CHAPTER 6

METALLURGICAL CHARACTERIZATION OF FRICTION STIR WELDED DISSIMILAR ALUMINUM ALLOYS

6.1 INTRODUCTION

FSW produces significant metallurgical changes along the weld line. It is essential to study the microstructural changes which influence the mechanical behavior of the joint. This chapter presents the metallurgical characterization of Friction Stir (FS) welded dissimilar aluminum alloys AA6351-T6 and AA5083-H111. The effect of process parameters on microstructure and microhardness is analyzed. The fracture surface and worn surface of selected specimens are discussed. The mode of fracture and wear are identified.

6.2 METALLURGICAL STUDIES

6.2.1 Macrostructure

Specimens were sectioned perpendicular to the joint line from the welded plates. All the specimens were polished using standard metallographic technique (Initial polishing with different grades of emery sheets and fine polishing with diamond paste up to 2 μm size) and etched with modified Keller reagent followed by Wecks reagent. The digital images of the macrostructure of the etched specimens were captured using a digital optical scanner.
6.2.2 Microstructural Analysis

The etched specimens were observed using an optical microscope (OLYMPUS-BX51M) and a scanning electron microscope (JEOL-JSM-6390). Photomicrographs were taken on various zones of the welded joints.

6.2.3 Microhardness Survey

The microhardness was measured using a microhardness tester (MITUTOYO-MVK-H1) at 500 g load applied for 15 seconds along the cross section of specimen obtained perpendicular to the welding direction. The indentation was made up to 15 mm (one indentation/mm) on either side of weld line of specimens.

6.2.4 Fracture Surface Morphology

The fracture surfaces of tensile tested specimen for different pin profile (T17, T18, T25, C01 and C02) were observed using a scanning electron microscope.

6.2.5 Worn Surface Morphology

The worn surfaces of wear tested specimen of different pin profile (T17, T18, T25, C01 and C02) were observed using a scanning electron microscope.

6.3 RESULTS AND DISCUSSIONS

6.3.1 Macro and Microstructural Analysis

The macrostructure of the dissimilar joints is shown in Figure 6.1. It is evident from the figure that the joint has no defects such as tunnels, piping or worm hole. The macrostructure suggests that sufficient frictional heat is
formed at the chosen process parameters to plasticize both the aluminum alloys which yielded defect free weld. The various zones typically present in FSW of aluminum alloys are visible. The macrostructure consists of base metal (BM), heat affected zone (HAZ), thermomechanically affected zone (TMAZ) and weld zone (WZ). In this research three different regions namely unmixed region, mechanically mixed region and mixed flow region were also observed in the WZ. The process parameters and tool pin profile which are considered in this present work contributes remarkably to the generation of frictional heat during welding.

Figure 6.1 Macrostructure of dissimilar FS Welded aluminum alloy (T25)

The effects of tool pin profile on macrostructure of the dissimilar joints are presented in Table 6.1. The joints fabricated using tool pin profiles SS, SH and SO (T25, C01 and C02) are defect free. A tunnel defect at the bottom of the joint was present when tapered tool pin profiles (T17 and T18) were used.
Table 6.1  Effect of tool pin profile on macrostructure (N= 950 rpm, S= 63 mm/min and F= 1.5 ton)

<table>
<thead>
<tr>
<th>Trail No.</th>
<th>P</th>
<th>RS</th>
<th>AS</th>
<th>Name of the defect</th>
<th>Probable reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>T17</td>
<td>TS</td>
<td></td>
<td></td>
<td>tunnel defect</td>
<td>Insufficient interaction of tool pin</td>
</tr>
<tr>
<td>T18</td>
<td>TO</td>
<td></td>
<td></td>
<td>tunnel defect</td>
<td>Insufficient interaction of tool pin</td>
</tr>
<tr>
<td>T25</td>
<td>SS</td>
<td></td>
<td></td>
<td>No defect</td>
<td>Sufficient pulsating stirring action and flow of plasticized material</td>
</tr>
<tr>
<td>C01</td>
<td>SH</td>
<td></td>
<td></td>
<td>No defect</td>
<td>Adequate stirring and heat generation</td>
</tr>
<tr>
<td>C02</td>
<td>SO</td>
<td></td>
<td></td>
<td>No defect</td>
<td>Adequate stirring and heat generation</td>
</tr>
</tbody>
</table>

