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 $1.5^0$ or $2^0$ 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°, 2°, 3°</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>
</tbody>
</table>
Table 5.1 Continued

<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>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,28mm/mn, 7 kN, pin dia 7mm</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/mn, 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></th>
<th>UTS (MPa)</th>
<th>YS (MPa)</th>
<th>% Elongation(On)</th>
<th>Hardness, Hv,</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<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
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.

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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>600</td>
<td>1080</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>600</td>
<td>1260</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>700</td>
<td>1080</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>700</td>
<td>1260</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>600</td>
<td>1080</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>600</td>
<td>1260</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>700</td>
<td>1080</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<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.
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°. Maximum tensile strength was reported for a tool tilt of 0° 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>
<th>Level</th>
<th>TILT</th>
<th>S</th>
<th>N</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.37</td>
<td>40.43</td>
<td>40.19</td>
<td>39.94</td>
</tr>
<tr>
<td>2</td>
<td>39.36</td>
<td>40.31</td>
<td>40.55</td>
<td>40.80</td>
</tr>
<tr>
<td>Delta</td>
<td>2.01</td>
<td>0.12</td>
<td>0.36</td>
<td>0.85</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table. 5.6. Response table for means

<table>
<thead>
<tr>
<th>Level</th>
<th>TILT</th>
<th>S</th>
<th>N</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>117.77</td>
<td>106.20</td>
<td>102.79</td>
<td>99.73</td>
</tr>
<tr>
<td>2</td>
<td>92.97</td>
<td>104.54</td>
<td>107.95</td>
<td>111.02</td>
</tr>
<tr>
<td>Delta</td>
<td>24.80</td>
<td>1.66</td>
<td>5.16</td>
<td>11.30</td>
</tr>
<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 $0^\circ$ 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](image-url)
5.3.3 Microhardness

The variation in microhardness for two cases; one with a tilt angle of $0^\circ$, 700 mm/min, 1080 rpm and other with $1.5^\circ$, 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 $1.5^\circ$ 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 $0^\circ$ tool tilt angle, whereas the microstructure hardness value is reduced to 45 in case of $1.5^\circ$ 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 $1.5^\circ$. 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

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

Volumetric defect

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

Void

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 Mg$_2$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 Al$_6$(Fe Mn) in base metal matrix.

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

![Microstructure of the base metal.](image1)

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

![Shoulder zone: (a) 0° tilt angle (b) 1.5° tilt angle.](image2)

**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 Mg$_2$Si 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.

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

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.

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