EXPERIMENTAL INVESTIGATION ON
FRICITION STIR WELDED ALUMINIUM–SCILICON ALLOY

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ABSTRACT

Friction Stir Welding has been recognized as a potential candidate for joining of non-ferrous materials which found its application in transportation, automobile, ship building and aerospace industries. The aim of the present study is to investigate the flow of material around different tool pin profiles. Tensile strength tests and hardness tests are to be carried out on aluminium–silicon alloy to determine the mechanical properties of weld. The flow of the material around the pin can be determined by tracing the flow lines. The Tensile failure characteristics of the weld are to be discussed.

The friction stir welding is done on AA6082 alloy, an Al-Mg-Si alloy. A few of silicon particles remain as such in the aluminium matrix and the remaining forms Mg$_2$Si compounds. The Mg$_2$Si compounds can be clearly seen as a black phase when viewed under optical microscope. During FSW, coarse grains get refined into finer grains and get deposited in the stir zone. Morphology, Size and Shape variation of grains are helpful in classifying the various zones of friction stir welding.

Friction stir welding of aluminium is widely applied in marine, aerospace, rail, automotive and some other transportation industries. Friction Stir Welding of AA6082

Key words: silicon alloy, Friction stir welding, CNC Lathe, fabrication.

1. INTRODUCTION

1.1. Need for Study
The need for study is to understand the complete process of friction stir welding; the forces involved in welding the material; defects caused during friction stir welding; and process parameters involved. This study has given a clear idea about the FSW process behaviour, setup and procedure of welding. Both mechanical and microstructural tests which were done on the specimen and its principle of operation was also studied.

1.2. Objective of the Project
The main objective of the project is to friction stir weld the Al-Si alloy using a conventional Vertical Milling machine; to carry out the microstructural investigation in Optical Microscope and to determine the flow of material around the tool pin profile by interpreting the microstructural analysis data; to conduct mechanical tests on the specimen (Tensile Test and Micro-Vickers Hardness Test) to establish the mechanically sound weld and to report microstructurally and mechanically optimal weld.

2. MATERIAL SELECTION

2.1. Plate Material
The main aim of the project work is the microstructural investigation i.e., analysing the microstructures at various zones of FSW. Classifying various region of FSW is a tedious process. It requires a deep knowledge in material science[1-5].

In case of pure aluminium or Al alloys with same microstructure, this investigation becomes much tougher. In such cases, the presence of second phase additives will act as medium to classify the various zones of FSW.

2.2. Silicon
Silicon was chosen as a second phase additive in this project. Silicon is naturally added to the Aluminium alloys to improve their strength. Silicon remains dispersed in the aluminium matrix without undergoing any atomic level interaction.

Silicon is a high thermal conductivity material and also it is cheap. These advantages make silicon a preferable additive in aluminium alloys.

But the main problem with the Silicon is that it is a brittle material. Excessive Silicon in the material turns a ductile material into a brittle one. So that in almost all aluminium alloys Silicon content is kept in very low percentages. Figure 1 shows the lump of silicon powders[6-9].

![Figure 1 Silicon powders](image-url)
This property of silicon makes it poor alloying elements for thin sections like plates, sheets, flats etc. If Silicon is present > 10%, it can’t be rolled into a sheet.

If it is at 2-10%, rolled sheets with cracks, voids and residual stresses will be formed. If Silicon is present < 2%, rolled sheets free of cracks and voids will be formed.

For this project, the presence of high level of Silicon is preferable because it helps in accurate differentiation of the zones. At the same time, the presence of lower percentage of Silicon is required for the specimen to be in sheet form. A compromise must be done while choosing between these two factors. A material must be chosen in such a way that it has sufficient amount of silicon to classify the zones and to roll the specimen into a sheet.

2.3. Tool Material – M2 Steel
M2 is a high-speed steel in tungsten–molybdenum series. The carbides in it are small and evenly distributed. It has high wear resistance. After heat treatment, its hardness is the same as T1 grade tool steel, but its bending strength can reach 4700 MPa, and its toughness and thermoplasticity are higher than T1 by 50%. It is usually used to manufacture a variety of tools, such as drill bits, taps and reamers. Its decarburization sensitivity is a little bit high.