Effects of tool rotational speed on macrostructure of the dissimilar joints are presented in Table 6.2. The upper and lower limit of tool rotational speed (T19 and T20) induced defect while the dissimilar joints welded at 950 rpm (T 25) had no defect.
Table 6.2 Effect of tool rotational speed on macrostructure
(P=SS rpm, S= 63 mm/min and F= 1.5 ton)

<table>
<thead>
<tr>
<th>Trail No.</th>
<th>N (rpm)</th>
<th>RS Name of the defect</th>
<th>AS Name of the defect</th>
<th>Probable reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>T19</td>
<td>600</td>
<td></td>
<td>Pin hole</td>
<td>Insufficient string tool pin profile</td>
</tr>
<tr>
<td>T25</td>
<td>950</td>
<td></td>
<td>No defect</td>
<td>Sufficient pulsating stirring action and flow of plasticized material</td>
</tr>
<tr>
<td>T20</td>
<td>1300</td>
<td></td>
<td>Tunnel</td>
<td>Excessive stirring of plasticized material</td>
</tr>
</tbody>
</table>

Effects of welding speed on macrostructure of the dissimilar joints are presented in Table 6.3. The upper and lower limit of welding speed (T21 and T22) respectively induced defect while the dissimilar alloys welded at 63 mm/min (T25) had no defect. Effects of axial force on macrostructure of the dissimilar joints are presented in Table 6.4. The upper and lower limit of axial force induced defect while the dissimilar joints welded at 1.5 ton had no defect.

The rubbing of tool shoulder on the work piece develops frictional heat. A straight pin profile tool has more contact area compared to tapered tool.
Table 6.3  Effect of welding speed on macrostructure (P=SS rpm, N= 950rpm and F= 1.5 ton)

<table>
<thead>
<tr>
<th>Trail No.</th>
<th>S (mm/min)</th>
<th>RS</th>
<th>AS</th>
<th>Name of the defect</th>
<th>Probable reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>T21</td>
<td>36</td>
<td></td>
<td>Tunnel</td>
<td>Insufficient consolidation of material</td>
<td></td>
</tr>
<tr>
<td>T25</td>
<td>63</td>
<td>No defect</td>
<td></td>
<td>Sufficient pulsating stirring action and flow of plasticized material</td>
<td></td>
</tr>
<tr>
<td>T22</td>
<td>90</td>
<td>Worm hole</td>
<td></td>
<td>High frictional heat generation.</td>
<td></td>
</tr>
</tbody>
</table>

The transportation of plasticized material from advancing side to retreating side is uniform from top to bottom of the joint when straight pin profile tool is employed. The interaction between tool and plasticized material is less in tapered pin profile tool owing to lesser contact area. The material swept across the depth of the joint is nonuniform and affects regular material flow characteristics. As a result, the shoulder experience lesser grip on the plasticized material and sliding condition is promoted over sticking condition. Therefore as the weld proceeds, a drop in frictional heat is experienced. Because, sliding condition generates lesser heat than that of sticking condition (Rai et al 2011).
Table 6.4 Effect of axial force on macrostructure (P=SS rpm, 
N= 950 rpm, S= 63 mm/min)

<table>
<thead>
<tr>
<th>Trail No.</th>
<th>F (ton)</th>
<th>RS</th>
<th>AS</th>
<th>Name of the defect</th>
<th>Probable reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>T23</td>
<td>1</td>
<td>Worm hole</td>
<td>Insufficient consolidation of material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T25</td>
<td>1.5</td>
<td>No defect</td>
<td>Sufficient pulsating stirring action and flow of plasticized material</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T24</td>
<td>2</td>
<td>Tunnel defect</td>
<td>High frictional heat generation and vertical flow of material</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Inadequate sweeping of plasticized material and reduction in frictional heat leave a tunnel at the bottom of the joint. The microstructure of the weld zone obtained using different tool pin profiles (T17, T18, T25, C01 and C02) is presented in Figures 6.2 to 6.6. It is evident from these figures that the microstructure of the dissimilar joint is dependent to a large extent on the position within the weld zone. Different microstructures are observed while moving across the breadth and depth of the weld zone. All the observed microstructures can be categorized into three different regions namely unmixed region, mechanically mixed region and mixed flow region. The mixed flow region is absent in the joints fabricated using tapered pin profiles. The formation of three kinds of regions within the weld zone agrees

