strength of the weld joint for various revolutionary pitch

These results indicate that a softening effect has occurred in the aluminum alloy AA2014-T6 due to FSW just as it did in the other heat treatable aluminum alloys. The softening due to precipitation dissolution of the joints is strongly affected by the welding parameters. The optimum welding conditions could be determined from the relation between the welding parameters and tensile strength. The revolutionary pitch 0.11 mm/rev corresponding to the tool rotation 1120 rpm and the weld speed of 120 mm/min, is the optimum for the ultimate tensile strength.

5.6  STATISTICAL ANALYSIS

In order to find out the significance of the two parameters (TR and WS) on tensile properties statistical analysis of experimental data was carried out using ANOVA. Table 5.2 shows the results of ANOVA with tensile
strength of weld. From the Table 5.2, it is observed that the weld speed
(P = 50.95 %), tool rotation (P = 7.23 %) and their interactions (WS and TR)
(P = 39.74 %), have statistical significance on the tensile strength obtained.
While comparing the percentage contribution, it is understood that the weld
speed is the more influencing factor than tool rotation. Ren et al (2007)
reported that tensile properties of Al-Mg-Si alloy were strongly influenced by
the welding speed. The factors such as weld speed, tool rotation and their
interaction I (WS and TRS) present a statistical significance Test F> Fα = 5%.
It is noticed that the error associated to the ANOVA for tensile strength is
approximately 5 %.

Table 5.2  ANOVA table for tensile strength

<table>
<thead>
<tr>
<th>Source of variance</th>
<th>Sum of squares(S)</th>
<th>Df(f)</th>
<th>Variance (S/f)</th>
<th>Variance ratio (Test F)</th>
<th>Fα=5%</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld speed (mm/min)</td>
<td>5618.60</td>
<td>2</td>
<td>2809.3</td>
<td>89.75</td>
<td>4.26</td>
<td>56.38</td>
</tr>
<tr>
<td>Tool rotation (rpm)</td>
<td>1447.23</td>
<td>2</td>
<td>723.61</td>
<td>23.11</td>
<td>4.26</td>
<td>14.05</td>
</tr>
<tr>
<td>Interactions (I= WS x TR)</td>
<td>2506.40</td>
<td>4</td>
<td>626.6</td>
<td>20.01</td>
<td>3.63</td>
<td>24.17</td>
</tr>
<tr>
<td>Error</td>
<td>281.72</td>
<td>9</td>
<td>31.30.00</td>
<td>1.00</td>
<td>-</td>
<td>5.40</td>
</tr>
<tr>
<td>Total</td>
<td>9853.94</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Df: Degree of freedom, Fα=5%: F-table, P: Percentage of contribution

5.7  PRECIPITATION DISSOLUTION

The hardness survey along the transverse direction of the weld was
conducted to study the softening due to thermal hysteresis. Test pieces were
prepared for hardness test along the transverse direction. A Vickers micro-
hardness testing machine was employed for hardness measurements.
Hardness survey of weld specimen welded with 355 rpm and 120 mm/min (trial E1) was carried out after FSW without any post weld heat treatment. Horizontal hardness profile across the weld and along the lines at distance of 2 mm from the top surface of the weld specimen is shown in Figure 5.10. The unaffected base material hardness is about 135 HV. From the hardness plot it is seen that a decrease in hardness towards the weld is found. A minimum hardness zone (~ 95 HV) is detected at approximately 5 ~ 6 mm from the weld centre on retreating side of the weld. The hardness of the weld material is found practically constant across the weld (~ 105 HV). It is observed from the hardness survey that a softened region would have formed in the welded region. This could be due to precipitate dissolution in the nugget and TMAZ zones (Shukla and Baeslack 2007).

![Hardness profile across the weld (trail E1)](image.png)

**Figure 5.10** Hardness profile across the weld (trail E1)

From the plotted microhardness it is inferred that the retreating side of the weld (nearby the tool pin) had lower hardness compared to the advancing side (left side in Figure 5.10). Also the advancing side had high hardness due to the strain developed in the plate by the welding tool (Liu et al 2003).
Localised frictional heat during FSW process produces significant microstructural changes which lead to local variations in the mechanical properties of the weld joint (Sato et al 1999). Horizontal hardness across the weld and along the lines at distance of 2 mm from the top surface of the weld specimen is plotted against the predicted peak temperature in Figure 5.11. The hardness of the base material does not change at temperature lower than 500 K. The hardness decreases with the increase in the peak temperature above 500 K. The peak temperatures above 600 K produces roughly same hardness as that of the solution treated base material. It is observed that the precipitation dissolution is not effectively influenced by peak temperature lower than 500 K.

