Effect of Preheating on Mechanical Properties of Hybrid Friction Stir Welded Dissimilar Joint

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Abstract

Hybrid friction stir welding is an innovative solid-state joining technology which has great potential to produce effective and defect free joint of dissimilar materials irrespective of high chemical affinity and completely different physical and mechanical properties like aluminum and copper. Although, these factors contribute to the asymmetry in both heat generation and material flow, these drawbacks may be overcome by introducing additional local heating to preheat the copper side up to 200°C and the optimum location of the tool to provide adequate metal flow around the tool. Preheating prevents the formation of a large amount of brittle aluminum-copper inter-metallic compounds. Among the possible preheating source, plasma arc provides unique combination of high arc stability, concentrated energy density and low equipment cost. Hence plasma assisted hybrid friction stir welding (P-FSW) of pure copper and AA1100 are investigated. The mechanical properties of welded joint indicatethatP-FSW of pure copper and AA1100 improves the welding efficiency and weld jointquality.

Keywords: Hybrid friction stir welding, preheating, intermetallic compounds, mechanical properties

1. Introduction

Many emerging applications in power generation, petrochemical, nuclear, aerospace, transportation, and electronics industries lead to the joining of dissimilar materials by different joining methods especially by friction stir welding (Rai et al., 2011). Due to different chemical, mechanical and thermal properties of materials, dissimilar materials joining present more challenging problems than similar materials joining (Kimapongand Watanabe, 2004). However, when joining dissimilar materials by friction stir welding (FSW), the problems not only arise from a material properties point of view, but also from the possibility of the formation of brittle inter-metallic and low melting point eutectics(Xue et al., 2010).

In this context friction stir welding (FSW) is an impeccable method to weld materials that are hard to be joined by the conventional fusion welding methods such as Cu-Al with optimum combination of process parameters. Murr et al. (1998) first reported sound welds without any defect were difficult to obtain using FSW. Afterwards, Ouyang et al. (2006) investigated the microstructural evolution during FSW of Al to Cu and concluded that complex microstructure with several intermetallic compounds such as Al₂Cu, AlCu and Al₄Cu₉ is possible. In addition, they claimed that direct FSW of Al to Cu was difficult due to the brittle nature of intermetallic compounds. Ochi et al. (2004) investigate the formation of intermetallic compounds(IMC) at interface of Cu-Al joint and effect of intermetallic compounds on joint strength. Many authors have detected the existence of IMC compound layers in Cu/Al dissimilar metal with FSW process. The layer of continuous and uniform with thicknesses of about 1 µm is possible. Xue et al. (2010) studied the effects of FSW parameters on the microstructures and properties of Cu-Al dissimilar joints, and suggested that a thin and continuous layer of inter-metallic compounds was necessary to achieve sound Cu-Al joints. Sahinet al. (2010) determines the phases that occurred during welding as grey layer and observed at the fracture surfaces of welded parts. However, this layer decreases the strength of the joints. Galvao et al. (2011) performed a thorough macro and microstructural analysis of Al-Cu welded joint. It was concluded that the formation of inter-metallic phases deeply influences the weld crown morphology, which remains one of the main concerns in Al/Cu joining by friction stir welding. The investigation on dissimilar FSW of Cu-Al system indicate that there are numbers of factors that influence on weld joint quality such as:different deformation behaviors, formation of intermetallic compounds, differences in thermo-physical properties and suitable position of material at the advancing side (Li et al., 2012; Bisadiet al., 2013). These factors also contribute to asymmetry in both heat generation and material flow during FSW (Deb Roy et al., 2010). However, when FSW has been adopted to join
dissimilar materials with a high difference in melting points, it is difficult to produce sound joints with satisfactory strength as applicable due to their significantly different plastic deformation and material properties (Murr et al., 1998; Li et al., 2012).

To overcome above mentioned problems, researchers investigated on the application of hybrid friction stir welding to join dissimilar of materials with the aid of external heat source. Merklein and Giera (2008) studied laser assisted friction stir welding of steel to aluminum alloy in butt joint configuration. The laser beam takes the role of preheating the steel blank to overcome asymmetry in heat generation to enhance the weldability. Bang et al. (2010), Bang et al. (2012) and Bang et al. (2013) reported laser or GTA assisted friction stir welding of steel to aluminum alloy. The joint strength was achieved ~ 90–93% with reference to Al alloy as compared to ~ 60 – 78% without the effect of external heat source. Furthermore, it was demonstrated that tool life and decrement of applied load was expanded during joining of dissimilar materials with the aid of external heat source.