The formation and characterization of the three regions are detailed as follows. To begin with, the unmixed region (Figures 6.2a, 6.3a, 6.4a, 6.5a and 6.6a) contains the microstructure of either AA5083 or AA6351. This region is observed at the top of the joints closer to shoulder region. The fine grain structure indicates that this unmixed region experienced dynamic recrystallization during welding. Secondly, the mechanically mixed region (Figures 6.2b to c, 6.3b to c, 6.4e, 6.5e and 6.6e) contains the microstructure of both the aluminum alloys. The etchant reveals AA5083 as darker and AA6351 lighter in color. The plasticized dissimilar alloys are mechanically coupled to each other. The penetration of one aluminum alloy into the other is not fully accomplished. But dynamic recrystallization of grains is evident.

Finally, the mixed flow region (Figure 6.4b to d, 6.5b to d, 6.6b to d) contains a structure of alternative lamellae of both the aluminum alloys. A complex vortex like flow pattern is visible. The mixed flow region presents extreme super plastic flow of plasticized material which creates chaotic intercalation patterns. The stirring action of the tool causes intense plastic deformation and in situ extrusion of aluminum alloys AA6351 and AA5083. The plasticized material is transported, layer by layer which forms such a lamellae structure. The penetration and mixing of both the aluminum alloys in this region is intense. The structure of mixed flow region obtained using SS tool pin profile differs slightly with those obtained using SH and SO tool pin profiles. Almost equal number of alternative lamellae of AA5083 and AA6351 alloys is visible using SH and SO tool pin profiles. All the straight tools employed in the present work have flat surfaces.

The geometry of the tool pin profile is uneven compared to a round or threaded tool which influences the plasticized material flow behavior. A
flat tool creates a pulsating stirring action due to the associated eccentricity (Elongovan et al 2009). The pulsating stirring action offers resistance to the regular flow of plasticized material which generates additional frictional heat. Consequently, the material is more plasticized. SS, SH and SO tool pin profiles due to their shape produce 63, 95 and 127 pulses/s, respectively at tool rotational speed of 950 rpm. The intensity and duration of the pulse are inversely proportional to the number of flat faces in a straight tool. Therefore, SS tool pin profile produces high intense and long duration of pulse when compared to other straight tool pin profiles which results in severe and random layer by layer transfer of material (Figure 6.4b to d). The pulsating action of SO tool is weak because the tool pin profile approaches closer to cylindrical shape. On the other hand, the tapered pin profile tools (TS and TO) are ineffective to produce pulsating stirring action and layer by layer transfer of plasticized material. Hence, the mixed flow region is not present.

The formation of mixed flow region is further observed to be dependent on other process parameters such as tool rotational speed, welding speed and axial force. It is mentioned earlier that the process parameters determine the generation of frictional heat and the amount of plasticized material. The microstructure of the weld zone obtained using SS tool with lowest tool rotational speed of 600 rpm (T19) and highest tool rotational speed of 1300 rpm (T20) are presented in Figure 6.7 to 6.8. Unmixed region was observed at top of the joints welded by lowest and highest tool rotational speed as shown in Figures 6.7a and 6.8a. Mechanically mixed region was observed in the joints welded by lowest and highest tool rotational speed (Figures 6.7 b to d and 6.8b to d). The mixed flow region is absent at lowest and highest tool rotational speed. Alvarez et al (2010) also noticed the absence of mixed flow region at tool rotational speed of 400 rpm in dissimilar friction stir welded AA7075-AA2024. The volume of plasticized material and interaction of tool is lower at lowest tool rotational speed of 600 rpm. At the
highest tool rotational speed much heat is produced which causes defect in the welded joints. Hence, the mixed flow region is not formed.

