CHAPTER 6

WELDING OF HYBRID AA 6063 MATRIX COMPOSITE AND AISI 1030

6.1 INTRODUCTION

Friction stud welding provides impressive results in joining metals with composites for automotive, ship building and electronic applications (Wysocki & Grabian 2007). Friction welding process enables the efficient union of metals and ceramics by harnessing the frictional heat induced by the faying surfaces. A unique characteristic weld is made in friction stud welding by production of heat by friction, melting of the metal and commencing the bond due to the upset (Zimmerman et al 2009). The fusion welding techniques for joining dissimilar metals are easily subjected to failure due to their brittle intermetallic compound formation. Moreover, the differences in their melting point results in inappropriate intermetallic structure, poor properties and inferior weld strength (Meshram et al 2007).

In the present work, 6% silicon carbide and 3% graphite reinforced AA6063 matrix composite is developed by stir casting technique. The SiC present in the hybrid matrix composite increases the thermo-physical and mechanical properties (Suresha et al 2010a) of the composite. It results in attractive properties like high thermal conductivity, low co-efficient of thermal expansion, high strength and good specific modulus. The inclusion of graphite (Suresha et al 2010b), a solid lubricant guarantees the usage of
hybrid matrix composite in many engineering applications that demands high strength and wear resistance.

On the other hand, there are many other potential problems in welding metal matrix composites with non-metallic reinforcements (Lee et al 1999). The differences in their density can lead to solidification effects such as segregation of the reinforcements in the molten metal and it also gives rise to non-uniform packing density (Celik et al 2012). The other issues are undesirable chemical reactions between the molten metal and the reinforcements during the extended exposure during fusion welding. Being a solid state welding technique and a novel variant of friction welding, friction stud welding is promising in some of the crucial situations of joining of dissimilar materials (Zhang et al 2013).

Hence, in the present study, joining feasibility of aluminum hybrid metal matrix composite and AISI 1030 steel is explored by friction stud welding technique using aluminum sheet as interlayer. The micro structural aspects were studied by SEM and EDX analysis and mechanical properties of the dissimilar joints are evaluated. In addition, the current work deals with the study of interaction of various process parameters in determining the impact strength and axial shortening distance of the welded joint.

6.2 MATERIALS AND METHODS

In the present work, investigation on joining of hybrid AA6063-6SiC\textsubscript{p}-3Gr\textsubscript{p} composite to AISI 1030 steel has been carried out using AA1100 interlayer. The composition of AA6063, AISI 1030 steel, AA1100 interlayer and hybrid composite are given in Tables 4.1, 4.2, 5.1 and 6.1 respectively. The Aluminum hybrid metal matrix composite has been developed using stir casting process. Aluminum alloy 6063 is chosen as the matrix material whereas silicon carbide (40 \textmu m, average size) and graphite (60 \textmu m, average
size) are selected as the particle reinforcements for the development of HMC. The selection of aluminum alloy as the matrix material is due to the optimal presence of magnesium, which affords the coalescence during the welding process.

Table 6.1 Composition of AA 6063 Hybrid Composite

<table>
<thead>
<tr>
<th>Element</th>
<th>AA 6063</th>
<th>SiC</th>
<th>Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight %</td>
<td>91</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

6.2.1 Stir Casting of Hybrid Composite

Particles of SiC (40 µm, average size) and graphite (60 µm, average size) are preheated at 1000°C for 2 hours in order to remove the absorbed hydroxide and other gases. The electrically operated aluminum stir casting furnace was first raised to 760°C (above the melting temperature) to melt the matrix completely and then the temperature was lowered to 740°C to cool down in order to keep the molten metal in a semi-solid state. At this stage, the preheated reinforcements are added into molten metal at a steady rate of 2g for every 30 seconds. After the addition, the molten metal mixture is vigorously stirred by a mechanical stirrer rotating at 400 rpm average stirring speed to avoid agglomeration of the particles for 5 minutes. During the final stage of mixing, the furnace temperature was kept at 740°C. The stirred molten mixture is then poured into the pre-form mould and allowed to cool and solidify at normal room temperature. Step by step procedure of stir casting of HMC is shown in Figure 6.1 to Figure 6.6. The casted bars are machined down to cylindrical rods of 12 mm diameter and 45 mm length (Figure 6.7). AISI 1030 steel stud samples of equal diameter and length with thread having a 1.75mm as pitch are machined. The successfully welded joints are shown in Figure 6.8.
Figure 6.1 Stir casting setup