In present work, an additional local heat source is introduced with conventional FSW process that preheats copper side up to 200°C. A low cost plasma arc is utilized to develop the hybrid FSW system. Preheat source located in the copper side ahead of the tool in the welding direction provides adequate metal flow around the tool and simultaneously prevents the formation of a large amount of brittle aluminum-copper intermetallic compounds. The mechanical properties of the welded joints are analyzed for several process conditions. It is expected that the hybrid FSW technology with preheating for pure copper and AA1100 dissimilar materials will improve the welding efficiency and weld joint quality.

2. Experimental details

The materials used in this study were 6 mm thick aluminum alloy (AA1100) and pure copper as illustrated in Fig. 1. The chemical compositions and mechanical properties are depicted in Table 1. PAW (Plasma arc welding) machine was used as preheating source during welding. PAW torch leading FSW tool (H13 tool steel) with shoulder diameter 18 mm, probe diameter 6 mm and pin length 5.7 mm was implemented for the welding process. Welding tool was perpendicular to welding surface and offset towards the Al alloy with pin offset of approximately 1 mm. To prevent surface oxidation during welding, 1.5L/min of shielding gas (argon) was applied through PAW torch.

The tool rotation speed, traverse speed and preheating current are main process parameters in determining the appearance and mechanical properties of FSW joint. In earlier investigations, the joining of Al and Cu has been obtained under different welding conditions. The literature indicates that the preheating in copper side minimizes the difference in deformation behavior during welding of Al and Cu. As shown in Fig. 1, the preceding PAW torch as preheating heat source of the copper plate was carried out at the point of 13 mm away from the shoulder edge with an angle of 60 degree adjacent to the joint, which ensure less effect of arc on tool and enhanced the material flow during welding. The aluminum alloy plate was located on the retreating side and the copper plate on the advancing side. P-FSW was performed under the different welding conditions depicted in Table 2.

Table 1 Chemical compositions of pure copper and AA1100 (wt. %).

<table>
<thead>
<tr>
<th>Material</th>
<th>Cu</th>
<th>Zn</th>
<th>Fe</th>
<th>Ni</th>
<th>Mn</th>
<th>Pb</th>
<th>Si</th>
<th>Ti</th>
<th>V</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure copper</td>
<td>Bal.</td>
<td>0.025</td>
<td>0.009</td>
<td>0.009</td>
<td>-</td>
<td>0.017</td>
<td>0.007</td>
<td>-</td>
<td>0.027</td>
<td></td>
</tr>
<tr>
<td>Aluminum alloy 1100</td>
<td>0.02</td>
<td>0.01</td>
<td>0.36</td>
<td>-</td>
<td>0.01</td>
<td>0.08</td>
<td>0.01</td>
<td>0.01</td>
<td>Bal.</td>
<td></td>
</tr>
</tbody>
</table>

In order to analyze the mechanical properties of the weld joints, optical microscopy, scanning electron microscopy (SEM) with X-ray energy dispersive spectroscopy (EDS) were used. Vickers hardness test and tensile test were carried out. The Vickers hardness was measured along the transverse cross section of the welded specimen using a load of 0.1Kgf and dwell time of 10 s. Tensile test of the welded specimens were conducted based on ASTM E8M-04 standard.