The microstructure of the weld zone obtained using SS tool with lowest welding speed of 36 mm/min (T21) and highest welding speed of 90 mm/min (T22) is presented in Figure 6.9 to 6.10. Unmixed region was observed at top of the joints welded by lowest and highest welding speed as shown in Figures 6.9a and 6.10a respectively. Mechanically mixed region was observed at the joints welded by lowest and highest welding speed (Figures 6.9b to c and 6.10b to d). FSW 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 welded joints. The reduced plasticity and rates of diffusion in the material may have resulted in a weak interface. At lowest welding speed enormous amount of heat is produced that cause defect at the joints. Hence, the mixed flow region is not formed.

The microstructure of the weld zone obtained using SS tool with lowest axial force of 1 ton (T23) and highest axial force of 2 ton (T24) is presented in Figure 6.11 to 6.12. Unmixed region was observed at top of the joints welded by lowest and highest axial force as shown in Figures 6.11a and 6.12a respectively. Mechanically mixed zone was observed at the joints made by lowest and highest axial force (Figures 6.11b to c and 6.12 b to d). Material flow in the FSW influenced by the extrusion process. The applied axial force and the motion of the tool pin propel the material after it has undergone the plastic deformation. The shoulder force is directly responsible for the plunge depth of the tool pin into the work piece and load characteristics associated with linear friction stir weld. As the axial load increases, both hydrostatic pressure under the shoulder and the temperature in the stir zone will increase and it will destroy the regular flow behavior of plasticized material in the stir zone. At lowest axial force the temperature
beneath the shoulder is less. This low temperature results in lack of stirring and insufficient coalescence of transferred material. Hence, the mixed flow region is not formed at axial force of 1 ton and 2 ton.

Figure 6.2 Microstructure of various regions in the weld zone as marked in the macrostructure using TS tool pin profile (Trail No. T17): (a) unmixed region (b) and (c) mechanically mixed region
Figure 6.3  Microstructure of various regions in the weld zone as marked in the macrostructure using TO tool pin profile (Trail No. T18): (a) unmixed region; (b) and (c) mechanically mixed region
Figure 6.4  Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile (Trail No. T25): (a) unmixed region; (b to d) mixed flow region and (e) mechanically mixed region
Figure 6.5  Microstructure of various regions in the weld zone as marked in the macrostructure using SH tool pin profile (Trail No. C01): (a) unmixed region; (b to d) mixed flow region and (e) mechanically mixed region
Figure 6.6 Microstructure of various regions in the weld zone as marked in the macrostructure using SO tool pin profile (Trail No. C02): (a) unmixed region; (b to d) mixed flow region and (e) mechanically mixed region
Figure 6.7  Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile with tool rotational speed of 600 rpm (Trail No. T19): (a) unmixed region; (b to d) mechanically mixed region
Figure 6.8 Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile with tool rotational speed of 1300 rpm (Trail No. T20): (a) unmixed region; (b to d) mechanically mixed region
Figure 6.9 Microstructure of various regions in the weld zone as marked in the macrostructure using SS Tool pin profile with welding speed of 36 mm/min (Trail No. T21): (a) unmixed region; (b) and (c) mechanically mixed region
Figure 6.10 Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile with welding speed of 90 mm/min (Trail No. T22): (a) unmixed region; (b to d) mechanically mixed region
Figure 6.11 Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile with an axial force of 1 ton (Trail No. T23): (a) unmixed region; (b) and (c) mechanically mixed region
Figure 6.12 Microstructure of various regions in the weld zone as marked in the macrostructure using SS tool pin profile with an axial force of 2 ton (Trail No. T24): (a) unmixed region; (b to d) mechanically mixed region

Material flow is clogged by the defect due to insufficient heat generation is clearly visible in the Figure 6.13 observed using scanning electron microscope.
Figure 6.13  SEM Photomicrograph of the defects of the joints welded using TS tool and material flow clogged due to the defects (Trail No.17)

Figure 6.14 and 6.15 shows TMAZ of advancing and retreating side respectively. Different Grain size of the TMAZ and WZ zone also observed with SEM image as shown in Figure 6.14. TMAZ, which is adjacent to the WZ, it has been plastically deformed and thermally affected. TMAZ exhibits
highly elongated grains of Al alloy due to stirring but it does not have a recrystallized microstructure as shown in Figure 6.14. Figure 6.16 shows complex material flow with precipitates in the bottom of WZ.