Figure 6.2 Melting of AA6063 rods

Figure 6.3 Addition of SiC and graphite particulates as reinforcement

Figure 6.4 Mechanical stirrer to avoid agglomeration of the particulates

Figure 6.5 Pouring of molten metal into the pre-form mould

Figure 6.6 Solidification of molten metal at room temperature
6.2.2 Experimentation

Experiments were carried out in a programmable logic controller based direct drive friction stud welding machine. A Programmable Logic Controller is employed to control all the parameters in the friction stud welding process. The desired welding conditions can be set using the PLC. The AA6063-6SiCp-3Grp HMC specimen is placed in the chuck and the AISI 1030 specimen is held by the stud holder that is connected to the pneumatic actuator of the pneumatic drive.
Table 6.2 Selection of parameters and levels in experimentation

<table>
<thead>
<tr>
<th>Variables/Levels</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational Speed in rpm (RS)</td>
<td>800</td>
<td>1150</td>
<td>1600</td>
</tr>
<tr>
<td>Friction Time in sec (FT)</td>
<td>3</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Friction Pressure in x 10^5 Pa (FP)</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Sheet Thickness in mm (ST)</td>
<td>0.5</td>
<td>0.95</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Design of Experiments (DOE) technique is applied during experimentation to ensure robust design (Figure 6.9). The Table 6.2 given above provides the details of the selection of parameters and their levels for experimentation in joining AA6063-6SiC_p-3Gr_p HMC and AISI 1030 steel. The experimental results obtained during experimentation are given in Table 6.3. The design of experiments is done based on four variables and three levels. Based on L9 orthogonal array of Taguchi’s method, nine experimental trials were conducted. A digital vernier caliper (Model No CD-12C, Mitutoya Corporation, Japan) is used to measure the axial shortening distance in the welded specimens.

Mechanical testing is carried out to evaluate the impact strength of the welded joints by means of Charpy impact testing machine at room temperature. According to ASTM A370, 10 x 7.5 x 50 mm impact test specimen is prepared with a “V” notch of 2 mm depth and a 45^0 groove. For micro structural examination, the specimen was sectioned perpendicular to the weld surface and mechanically polished by using emery papers and etched with ferric chloride solution. The prepared specimen undergoes micro structural evaluation using SEM, (Hitachi, SU1510-Japan), EDX analysis and micro hardness measurement. Variation in micro hardness across the welded
joint is studied using Vickers hardness tester. Using a load of 5 kg and a holding time of 20 seconds, indents were made on the welded specimen. The indenter is then removed from the surface of the specimen and the indentation dimensions were measured using an optical microscope.

**Table 6.3 Tabulation of results**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Coded Values</th>
<th>Actual Process Variables</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RS</td>
<td>FT</td>
</tr>
<tr>
<td></td>
<td>rpm</td>
<td>sec</td>
<td>x10^5 Pa</td>
</tr>
<tr>
<td>1.</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>4.</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>5.</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>6.</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>7.</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>8.</td>
<td>+</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>9.</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>
6.3 RESULTS AND DISCUSSION

6.3.1 Micro Hardness Measurement

Figure 6.10 shows the micro hardness profile across the welded specimen. Micro hardness value is high at the weld interface and it changes when moving away towards the base materials. In both steel side and HMC side, it decreases and reaches constant value same as that of parent materials. This change in hardness values indicates the presence of different zones in the heat affected area of the welded joint.

![Micro hardness profile of welded AISI 1030/AA6063-6SiCp-3Grp joint](image)

In the fully plasticized zone, maximum hardness value of 205Hv is observed. This is due to the plastic deformation caused due to the upsetting pressure during the friction stud welding process. Fine dynamically recrystallized grains increases hardness value as well as strength of the joint according to Hall petch’s equation (Sathiya et al 2007). A dip in the hardness value indicates the presence of partially deformed zone. Further decrease and then a set of consistent values refer to the third unaffected zone, where hardness value is same as that of the parent materials.
6.3.2 Micro Structure

![Image](image1)

**Figure 6.11** SEM micrograph of AISI 1030/AA 6063-6SiCₚ-3Grₚ joint showing different zones

![Image](image2)