3. FABRICATION AND HARDENING OF TOOL
3.1. Fabrication of M2 Tool Steel
The machining was done and the metal was removed from the rod by CNC lathe machine. The machine was operated at a constant rotational speed throughout the process. The final finishing to the job was given by cylindrical grinding.

Shaping of M2 tool steels can be carried out using grinding methods. However, they have poor grinding capability and hence they are regarded as "medium" machinability tool steel under annealed conditions. The machinability of these steels is only 50% of that of the easily machinable W group or water hardening tool steels[10-14].

3.2. Heat Treatment of M2 Tool Steel
M2 tool steels were heat treated to achieve Rockwell harness value in range of 55 – 60. They were pre-heated prior to hardening at 2610°C (4730°F) followed by rapid heating from 2610°C (4730°F) to 3960°C (7160°F). These steels were then cooled for 3 to 5 min and quenched in air, salt bath or oil.

Annealing: M2 tool steels were annealed at 2925°C (5297°F) and cooled at 72°C (162°F) per hour or even less.

Tempering: M2 steels were tempered at 1890°C (3434°F) to obtain Rockwell C hardness from 60 to 65.

Hardening: Finally, M2 steels were hardened by heat treatment and quenching.

Figure 2 Fabricated and Hardened Tool
3.3. Steps to Harden M2 Tool Steel

Hardening of a tool steel is an important process of tool making. The hardening must be performed carefully otherwise it leads to tool failure. A tool once hardened cannot be de-hardened. The fabricated and hardened tools used in this work are shown in Figure 2 and 3. The following are the steps that were followed while hardening the tool steel.

Hardening steel causes the structure of carbon to crystallize, similar to the way coal or graphite changes to diamond under the heat and pressure within the earth. Without other metals alloyed with it, steel to be hardened needs to have a carbon content of about 1.0 percent. This kind of steel is called high-carbon steel or tool steel.

Heat the entire piece of tool slowly at first. Then, concentrate the heat on the area that has to be hardened, until that area glows red hot.

Shoulder Action: The table was then raised. The table along with the plates was pressed against the tool. The rotating tool easily penetrates into the specimen because of AA6082 was then in plastic state. Once the shoulder comes in contact with the plate surface, the table movement rate was reduced. After the shoulder has plunged into the plate at 0.5mm depth, the table movement was ceased.

Figure 3 During FSW

Transverse Movement: The table along with the plate was moved in transverse direction as shown in Figure 8.5. The table gear was engaged with the lead screw by tripping the lever. The table was moved at 30mm/min using a specific combination of gears[15-18]. Once the weld was completed throughout the weld length, the table was lowered and the spindle was switched OFF. The final welds obtained are shown in Figure 4.

Figure 4 Welds Obtained using various Pin Profiles
3.4. Post Weld Surface Cleaning
The burrs on the weld surface were removed by using chisels. The weld marks were then removed by polishing it with rough emery sheet. The surface of the weld was then cleaned with cleansing solution and it is wiped off with a dry cloth. The welds were ready for testing.

4. MICROSTRUCTURAL INVESTIGATION MOUNTING OF SPECIMEN
The FSW specimens were cut in a band saw to reveal its cross section. The surface on which the microstructures were to be seen is kept over a glass plate. A short hollow pipe, in this case it is pvc was then placed encircling the specimen. Cold setting powder was then spread over the specimen within the pvc. The powder must be filled in the pvc in such a way that the specimen gets completely submerged into it. The cold setting solution was then added to the powder. The cold setting solution solidifies the cold setting powder around the specimen. A setting time of about 10 hours was provided for complete setting. After that the specimen was ready for polishing. The mounted specimen is shown in Figure 5

4.1. Rough and Fine Polishing
The mounted specimens were subjected to rough polishing in five grades of emery. Once the surface was devoid of scratches, diamond polishing was done. Diamond polishing was done by rubbing the specimens against a velvet wheel with alumina solution as a lubricant. Alumina solution removes the Aluminium oxide layer formed on the surface.