Figure 6.14 SEM Photomicrograph of combined region of TMAZ and WZ of dissimilar joints at advancing side

Figures 6.17 to 6.21 depict the SEM microstructure of WZ zone of friction stir welded dissimilar aluminum alloy AA6351 and AA5083 using different tool profiles. The WZ region of the joint fabricated using straight square pin profile contains very fine equiaxed microstructure (Elongovan et al 2008a) (Figure 6.18) compared to other joints. The higher number of pulsating action experienced in the stir zone of square pin profile produced smaller grains with uniform distribution. The fine recrystallized structure at the WZ is due to heavy plastic deformation followed by dynamic recrystallization occurred during thermo mechanical processing.
Figure 6.15  SEM Photomicrograph of combined region of TMAZ and WZ of dissimilar joints at retreating side

Figure 6.16  SEM Photomicrograph of material flow at the bottom side of WZ of dissimilar joints
Figure 6.17  SEM Photomicrograph of WZ of dissimilar joints using SH tool (Trail No. C01)

Figure 6.18  SEM Photomicrograph of WZ of dissimilar joints using SS tool (Trail No. T25)
Figure 6.19  SEM Photomicrograph of WZ of dissimilar joints using SO tool (Trail No. C02)

Figure 6.20  SEM Photomicrograph of WZ of dissimilar joints using TS tool (Trail No. T17)
Figure 6.21 SEM Photomicrograph of WZ of dissimilar joints using TO tool (Trail No. T18)

6.3.2 Microhardness Survey

Figures 6.22 to 6.25 show the microhardness profiles obtained across friction stir welded dissimilar aluminum alloys AA6351 and AA5083 using different tool pin profiles and process parameters. All the tool pin profiles and process parameter have the similar trend consisting of three different regions viz. WZ, TMAZ and HAZ on either side of the center of weld line irrespective of the tool pin profile.

The microhardness of the base aluminum alloy AA6351-T6 is higher compared to AA5083-H111 due to precipitation hardening. The microhardness variation across the WZ is minimum. It is well known that higher hardness variation will cause the joint to fail in the weld zone (Murr 2010). The average microhardness of the weld zone is lower than the microhardness of both the aluminum alloys. The drop in the microhardness of the aluminum alloy AA6351-T6 near the TMAZ can be attributed to the
dissolution of precipitates due to frictional heat. A similar drop in the microhardness of the aluminum alloy AA5083-H111 near the TMAZ can be attributed to loss of cold work in the HAZ due to annealing effect. A similar observation was reported in literatures. Peel et al (2006a) noticed a 35% drop in microhardness in the HAZ of AA5083 side of the dissimilar joint consisting of aluminum alloys AA5083 and AA6062.

It is evident from the Figure 6.22 that the hardness on AA6351 side is influenced by tool pin profiles. The hardness variation can be attributed to dissolution of precipitates. The frictional heat generated by SS tool was higher compared to other tools. Hence the dissimilar joints welded by SS tool pin profile shows slightly lowest hardness due to softening in the TMAZ of AA5083 and lower hardness in the TMAZ of AA6351 side due to excessive dissolution compared to other tool pin profiles.

It is evident from the Figure 6.23 that the hardness on AA6351 side is influenced by tool rotational speed. More hardness drop is observed in the TMAZ of AA6351 side and AA5083 side at tool rotational speed of 1300 rpm compared to other tool rotational speed because highest tool rotational speed produce more heat that causes excessive dissolution in TMAZ of AA6351 side and high thermal softening in the TMAZ of AA 5083. Similarly hardness drop is observed at highest axial force of 2 ton (Figure 6.24) and lowest welding speed of 30 mm/min (Figure 6.25) due to more frictional heat produced during FS welding.
Figure 6.22 Effect of tool pin profile on microhardness of dissimilar aluminum alloy

Figure 6.23 Effect of tool rotational speed on microhardness of dissimilar aluminum alloy
Figure 6.24 Effect of welding speed on microhardness of dissimilar aluminum alloy