**Figure 6.12** SEM observation of grain size reduction

While examining the SEM micrograph of the welded specimen as shown in the Figure 6.11, following three regions were observed. Fully plasticized deformed region was found at the interface due to plastic deformation and rise in input. Partially deformed region undergoes some amount of reduction in grain size on both the sides. Higher amount of reduction in grain size is seen in the HMC since the melting point of HMC is less. Then there are unaffected regions where there are no changes in grain size on both HMC and AISI 1030 steel.
Dynamic recrystallization has occurred in the fully plasticized deformed region and so there is a reduction in the size of dynamic recrystallization grains. In the partially deformed region, recrystallization has taken place and reductions in grain size were observed than the grains in the unaffected parent materials. Microstructure of the particles in HMC side has been altered to a great extent than the changes that took place at the AISI 1030 steel side. This is due to the low friction time and friction pressure selected in the experimentation. The SiC particles close to the weld zone were reduced into the size of ultra-fine grains. This is due to the breaking up of the SiC particles during friction and upset pressure. These ultra-fine grains found at the interfacial region resulted in increase of micro hardness value at the weld interface. The size of the ultra-fine grains is of the range of 300 to 600 nm (Figure 6.12). SiC particles appear as light gray spots in the HMC near weld interface and reinforced graphite particles appear dark black in the
micrograph (Figure 6.13). White inclusion refers to aluminium oxide formed at the weld interface.

6.3.3 EDX Analysis

![EDX Analysis](image)

Figure 6.14 (a) SEM micrograph at the interface (b) EDX analysis at point “A”, (c) EDX analysis at point “B” and (d) EDX analysis at point “C”

6.3.4 Fractography

EDX analysis has been carried out on three points A, B and C on friction stud welded AISI 1030/AA 6063-6SiC$_p$-3Gr$_p$ joints. Micrograph on the weld interface is shown in the Figure 6.15. It appears that the mechanism of bonding is achieved only by means of mechanical interlocking. There is no diffusion of iron atoms from AISI 1030 steel into HMC side. Diffusion of
aluminium atoms into AISI 1030 steel is hindered as well. Mobility of carbon atoms is limited to the joint interface. However, formation of iron oxide and aluminium oxide at joint interface is found to be unavoidable. Presence of intermetallic phase was confirmed as Fe$_2$Al$_3$ which is very brittle in nature. Formation of this brittle intermetallic compound at the joint interface deteriorates the strength of the joint and leads to brittle mode of fracture.

Figure 6.15  SEM image of the fractured surface of impact specimenAt AISI 1030 side (1,000X)  (b) At AISI 1030 side (5,000X) (c) At HMC side (1,000X)  (d) At HMC side (5,000X)

Figure 6.15 shows the micrograph of fractured surface of the impact specimen on both AISI 1030 and HMC sides. Figure 6.15a and Figure 6.15b show the fractured surface at AISI 1030 steel side. Remnants of HMC
are visible in many spots on the fractured surface of AISI 1030 steel. Figure 6.15a the features of the surface indicate flat planes and cracks. River lines of cleavage fracture are clearly seen in many places (Figure 6.15b). This type of brittle fracture is characterized by rapid crack propagation with low energy release and without significant plastic deformation.

Figures 6.15c and 6.15d show the fractured surface at the AA 6063-6SiC_p-3Gr_p(HMC) side. In Figure 6.15c the features of the surface indicate flat planes, sharp edges, and cracks. Trans granular cleavage fracture has occurred through the grains along crystallographic cleavage planes. River pattern of micro cracks are seen in the micrograph (Figure 6.15d) further confirms brittle mode of fracture. Since, brittle fracture mode is a low energy fracture mode; the energy absorption is low at the interface. This can be attributed to the low toughness of the friction stud welded AISI 1030/AA 6063-6SiC_p-3Gr_pjoints.

### 6.4 STATISTICAL ANALYSIS

ANOVA tool is used for analysing the statistical data obtained from the experiments. It evaluates the significance of the response variables by examining the means of the response variables at different levels. In this study, the contributing parameters for axial shortening and impact strength are identified using ANOVA.