![Graph](image)

**Figure 5.11  Relation between temperature and hardness across the weld specimen**

Hardness measurement of weld specimens welded with 355 rpm and 710 rpm (trials E4 & E5) was carried out after post weld heat treatment natural aging. It is seen from Figure 5.12 that the solutionised nugget zone gained hardness due to natural aging process. But in HAZ, the θ' reversion could have caused the decrease in hardness.
5.8 EFFECT OF PROCESS PARAMETERS ON MICROSTRUCTURE

Microstructural analysis of friction stir welds was performed by optical microscopy and scanning electron microscopy (JEOL SEM Model JSM-6360). The microstructures at different regions are revealed by etching in Keller’s reagent and observed by optical microscopy (Jata et al 2000, Sutton et al 2002).

Figures 5.13 and 5.14 show macrograph and microstructures of weld joint. The microstructure in the cross section of a FSW joint can be divided into several zones (weld nugget, TMAZ, HAZ). In the centre lies the nugget, which has a fine grain size and contains onion ring structure. The fine grain size in the nugget could be due to recrystallisation process during welding. Adjacent to nugget region, the boundary between the nugget and the
TMAZ regions shows the severe deformation of grains, which are reoriented due to the stirring action of the tool pin. It should be noted that the TMAZ/nugget boundary on the advancing side is slightly sharper than that on the retreating side. This indicates the asymmetry of friction stir welding. Beyond TMAZ is the HAZ, which is affected by the heat but not by deformation. The HAZ shows the elongated grain structure.

![Macrograph of the weld specimen](image)

**Figure 5.13** Macrograph of the weld specimen

![Microstructures of (a) nugget zone (b) TMAZ (c) HAZ (d) Parent metal](image)

**Figure 5.14** Microstructures of (a) nugget zone (b) TMAZ (c) HAZ (d) Parent metal
From the hardness survey, it is observed that a hardness degradation region composed of a weld nugget, two thermomechanically affected zones (TMAZ) and two HAZs have occurred in the joints.

Immersion testing in a solution of 57 g/l (0.98M) NaCl and 10 ml/l 30 vol. % H$_2$O$_2$ (0.09M) was conducted according to ASTM G110 to study the grain sizes (Jariyaboon et al 2006). The transverse cross sections of welds were immersed in the solution for 4 h and 30 min. Figure 5.15 shows SEM images of the grain structure in the nugget region (approximately 1 mm from top surface) as a function of welding parameters. The SEM images were taken after immersion of the samples in 57 g/l (0.98M) NaCl and 10 ml/l 30 vol. % H$_2$O$_2$ (0.09M) for 4 h and 30 min followed by brief treatment in Keller’s reagent.

It is evident that the welding parameters, tool rotation, welding speed affect the grain size in the nugget region of the weld. At a fixed welding speed, an increase in TR increases the grain size due to the higher heat input. At a chosen tool rotation there is little change in grain size when changing the weld speed. Similar finding were reported by Jariyaboon et al (2006) while welding AA 2024-T351.
Figure 5.15  Microstructures of nugget at various parameters
5.9 SUMMARY

1. From the statistical analysis, it is observed that temperature at weld zone is more influenced by the tool rotation. And it is also observed from the thermal history that for given welding speed, higher tool rotation resulted in higher energy input per unit length of the weld.

2. From the ANOVA analysis of tensile property data of joints, it is seen that the welding speed is the main input parameter that has the highest statistical influence on tensile properties. Tensile strength increases with increase in revolutionary pitch upto 0.11 mm/rev. Under the condition of optimum revolutionary pitch 0.11 mm/rev, the tensile strength of the joint is maximum, which is equivalent to 78% that of the base metal.

3. Correlation of peak temperature across the weld direction with hardness of the material AA2014 shows that grain coarsening and dissolution of precipitates take place at temperature higher than around 500 K. The part of the weld zone which experience temperature more than 600 K produces the same hardness as that of solution treated material.

4. From the microstructural analysis, the welding parameters, tool rotation, welding speed affect the grain size in the nugget region of the weld. At a given welding speed, an increase in TR increases the grain size due to the higher heat input. At a given tool rotation there is little change in grain size when changing the welding speed.