Figure 6.25 Effect of axial force on microhardness of dissimilar aluminum alloy
6.3.3 Fracture Surface Morphology

The fracture surfaces of tensile tested dissimilar weld specimens using different pin profiles at tool rotational speed of 950 rpm, welding speed of 63mm/min and axial force of 1 ton is shown in Figure 6.26 to 6.30. All the fracture surfaces are covered with a large population of microscopic voids which vary in size and shape. Some flat zones are visible in the fracture surfaces of dissimilar welds fabricated using tapered tools. The failure of the dissimilar joint is dictated by the coalescence of those microscopic voids in all cases. The tensile specimens were elongated to a large extend and then fractured. The observed failure mode is ductile fibrous fracture. The depth of microscopic voids using tapered tools is lower compared to those using straight tools which can be attributed to the early coalescence of prematurely grown micro voids.

Figure 6.26 SEM Photomicrograph of fracture surface of dissimilar FS welded aluminum alloy SS tool (Trail No. T25)
Figure 6.27  SEM Photomicrograph of fracture surface of dissimilar FS welded aluminum alloy using SH tool (Trail No. C01)

Figure 6.28  SEM Photomicrograph of fracture surface of dissimilar FS welded aluminum alloy using SO tool (Trail No. C02)
Figure 6.29  SEM Photomicrograph of fracture surface of dissimilar FS welded aluminum alloy using TS tool (Trail No. 17)

Figure 6.30  SEM Photomicrograph of fracture surface of dissimilar FS welded aluminum alloy using TO tool (Trail No. 18)
6.3.4 Worn Surface Morphology

Figures 6.31 to 6.33 shows the SEM micrographs of worn surface of the dissimilar FS welded aluminum alloy using SS, SH, SO tool pin profile respectively. The grooves are apparently shallow and continuous. The frictional heat increases worn surface temperature which causes plastic deformation and dislocation in the inner surface of joints. The congestion of dislocation results in stress concentration and initiation of cracks. Fewer cracks are seen due to absence of the defects in the joints. Since the degree of development of cracks on the worn surface is less the wear resistance of the dissimilar joints made by the straight tool is more.

Figure 6.34 to 6.35 show the SEM micrographs of worn surface of the dissimilar FS welded aluminum alloy using TS and TO tool pin profile respectively. Welded joints made of tapered tool exhibits less wear resistance because the grooves have become deep and severely damaged regions are seen due to defects on the joints. The deformation of the subsurface is more. Straight Square tool exhibits highest wear resistance due to the strong bond between AA6351 and AA5083. Also the grain refining action of FSW process parameters can be considered to play a role in increasing wear resistance.
Figure 6.31 SEM Photomicrograph of worn surface of FS welded dissimilar aluminum alloy using SS tool (Trail No. T25)

Figure 6.32 SEM Photomicrograph of worn surface of FS welded dissimilar aluminum alloy using SH tool (Trail No. C01)
Figure 6.33 SEM Photomicrograph of worn surface of FS welded dissimilar aluminum alloy using SO tool (Trail No. C02)

Figure 6.34 SEM photomicrograph of worn surface of FS welded dissimilar aluminum alloy using TS tool (Trail No. T17)
SUMMARY

- The macrostructure consists of base metal (BM), heat affected zone (HAZ), thermomechanically affected zone (TMAZ) and weld zone (WZ).

- In the weld zone three different regions namely unmixed region, mechanically mixed region and mixed flow region were observed.

- Macrostructure and Material flow behavior of dissimilar joints (AA6351 - AA5083) produced by FSW were affected by the tool pin profile.
• Each FSW process parameter significantly influenced the macrostructure and Material flow behavior of the dissimilar FS welded dissimilar aluminum alloy.

• Very fine grain microstructure was observed in the weld zone.

• Microhardness was measured across the dissimilar FS welded joints and it is found that Each FSW process parameter significantly influenced the microhardness.

• Fracture mode was analyzed for tensile tested specimen and it was found that the observed failure mode was ductile fibrous fracture.

• Worn surface of the FS welded joints was done and it was observed that straight tool exhibits less damaged area then the tapered tool.