#### 6.4.1 Analysis of variance of Axial Shortening Distance

The ANOVA table for axial shortening distance is shown below in Table 6.4. The percentage contribution of factors for axial shortening distance is given in pie chart as shown in Figure 6.16. It is observed that rotational speed is the most significant factor with 71% of contribution and interlayer sheet thickness provides the least impact on axial shortening distance. When
the rotational speed increases, the friction coefficient increases. This in turn increases heat input due to the stirring action. The softened HMC material flows out as a flash covering the steel and more material is consumed resulting in increase of axial shortening distance.

Table 6.4 ANOVA for Axial Shortening Distance using adjusted SS for tests

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degree of freedom</th>
<th>Seq Sum Squares</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>2</td>
<td>30.220</td>
<td>14.640</td>
<td>14.640</td>
<td>10.24</td>
<td>0.085</td>
</tr>
<tr>
<td>FT</td>
<td>2</td>
<td>0.215</td>
<td>1.593</td>
<td>1.593</td>
<td>1.11</td>
<td>0.402</td>
</tr>
<tr>
<td>FP</td>
<td>2</td>
<td>6.189</td>
<td>3.026</td>
<td>3.026</td>
<td>2.12</td>
<td>0.283</td>
</tr>
<tr>
<td>ST</td>
<td>2</td>
<td>0.788</td>
<td>0.788</td>
<td>0.788</td>
<td>0.55</td>
<td>0.535</td>
</tr>
<tr>
<td>Residual</td>
<td>1</td>
<td>2.859</td>
<td>2.859</td>
<td>1.430</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>40.271</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.16 Percentage contribution of process parameters to axial shortening distance
The main effect plots for axial shortening are shown in the Figure 6.17. Main effect plot is drawn by the average of observations at each linking. The steeper the slope of the line, the greater is the magnitude of the main effect. The main effect plots for the rotational speed, friction time, and friction pressure and sheet thickness are placed in together in one graph to compare their relative magnitudes. Interaction plots are studied to understand whether the effect of one factor depends on the level of the other factor. Interaction plots are used to visualize possible interactions. Parallel lines in an interaction plot indicate no interaction. The greater the difference in slope between the lines, higher is the degree of interaction. However, the interaction plot doesn’t give information if the interaction is statistically significant. The interaction plot for axial shortening is given in Figure6.18.

![Main Effects Plot for AX](image)

**Figure 6.17 Main effect plots for axial shortening distance (AX)**
Figure 6.18 Interaction plots for axial shortening distance (AX)

6.4.2 Analysis of Variance for Impact Strength

The ANOVA table for impact strength is shown Table 6.5. The percentage contribution of factors for impact strength is given in pie chart is shown in the Figure 6.19. It is observed that the rotational speed and interlayer sheet thickness are the significant factors and the friction time provides the least influence on impact strength of the welded joints. Aluminum interlayer increases the wetting ability at the weld interface and offers superior bonding properties. Besides it reduces the heat affected zone. But selection of interlayer with optimum thickness of 5mm gives good results.
Table 6.5 ANOVA for impact strength using adjusted SS for test

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degree of freedom</th>
<th>Seq Sum of Squares</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F ratio</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>2</td>
<td>3530</td>
<td>4930</td>
<td>4930</td>
<td>0.13</td>
<td>0.753</td>
</tr>
<tr>
<td>FT</td>
<td>2</td>
<td>142</td>
<td>536</td>
<td>536</td>
<td>0.01</td>
<td>0.916</td>
</tr>
<tr>
<td>FP</td>
<td>2</td>
<td>7967</td>
<td>2003</td>
<td>2003</td>
<td>0.05</td>
<td>0.840</td>
</tr>
<tr>
<td>ST</td>
<td>2</td>
<td>4634</td>
<td>4634</td>
<td>4634</td>
<td>0.12</td>
<td>0.760</td>
</tr>
<tr>
<td>Residual</td>
<td>1</td>
<td>75760</td>
<td>75760</td>
<td>37660</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>92033</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.19 Percentage contribution of process parameters to impact strength

The main effect plots for upset are given in Figure 6.20. From the Figure 6.20, it is observed that impact strength is influenced to a maximum level by rotational speed and sheet thickness. Friction time and friction pressure have the least effect on impact strength. The interaction plot for impact strength is given in Figure 6.21.
Figure 6.20 Main effect plots for impact strength (IS)