5. MECHANICAL TESTING
Mechanical testing reveals the elastic and inelastic behaviour of material when force is applied. A mechanical test shows whether a material or a part is suitable for its intended mechanical applications by measuring elasticity, tensile strength, elongation, hardness, fracture toughness, impact resistance, stress rupture and fatigue limit. The following two mechanical tests were performed on the weld specimen.

- Tensile Test
- Micro-Vickers Hardness Test
5.1. Tensile Testing
Tensile testing, also known as tension testing is the fundamental materials science test in which a sample is subjected to controlled tension until failure. The results from the test are commonly used to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area.

Uniaxial tensile testing is most commonly used for obtaining the mechanical characteristics of isotropic materials. For anisotropic materials like composite materials and textiles, biaxial tensile testing is required.

The tensile test was performed on computerized tensile testing machine as shown in Figure 6 at a loading rate of 5kN/min.

![Computerized Tensile Testing Machine](image)

**Figure 6** Computerized Tensile Testing Machine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Load</td>
<td>5 tonne</td>
</tr>
<tr>
<td>Gear rotation speed</td>
<td>1.25, 1.5 &amp; 2.5 mm/min</td>
</tr>
<tr>
<td>Software</td>
<td>FIE make india</td>
</tr>
</tbody>
</table>

**Table 1** Tensile Testing Machine Specification

5.2. Tensile Test Specimen Preparation
The weld specimen was cut using a vertical milling machine. The specimen was cut as per ASTM E8 standard as shown in Figure 7. Cutting was made in such a way that the weld was at the centre of the specimen as seen in Figure 8.

![ASTM E8 Tensile specimen](image)

**Figure 7** ASTM E8 Tensile specimen (Sattari 2012)
The tensile specimen was held between the fixed and moving beam by grippers. The initial gauge length was noted. The machine was switched ON. The curve was generated by the software. When the weld breaks, the machine was switched OFF and the specimen was removed. The final gauge length and final area of cross section was measured and fed into the software.

5.3. Tensile Test Results
The tensile testing of the various welds provide information about the ultimate tensile strength, fracture point, % of elongation, maximum elongation, reduction in area etc. Other properties like 0.2% proof stress was measured from the curve, joint efficiency can be calculated using the following formula.

The stress vs strain curves obtained from the software for all the four different welds are given in the following Figures 9, 10, 11 and 12.

Figure 8 Weld Specimen Cut to E8 Standard

Figure 9 Stress vs Strain curve for Taper Cylindrical Threaded Pin Weld
Figure 10 Stress vs Strain curve for Plain Cylindrical Threaded Pin Weld

Figure 11 Stress vs Strain curve for Taper Cylindrical Pin Weld

Figure 12 Stress vs Strain curve for Plain Cylindrical Pin Weld
Table 2 Comparison of Tensile Test Results

<table>
<thead>
<tr>
<th>Properties</th>
<th>Ultimate Tensile Strength (kN/mm²)</th>
<th>0.2% Proof Stress (kN/mm²)</th>
<th>% of Elongation</th>
<th>Reduction in Area (%)</th>
<th>Joint Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taper cylinder threaded</td>
<td>0.182</td>
<td>0.138</td>
<td>14.867</td>
<td>35.964</td>
<td>58.71</td>
</tr>
<tr>
<td>Plain cylinder threaded</td>
<td>0.183</td>
<td>0.132</td>
<td>3.5</td>
<td>9.222</td>
<td>59.03</td>
</tr>
<tr>
<td>Taper threaded</td>
<td>0.167</td>
<td>0.127</td>
<td>6.667</td>
<td>32.645</td>
<td>53.87</td>
</tr>
<tr>
<td>Plain threaded</td>
<td>0.134</td>
<td>0.083</td>
<td>1.033</td>
<td>6.761</td>
<td>43.23</td>
</tr>
</tbody>
</table>

From Table 10.2, it is seen clearly that threaded pins have dominant tensile properties than the unthreaded pins. Between the two threaded pin profiles, the taper cylindrical threaded pin profile has higher elongation characteristics than the plain cylindrical threaded pin profile. In case of UTS and joint efficiency, the variation between the two threaded profiles was not much high. So, it could be concluded that the weld made of taper cylindrical threaded pin profile has dominant tensile characteristics among the four pin profiles.

