EVALUATION OF JOINT PROPERTIES OF FRICTION STIR WELDED AL/CU BIMETALLIC LAP JOINTS FABRICATED BY THREADED TOOL

M Satyanarayana Gupta
Professor, Department of Aeronautical Engineering
MLR Institute of technology

Parthasarathy Garre
Associate Professor, Department of Aeronautical Engineering
MLR Institute of technology

Alekhya N
Assistant Professor, Department of Aeronautical Engineering
MLR Institute of technology

P Poornima Reddy
Assistant Professor, Department of Mechanical Engineering
Vardhaman College of Engineering

Athota Rathan
Assistant Professor, Department of Aeronautical Engineering
Institute of Aeronautical Engineering

ABSTRACT

Friction stir welding (FSW) is an emerging hot shear, solid Phase joining method used for joining of materials which are difficult to join. Today this technology has been finding increasingly widespread acceptance of industrial community for welding various similar and dissimilar materials. The rotating tool pin profile plays an important role on quality of the friction welded joints. The main objective of this paper is to evaluate joint properties of friction stir welded Al/Cu lap joints made by threaded tool by varying rotational speed, welding speed and plunging speed. The tensile shear strength of the joints increases with decrease in rotating speed and welding speed. The plunging speed has the little influence on tensile shear strength.

Key words: Friction Stir Welding, Al/Cu Lap Joints, Mechanical Properties, Microstructure.
1. INTRODUCTION

The concept of the FSW is very simple. The plates to be joined are firmly kept in position using mechanical clamps on machine table. A rotating tool composed of a shoulder and specially designed pin plunges into the sheets to be weld until the shoulder touches the upper surface of the sheets and moves along the axis of the weld as shown in figure 1.

![Schematic Diagram of FSW](image)

The flow of material in friction stir welding has occurred due to the rotational and longitudinal movement of the tool [1]. The material flow is in bulk due to the shoulder, while layer by layer material flow by pin. Geometric nature due to the combined effect of vertical flow of the material by interaction of shoulder and pin result the onion ring formation in the FSW. The geometry of the rotating tool plays an important role in quality of the joint [2].

The attempt to join Al to Cu by welding at the temperature 125 0C or higher will result in the formation of brittle inter-metallic compounds. This is due to the high affinity which these metals exhibit each other. Moreover, these compounds are not mechanically and electrically stable due to the existence of covalent non-metallic bonds. Therefore, a reliable weld is not obtained by traditional welding methods in which thermal energy is applied to fuse the metals. Due to the above reasons, the solid phase welding methods such as explosion welding, friction welding, FSW were accepted methods for joining Al/Cu metals due to formation of very little inter-metallic compounds.

The electrical resistance in friction stir welded lap joints is negligible as in manufacturing condition [3]. The friction stir welded Al/Cu bimetallic lap joints are used in electrical and electronics industries. The friction stir welding is used to join similar and dissimilar material [4-8]. The composite materials wildly used in aerospace industry [9]. Nowadays FSW is also using to weld composites. The stirring of the tool, heat due to friction and thermal conductivity of Al and Cu could produce various structures on both sides of nugget zone [10]. The present paper mainly focuses on evaluation of mechanical and metallurgical properties of friction stir welded Al/Cu bimetallic lap joints fabricated by threaded tool pin.
2. EXPERIMENTAL WORK

The base material properties can influence the quality of the welded joints [11]. In this study pure Al and Cu plates of 3 mm thickness each were used for friction stir welding. Table 1 gives the chemical composition of the base metals aluminum and copper and the mechanical properties of the base metals are given in table 2. High speed steel M-2 has been selected for present investigation based on their rich required properties and availability in the market. The chemical composition of high speed steel M-2 is given in table 3.

<table>
<thead>
<tr>
<th>Table 1 Chemical compositions of base metals (Weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base material</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Pure Copper</td>
</tr>
<tr>
<td>Pure Al</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of base metals

<table>
<thead>
<tr>
<th>Base Material</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y.S (MPa)</td>
</tr>
<tr>
<td>Pure Copper</td>
<td>108</td>
</tr>
<tr>
<td>Pure Al</td>
<td>95</td>
</tr>
</tbody>
</table>

Y.S: Yield stress; T.S: Tensile Stress; TSS: Tensile Shear Stress

Table 3 Chemical compositions of tool materials (in Wt %).