Table 2 Hybrid Friction Stir Welding process parameters of Dissimilar Pure Copper and Aluminum AA1100.
3. Results and discussion

3.1. Joint appearance

Fig. 2 shows surface appearances and cross sections of Al/Cu joints produced at different welding conditions. At traverse speed of 98 mm/min and 815 rpm rotational speed, the boundary of Al and Cu plates could be discernible from the surface appearance. Voids are observed in the cross-sectional macrograph indicating incomplete mixing between Al and Cu. This defect is usually associated with insufficient material flow caused by insufficient heat input. While at a lower speed and without preheating, a good appearance with few flash is observed with large voids in cross section. With the increase in preheating current, voids size of joint decreases due to improvement in material flow as observed in Fig. 2. The weld quality reduces with a further increase in preheating current in case of Exp. 5 of Table 2. Unlike FSW of similar materials, typical cross section of FSW dissimilar joint is difficult to be divided into different regions. Moreover, the nugget zone does not exhibit the classical onion ring structure due to different materials flow patterns and formation of intermetallic compound. The weld quality is greatly influenced by the preheating and the fixed location of tool pin besides process parameters (tool rotational speed, traverse speed and offset). In the present study sound joints are obtained when hard material i.e. Cu is fixed at the advancing side and applied preheating on it.

3.2. Mechanical properties

The preheating effect in respect of mechanical properties is carried out on the basis of tensile strength, micro-hardness, fractography analysis and bending strength.

3.2.1. Micro hardness distribution

The micro hardness distribution profile on the transverse cross-section of the joint welded at five different welding conditions is shown in Fig. 4 (a-e) as per hardness points illustrated in Fig. 3. The average hardness values of base metals Al and Cu are 46 HV and 130 HV, respectively. The hardness of HAZ in Al side is lower than that of base metal due to HAZ softening. The occurrence could be probably attributed to the grain coarsening and dissolution of strengthening precipitates induced by the heat generated during P-FSW process. An inhomogeneous distribution of hardness values is observed in the nugget zone. The higher hardness value in the nugget zone relative to Al base metal is primarily associated with the formation of very fine recrystallized grains and the Cu-rich dispersed particles, corresponding to the effect of preheating observed in Fig. 3. It is worth noticing that an abrupt change in hardness value occurs adjacent to the interface. The values at the interface of top, middle and bottom are reached to 172.4 HV and 195.3 HV, which are far higher than the base metals.

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Hybrid Friction Stir Welding Process parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transverse speed (mm/min)</td>
</tr>
<tr>
<td>1</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td>98</td>
</tr>
</tbody>
</table>

3.2.2. Tensile strength and fracture behavior

The comparison of tensile strength of joints welded at different preheating current corresponding to Table 2 is shown in Fig. 5. The tensile strength of joint produced at relatively low and without preheating current is rather weak with average value of 46-65 MPa. However, the maximum strength of joint fabricated at 45 amp preheating current reached 107.2 MPa, representing joint efficiency of 75.6% with reference to Al alloy. The results indicate that the tensile strength of P-FSW welds is improved with increase in preheating current up to some optimum value.
Figure 6 indicates that there is little improvement of ductile fracture behavior in case of P-FSW. This result also indicates that the improvement of material flow and partial annealing effect in dissimilar materials by P-FSW significantly increases elongation and improves joint strength between aluminum alloy and pure copper when preheating occurs towards copper side. It is noteworthy that without preheating the weld joint shows brittle fracture behavior. Also, a large number of voids are observed without preheating due to lack of proper material flow caused by insufficient stirring and heat generation. In case of P-FSW, increase of tensile strength and elongation is caused by additional heat input due to preheating towards copper side.

**Figure 4** Hardness profiles along top, middle and bottom lines of weld cross-section (a-e) corresponding to Exp. No. (1-5)

**Figure 5** Tensile strength of different welding condition in Table 2

Fracture locations of tensile test specimen at different welding conditions (Table 2) are depicted in Fig. 7 (a). The differences in appearance can be distinguished from their fracture locations although joints fracture at the stir zones. The crack initiates from

**Figure 6** Percentage of elongation of different welding condition in Table 2
the cavity defect and propagates to the upper part of the plate. In the case of joint produced at 45 amp preheating current, the zigzag feature is observed. The crack propagation is found along the Al/Cu border in the upper weld but extended into the stir zone close to Al side in the lower part. This fracture behavior shows that the reaction phases at the lower weld exhibit high resistance to crack propagation.