5.4. Micro-Vicker’s Hardness Testing

Micro-Vickers hardness test is used to determine the hardness of the material to deformation. When testing metals, indentation hardness correlates linearly with tensile strength. Figure 13 is the Micro Vickers hardness tester used.

![Micro Vickers Hardness Tester](image)

Table 3 Micro Hardness Testing Machine Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Range</td>
<td>10 gm to 1 kg</td>
</tr>
<tr>
<td>Magnification</td>
<td>100x and 1500x</td>
</tr>
<tr>
<td>Make &amp; Model</td>
<td>Baieiss – V test</td>
</tr>
</tbody>
</table>

In Micro-Vickers hardness test, a diamond indenter of specific geometry was impressed into the surface of the test specimen using 3 kN loads. It has forces of 2N and produce indentations of about 50 m. The specifications of Vickers tester is given in table 14. It has been found that microhardness of almost any material was higher than its macrohardness.
Micro-Vickers hardness test did not require any special specimen preparation. The specimen that was used for micro examination was used for finding hardness. The specimen was placed on the table. The microscope was adjusted to get a clear image of the surface. The table was moved towards the indenter. Now the indenter controller was switched ON. The load of 300 gms was applied using the diamond tip indenter for a time of 10 secs. The indenter automatically made an impression and returns back to its home position. The table was moved towards the microscope. The focusing on the surface was done if required. In the software, all the four corners of the indentation were marked. The software automatically calculated the hardness value.

![Micro-Hardness Curve for AA 6082 Welds](image)

**Figure 14** Micro-Hardness Curve for AA 6082 Welds

<table>
<thead>
<tr>
<th>Pin Profile</th>
<th>Hardness Number (VHN)</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taper Cylindrical Thread</td>
<td>68.71</td>
<td>Non-Uniform (max. at the RS and decreases towards the AS)</td>
</tr>
<tr>
<td>Plain Cylindrical Thread</td>
<td>75.03</td>
<td>Almost uniform (high at the interface and low at weld centre)</td>
</tr>
<tr>
<td>Taper Cylinder</td>
<td>68.43</td>
<td>Non-Uniform (max. at the RS and decreases towards the AS)</td>
</tr>
<tr>
<td>Plain Cylinder</td>
<td>50.87</td>
<td>Uniform (lowest at the weld centre)</td>
</tr>
</tbody>
</table>

It can be seen from the hardness curve in Figure 14 and Table 4, plain cylindrical threaded pin weld has highest hardness of them all. So, it could concluded that plain cylindrical threaded pin profile has high microhardness characteristics[19-20].

6. RESULTS & DISCUSSIONS

The microstructural analysis and mechanical testing on the friction stir welded joints were performed and their results were obtained. By carefully interpreting these results, the microstructural and mechanical characteristics of the four different welds could be briefly described.

In case of the material flow around the pin, the threaded pins have given better material mixing than the unthreaded pin profiles. This is because of the fact that the threads in the pin transported the material from bottom to the top. In Taper cylindrical threaded pin profile, the material near the threads gets caught by the rotating threads and moved the material upwards.
On moving up, the material undergoes a pressure rise because of the tapered profile. The tapered pin occupies most area at the top region than at the bottom. The material then comes out to the surface because of pressure. That material was again pushed back into the weld zone by the shoulder. The material then moves downwards due to the shoulder effect. The material flow in Plain cylindrical threaded pin profile was almost same to that of taper cylindrical threaded pin with only exception that the pressure throughout the flow was uniform and high.

In taper cylindrical pin profile, the material movement in vertical direction was restricted because the surface was devoid of threads. The rotating pin imparted centrifugal force to the material that comes in immediate contact with it. The material moved only around the tool in its horizontal plane with no movement in vertical. In plain cylindrical pin profile, the pressure was high throughout the thickness direction and flow was similar to taper cylindrical pin profile.