<table>
<thead>
<tr>
<th>Tool material</th>
<th>Chemical compositions (Weight %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSS(M2)</td>
<td>C: 0.8, Si: 0.4, Mn: 0.4, Cr: 4.15, Mo: 5, W: 6.1, V: 1.9</td>
</tr>
</tbody>
</table>

The tool used in this investigation is tapered threaded pin tool. This tool contains the taper pin of maximum and minimum diameters of 4.5mm and 3.5mm respectively and provided 0.5 mm threads on taper pin in order to increase the vertical movement of the material. The tapered pin tool used for fabrication of Al/Cu dissimilar lap joints is shown in figure2.

Figure 2: a) Threaded Taper Pin Tool b) Zoomed Image of the Shoulder and Tool Portion
The joint design that has been used in this investigation is the lap joint configuration. Based on trial experiments the top plate has been chosen as the Al and bottom plate has been taken as Cu plate. The copper is placed below the aluminum because viscosity of the copper is less than the viscosity of the aluminum due to this the vertical flow of the copper is more efficient compared to the vertical flow of the aluminum. Based on diameter of the tool shoulder the overlap between two plates was taken as 30mm. Figure3 shows the relative position and dimensions of Al and Cu in lap joint design configuration used in this study.

Figure 3 Dimensions and Relative Position of Al and Cu Plates

In this investigation $2^3$ full factorial design matrix has been utilized to optimize the number of experiments. Eight ($2^3$) sets of coded conditions utilized to form the design matrix is given in table4. The other variables: tool tilting angle is zero degrees, frictional heating time is 10 sec, and plunging depth has been kept constant.

Table 4 Important processes parameters and their limits used FSW.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Input parameters</th>
<th>Parameter Designation</th>
<th>Unit</th>
<th>Design Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rotational speed</td>
<td>N</td>
<td>Rpm</td>
<td>1500</td>
</tr>
<tr>
<td>2</td>
<td>Welding speed</td>
<td>V</td>
<td>mm/min</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Plunging speed</td>
<td>P</td>
<td>mm/min</td>
<td>10</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties

3.1.1. Tensile Shear Strength
The failure loads, shear strengths, failure locations and weld beads of the FSW Al/Cu lap joints made by tapered threaded pin tool are given in table5. The maximum value of shear strength obtained was 71MPa. It is 100% of parent material Al and 70% of parent material Cu. The maximum tensile shear strength obtained was much more than the maximum shear strength obtained by the previous studies. The minimum tensile shear strengths are recorded in the joints made at low welding speed and high rotational speed irrespective of plunging speed.

This may be due to the high heat inputs at low welding speeds and high rotational speeds. As heat inputs increases the thickness of inter-metallic compound layer increases and that reduces the shear strength of the joints.
Evaluation of Joint Properties of Friction Stir Welded Al/Cu Bimetallic Lap Joints Fabricated by Threaded Tool

Table 5 Tensile shear test results and weld beads of the FSW Al/Cu lap joints

<table>
<thead>
<tr>
<th>Ex. number</th>
<th>Factors</th>
<th>Failure Loads (kN)</th>
<th>TSS (MPa)</th>
<th>Fracture location</th>
<th>Weld bead</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1500</td>
<td>30</td>
<td>10</td>
<td>7.2</td>
<td>71</td>
</tr>
<tr>
<td>T2</td>
<td>2500</td>
<td>30</td>
<td>10</td>
<td>4.15</td>
<td>41</td>
</tr>
<tr>
<td>T3</td>
<td>1500</td>
<td>80</td>
<td>10</td>
<td>6.28</td>
<td>62</td>
</tr>
<tr>
<td>T4</td>
<td>2500</td>
<td>80</td>
<td>10</td>
<td>6.48</td>
<td>64</td>
</tr>
<tr>
<td>T5</td>
<td>1500</td>
<td>30</td>
<td>20</td>
<td>6.99</td>
<td>69</td>
</tr>
<tr>
<td>T6</td>
<td>2500</td>
<td>30</td>
<td>20</td>
<td>4.46</td>
<td>44</td>
</tr>
<tr>
<td>T7</td>
<td>1500</td>
<td>80</td>
<td>20</td>
<td>6.18</td>
<td>61</td>
</tr>
<tr>
<td>T8</td>
<td>2500</td>
<td>80</td>
<td>20</td>
<td>5.98</td>
<td>59</td>
</tr>
</tbody>
</table>