Fig. 7 (b-f) shows the SEM morphologies of fracture surfaces corresponding to Fig. 7 (a). It can be observed from Fig. 7 (b) that the feature of fracture surface is characterized by smooth surface without severe deformation without preheating. The cavity defect coupled with no metallurgical bonding results in the low strength shown in Fig. 2. However, in Fig. 7 (c-f) the fracture morphology of joint with preheating is characterized by dimples in different sizes. Dispersed Cu particles are observed in the dimples indicating the occurrence of tearing in the stir zone. As compared with FSW (Fig. 7 (b)) and P- FSW (Fig. 7 (c-f)), the larger dimples indicating the strengthening particles which played a significant role in preventing crack propagation due to improved material flow caused by preheating.

![Figure 7Fracture locations (a) and Fracture surface morphologies of joints at different welding condition in Table 2 Exp. No. 1-5 (b-f).](image)

### 3.2.3. Bending strength

Bending properties are tested to determine the flexural strength and ductility of the Al/Cu joints which are always required in industrial application. The bending tests are carried out as per ASTM E08 for welded specimen. The dimensions for the bending specimen are 100 x 12 x 6 mm. The experimental bending results for 5 combinations of process parameters are listed in Table 3.

The appearance of the sample after the bending test is shown in Fig. 8 (b). The bending load is applied in the weld center viewed from the back surface. Bending test result indicates that the joint bending strength is increased with increase in preheating current. Crack is observed on the outer surface and the bending strength and bending angle increase with the effect of preheating. Increase in preheating current allows weld joint to bend at higher bend angle which shows improvement in ductility of weld joints. This improvement belongs to the increase in temperature as the preheating current is increased and increased plastic flow of material. But temperature is not enough to soften the base material (Cu) at low current without preheating. The materials are not sufficiently plasticized to be stirred and forged easily, resulting in lesser bending strength. Defect is in the root for all the joints are observed and this defect is known as the tunnel-hole defect. Although the appearance of the welded surface seems to be good, tunnel defects can be observed at the advancing side of stirred zone in the weld.

![Figure 8(a) Bending test specimen (b) Tested specimen after the bending test Exp. (1-5) (i-v).](image)

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Ultimate Load in N</th>
<th>Disp.at Failure in mm</th>
<th>Max. Disp. in mm</th>
<th>Bend angle in Deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>812.93</td>
<td>1.84</td>
<td>3.51</td>
<td>5°40'</td>
</tr>
<tr>
<td>2</td>
<td>818.31</td>
<td>1.91</td>
<td>4.64</td>
<td>12°26'</td>
</tr>
<tr>
<td>3</td>
<td>829.45</td>
<td>2.10</td>
<td>3.56</td>
<td>13°09'</td>
</tr>
<tr>
<td>4</td>
<td>1019.04</td>
<td>2.33</td>
<td>4.86</td>
<td>16°56'</td>
</tr>
<tr>
<td>5</td>
<td>829.13</td>
<td>2.03</td>
<td>4.01</td>
<td>10°01'</td>
</tr>
</tbody>
</table>

Overall, bonding strength of Al–Cu joint is enhanced by introducing preheating in copper side. Excellent metallurgical bonding of the Al–Cu interface is achieved by preheating due to improved plastic flow and formation of continuous and uniform inter-metallic compound layers.

### 4. Conclusions

In present work friction stir welding of aluminum alloy to pure copper is improved by introducing
preheating. The following conclusions are drawn from the analysis:

a) With the increase of preheating current, the material flow also increase and tend to decrease the void formation in weld joint.

b) An inhomogeneous distribution of hardness values is observed in the nugget zone. The values of hardness in weld zone in some point are 172.4 HV and 195.3 HV, which is far higher than Al and Cu base metals due to formation of hard inter-metallic compounds.

c) The improved tensile strength is obtained in the weld due to improve in stirring action of P-FSW. It is about 83% of the base metal (Al) in case of P-FSW but 47% in case of FSW without the effect of preheating.

d) Fracture patterns of crack propagation in P-FSW welds exhibits ductile fracture mode showing dimples at the fracture surface and locally brittle fracture mode with cleavage face which are hardly accompanied by plastic deformation. This result indicates that the sufficient plastic flow and partial annealing effect in weld joint by plasma preheating on the copper side results in significantly increase elongation and joint strength.

e) The bending test result indicates that the joint bending strength is increased with increase in preheating current due to the enhanced plastic flow and partial annealing effect in dissimilar materials when the plasma arc is attached in copper side.

References