Figure 6.21 Interaction plots for impact strength (IS)
6.4.3 Regression Analysis for Axial Shortening

The regression equation for axial shortening is

\[ AX = -6.46 + 0.00620*RS + 0.339*FT + 0.968*FP - 1.88*ST \]

(6.1)

Table 6.6 Regression coefficients of weld parameters vs. axial shortening distance

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-6.334</td>
<td>2.427</td>
<td>-2.61</td>
<td>0.059</td>
</tr>
<tr>
<td>RS</td>
<td>0.0058458</td>
<td>0.000997</td>
<td>5.86</td>
<td>0.004</td>
</tr>
<tr>
<td>FT</td>
<td>0.2683</td>
<td>0.1999</td>
<td>1.34</td>
<td>0.251</td>
</tr>
<tr>
<td>FP</td>
<td>0.9650</td>
<td>0.3999</td>
<td>2.41</td>
<td>0.073</td>
</tr>
<tr>
<td>ST</td>
<td>-1.2592</td>
<td>0.9970</td>
<td>-1.26</td>
<td>0.275</td>
</tr>
</tbody>
</table>

Figure 6.22 Scatter between predicted and observed values of axial shortening distance
Regression coefficients of weld parameters vs. axial shortening are given in Table 6.6. The scatter plot and normal probability plot for axial shortening distance is given in Figures 6.22 and 6.23 respectively.

![Normal Probability Plot](image)

**Figure 6.23 Normal probability plots for axial shortening distance**

### 6.3.4 Regression Analysis for Impact Strength

The regression equation for impact strength is

\[
IS = -22 + 0.114*RS + 6.2*FT + 25*FP - 144*ST \quad (6.2)
\]

Regression coefficients of weld parameters vs. Impact strength are given in Table 6.10. The scatter plot and normal probability plot for Impact strength are given in Figures 6.24 and 6.25 respectively.
Table 6.7 Regression coefficients of weld parameters vs. impact strength

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>29.23</td>
<td>43.95</td>
<td>0.67</td>
<td>0.542</td>
</tr>
<tr>
<td>RS</td>
<td>0.03181</td>
<td>0.01805</td>
<td>1.76</td>
<td>0.153</td>
</tr>
<tr>
<td>FT</td>
<td>0.824</td>
<td>3.620</td>
<td>0.23</td>
<td>0.831</td>
</tr>
<tr>
<td>FP</td>
<td>0.657</td>
<td>7.241</td>
<td>0.09</td>
<td>0.932</td>
</tr>
<tr>
<td>ST</td>
<td>-11.10</td>
<td>18.05</td>
<td>-0.62</td>
<td>0.572</td>
</tr>
</tbody>
</table>

Figure 6.24 Scatter between predicted and observed values of impact strength
6.4 SUMMARY

The present work shows that SiC and graphite reinforced aluminium hybrid composite can be friction stud welded to AISI 1030 steel successfully using AA 1100 interlayer.

1. Micro hardness profile shows increase in hardness value at the fully plasticized deformed zone of the interfacial region. This is due to the plastic deformation caused by upsetting pressure.

2. Micro structural examinations reveal three separate zones namely fully plasticized zone, partially deformed zone and unaffected base material zone. Ultra-fine dynamically recrystallized grains of about 341nm are observed at the fully plasticized zone.
3. EDX analysis confirms the presence of intermetallic compound at the joint interface. It is identified as Fe$_2$Al$_3$, which has cubic structure. Increase in the micro hardness could also be attributed to the presence of Fe$_2$Al$_3$.

4. SEM micrograph at the fractured surface shows features with flat planes, sharp edges, and cracks. Trans granular cleavage fracture has occurred through the grains along crystallographic cleavage planes. River pattern of micro cracks is also visible in the micrograph. Hence, brittle mode of fracture has occurred in the impact specimen.

5. Rotational speed and interlayer sheet thickness contribute about 39% and 36% respectively in determining the impact strength of the welded joints.

6. It is observed that rotational speed is the most significant factor with 71% of contribution in determining axial shortening distance. When the rotational speed increases heat input increases due to the stirring action. The softened HMC material flows out as a flash covering the steel and more material is consumed resulting in increase of axial shortening distance.

7. Based on the experimental results, regression model has been developed to predict impact strength and axial shortening distance with reasonable accuracy.