3.1.2. Evaluation of Hardness

Micro-hardness measurements have been carried out utilizing 500gr load and dwell time of 10 sec to get an experimental indication of the temperature distribution during the FSW process and the influence of the heat input on mechanical properties of the parent materials Al and Cu. The measured hardness values for the joint T1 are shown in figure4. The position of the tool pin during the FSW is represented by vertical line. The hardness values varied between 35 and 44.3 HV0.5 and between 62 and 70 HV0.5 for Al and Cu sheets respectively. Minimum hardness in Al and Cu has been observed in the HAZ of both the retreating and advancing side. Maximum hardness in Al and Cu has been observed in stir zone. This indicates the localized softening of the metals in HAZ, due to the thermal action of the FSW. The hardness of the nugget is more than the base metal and HAZ. This may be due to the formation of hard and brittle inter-metallic layer and very fine grains due to the dynamic re-crystallization in the nugget zone and grain growth in HAZ.
3.2. Evaluation of Microstructures

The microstructures of the Aluminium in different zones are shown in the figure 5. It can be seen from the figure 5a, the microstructure of the nugget zone or stir zone of Aluminium is specified by very fine grains. The grains in the HAZ are characterized by coarse grains compared to grains in the stir zone as shown in the figure 5b. This indicates the grain growth in HAZ due to the thermal cycle during the FSW. This is the reason for obtaining more hardness in stir zone compared to the HAZ.

Figure 5  Microstructures of Aluminium in the joint T₁ made by threaded tapered pin tool  a) Stir zone  b) Elongated grains in HAZ

In a narrow TMAZ (Thermo mechanical zone) has been observed in between Nugget zone and HAZ. The microstructure of the copper in nugget zone, TMAZ and HAZ are shown in the figure 6. The microstructure of the Cu in stir zone is also characterized by fine grains as shown in figure 6a. The microstructure of the Copper in HAZ is specified by coarse grains compared to the grains in stir zone and TMAZ as shown in the figure 6c. The fine grains in stir zone indicates the influence of rotating pin on the grain deformation and continuous dynamic recrystallization in the nugget zone of the Cu material. The flow of the material from the trailing side to the leading side at top surface of the joint is a common mechanism in friction stir welding, which causes the vertical flow of the material in longitudinal axis of the joint. The coarse grains in HAZ indicates the grain growth in the HAZ. This is the reason for more hardness observed in nugget zone compared to the HAZ.
Evaluation of Joint Properties of Friction Stir Welded Al/Cu Bimetallic Lap Joints Fabricated by Threaded Tool

![Figure 6](image1.png)

**Figure 6** Microstructure of Copper in the joint T₁ made by threaded tapered pin tool a) Stir zone and b) TMAZ c) HAZ

The interface structure of Al and Cu is very complex. The boundary between Aluminium and Copper is shown in the figure7a. Figure7b shows the mechanically mixed layers of Copper and Aluminium formed in the area near to the interface. The light gray layers are also observed along with the Cu/Al layer structure.

![Figure 7](image2.png)

**Figure 7** Microstructures at interface in the joint T₁ made by threaded tapered pin tool a. Boundary between Al and Cu at interface b. mechanically mixed Cu and Al layers

**CONCLUSIONS**

1. Sound and defect free Aluminium/Copper bimetallic lap joints have been fabricated successfully using threaded tapered tool.
2. The maximum value of shear strength obtained was 71MPa. It is 100% of parent material Al and 70% of parent material Cu.
3. The hardness values varied between 35 and 44.3 HV₀.₅ and between 62 and 70 HV₀.₅ for Al and Cu sheets respectively. Minimum hardness in Al and Cu has been observed in the HAZ of both the retreating and advancing side.
4. The microstructure of the nugget zone of Al and Cu is specified by very fine grains. The grains in the HAZ are characterized by coarse grains compared to grains in the stir zone.
REFERENCES