Table 5 Grain Size Comparison

<table>
<thead>
<tr>
<th>Pin Profile</th>
<th>Taper cylindrical thread</th>
<th>plain cylindrical thread</th>
<th>Taper thread</th>
<th>plain thread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size (mm)</td>
<td>3 – 4</td>
<td>4 – 5</td>
<td>4 – 5</td>
<td>6 – 7</td>
</tr>
</tbody>
</table>

Table 5 indicates the grain size obtained in the weld nugget of the four different welds made. From the table, it is clear that the taper cylindrical threaded pin results in finer refinement of the grains. The taper cylindrical threaded pin refined the grains of 25 – 30 mm size in the base material to 3 – 4 mm size at the weld nugget. The fine refinement of grains in the weld nugget indicates that taper cylindrical threaded pin has given better weld than the rest of the profiles.

Table 6 Percentage of Elongation Comparison

<table>
<thead>
<tr>
<th>Pin Profile</th>
<th>Taper cylindrical thread</th>
<th>plain cylindrical thread</th>
<th>Taper thread</th>
<th>plain thread</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of Elongation</td>
<td>14.867</td>
<td>3.5</td>
<td>6.667</td>
<td>1.033</td>
</tr>
</tbody>
</table>

Table 6 indicates the % of elongation obtained through tensile testing of the four different welds. From the table, it is clear that the weld made of taper cylindrical threaded pin profile has high ductility and fails after an elongation of 14.867%. Only taper cylindrical threaded pin has given such elongation. The remaining welds had not given atleast half the elongation. So, the tensile properties of the weld made of taper cylindrical threaded pin were better than the rest of welds.

Table 7 indicates the micro-hardness obtained through Micro-Vickers hardness testing

<table>
<thead>
<tr>
<th>Pin Profile</th>
<th>Taper cylindrical thread</th>
<th>plain cylindrical thread</th>
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<tr>
<td>Hardness No (VHN)</td>
<td>68.71</td>
<td>75.03</td>
<td>68.43</td>
<td>50.87</td>
</tr>
</tbody>
</table>

Table 7 indicates the micro-hardness obtained through Micro-Vickers hardness testing of the welds. The micro-hardness value of the weld made of plain cylindrical threaded pin profile was the highest among the welds made. The plain cylindrical threaded pin has hardness value of 75.03 VHN. But its % of elongation was only 3.5%. So, it could be said that the weld made of plain cylindrical threaded pin was more brittle and couldn’t be said as better weld. On moving to the next highest hardness value, weld made of taper cylindrical threaded
pin has hardness value of 68.71 VHN and 14.867% of elongation. This clearly indicates that it has undergone a ductile fracture. So, the weld made of taper cylindrical threaded pin profile exhibit high mechanical properties than the rest of welds.

It could be summarized that the weld made of taper cylindrical threaded pin has high mechanical properties and finer grain refinement in weld nugget. The weld made of taper cylindrical threaded pin is the optimal weld among the four welds made.

7. CONCLUSIONS

In the present research work, effects of tool pin profile on microstructure and mechanical properties of Friction stir welded Al - Si joints were investigated using four different tool pin profiles, i.e., taper cylindrical threaded, plain cylindrical threaded, taper cylindrical and plain cylindrical pin profiles. Based on the results obtained in this work, the following conclusions could be drawn:

- Sample welded using taper cylindrical threaded pin profile showed fine recrystallized grains of about 3 m. The grains were evenly distributed throughout the weld nugget region.
- The mechanical properties of the joints were in relationship with the grain size and therefore, sample welded using taper cylindrical threaded pin profile showed higher mechanical properties relative to sample welded using other pin profiles. It has the elongation of 14.867% which was highest among the welds made.
- The axisymmetric flow of material around the tool pin and also along the vertical direction was a prime reason for such grain refinement and increased mechanical properties in weld made of taper cylindrical threaded tool pin profile.

REFERENCES

Experimental Investigation on Friction Stir Welded Aluminium–Silicon Alloy


