Development of dissimilar metals joint is in great demand of present industries. Copper (Cu) and Aluminium (Al) is one of such combinations, which is widely used for electrical, chemical, and thermal engineering applications, due to their higher electrical and thermal conductivities, corrosion resistance, and mechanical properties. Welding Cu and Al is an outstanding challenge, due to large differences in mechanical, metallurgical and chemical properties. In the present investigation, Laser Beam Welding (LBW) and Gas Tungsten Arc Welding (GTAW) were used to check the feasibility of welding Cu (pure) and Al (6061-T6). Power, welding speed, and joint configuration were the concerned parameters in LBW, while current, speed, weld edge preparation, and use of compatible filler wire were the major parameters in GTAW. Laser power of 3000 W with welding speed of 2-3 m/min were used. In GTAW, current ranging from 80-200 A with welding speed of 30-65mm/min and filler wire of AlSi12, ER-CuAl-A2 and Ag-Bro were applied. Samples of Cu and Al were welded in manual as well as automatic mode with and without the filler wire. Visual examination, Micro and Macro-structure characterisation, Tensile test, Vickers Hardness test, and Fractography were performed for analysis of welded samples. Results revealed the presence of Intermetallic Compounds, cracks, porosities, microstructural heterogeneity, lack of fusion, and local accumulation of Cu particles. Effect of these defects on mechanical properties were observed from the results of tensile and microhardness tests. Maximum tensile strength of 25.2MPa with 1.5% elongation was observed.

Key words: Aluminium; Copper; Dissimilar metal welding; Gas Tungsten Arc Welding; Laser Beam Welding

1. Introduction

The dissimilar metals joints are increasingly applied in different sectors of industries due to their technical and economic advantages. Copper (Cu) and Aluminium (Al) is one of such combinations, which is required for hybrid vehicle batteries, electrical bus-bars, heat exchangers tubes, and microelectronics. Wide applications of their joints are due to low availability of Cu, advantage of lower weight and cost [1]. However, it is very difficult to obtain this joint, because of large difference in their mechanical, chemical and metallurgical properties. Properties such as melting temperature, thermal conductivity, and thermal coefficient of expansion play major role. Melting temperature and thermal conductivity of Cu are almost twice of Al. Due to these properties, Cu needs high amount of heat, but simultaneously, on the other hand Al requires very less heat input. Another thermal property, Thermal coefficient of expansion of Cu is little lower than the Al. It leads to residual stresses, cracking, and distortion, due to unequal expansion [2]. Other than thermal properties, solubility of both the metals in each other is a major challenge. The solid solubility of Cu in Al is maximum of 5.65 wt% (at 548°C) and Al in Cu is 9.4 wt% (at 363°C) [3]. This lead to formation of gross heterogeneity, cracks, macro-segregation and brittle Intermetallic Compounds (IMC) such as CuAl2, Cu5Al4, Cu3Al2, and Cu4Al3 [4]. These metals are very prone to form oxides and the rate of their formation increases with the temperature. These oxides directly interrupt the fusion and results into insufficient bonding. If the shielding is not sufficient enough, hydrogen can be entrapped in Al and form porosities [5]. During service, difference in electro-potential of these metals create problem by forming localized galvanic cell. It leads to corrosion of Al, due to its higher electronegativity [3].

With these challenges, joining these two materials is considered as one of the key research works in recent time. In order to overcome such problems, highly controlled process with optimized
parameters, is required. In present time, Laser Beam Welding (LBW) is one of such process, which provides controlled heat input and minimizes the metallurgical changes in base metals [3]. Another such process is Gas Tungsten Arc Welding (GTAW), which is well known for quality welds. Using GTAW is advantageous due to versatility, quality welds, and wide availability of equipment at low cost [6]. Considering technical, and economical benefits, LBW and GTAW were selected for the research work. Various parameters of LBW were suggested by some of the researchers for proper Cu-Al joint. Laser power and welding speed are majorly influencing. Sujin et al. [7] observed that the low welding speed leads to formation of IMC and cracks. Higher speed prevents IMC, by higher cooling rate and lower atomic diffusion. On the other hand, Mai et al. [8] found higher speed results in more solidification cracks, due to higher cooling rate. Some of the researchers have suggested the use of sinusoidal laser power to achieve controlled penetration in Al, as the power intensity at the peak of sine pulse is sufficient to create a deep weld and at the next moment reduction in intensity solidify the weld quickly[9]. In case of Cu, Heider et al. [10] reported the use of pulsed laser to reduce melt ejections and porosities. It provides high control of weld pool dynamics by allowing lesser time for formation and bursting of vapor cavity. Weigl et al. [11] have investigated the effect of beam offset. Beam offset of 0.2 mm towards Al was used with the addition of AlSi12 filler wire. Strength was 30% higher than in the case of without beam offset. Standfuss et al. [12] also used beam offset of 0.1 mm towards Al from the center line. Higher reflectivity of Cu interrupts absorption of laser energy. At room temperature absorption of the laser having wavelength >1 µm is ~3%. But it increases with the increase of temperature. Another key factor is higher absorption of lower wavelength laser by Cu. Hess et al. [13] used green laser (GL) with Infrared (IR) laser. Low power GL (<100 W) was used to preheat and pre-melt the material, which opens the way for higher absorption of IR laser, as component is already at high temperature. Lastly, Joint geometry and configuration such as butt and lap are very important in LBW, and it requires proper consideration. So far, only “The Welding Institute” (TWI), UK and the “Fraunhofer”, Germany institutes have achieved the successful joint. TWI achieved with the use of high power laser of 5kW with the welding speed of 6m/min [14].

Unlike LBW, GTAW is very less developed for Cu-Al joints. The complexity of the process is high due to large no of parameters. Heat source in GTAW is less concentrated, which gives higher heat input, resulting in various metallurgical changes, and deterioration of weld properties. But, it can be advantageous, as the torch can be shifted towards Cu, providing proportional heat in accordance of the difference in properties. Further, thermal conductivity of Cu is higher. To compensate this in thicker samples, preheating is mandatory. Generally, it is done about 500 °C for 5-10 min [15]. Heat input can be controlled even by proper joint geometry. Some of the researchers have tried special joint geometry on other metal combinations and similar can be tried for Cu-Al. Sajjad et al. [16] experimented on Cu-Stainless steel (SS), using 45° beveled edge preparation on Cu side, to compensate the effect of higher thermal conductivity of Cu. Electrode selection is very important in arc welding, specifically for dissimilar metals, which demand two different power source characteristics. Welding of Cu is better done through DCEN, while of Al is done by AC mode [6]. So, the electrode and its design must fulfill the requirement of both the metals. In order to withstand and establish stable arc in AC and DC both, EWCe and EWZr electrodes are generally recommended [6]. Similarly, the arc medium i.e. shielding gas affects significantly. If the thickness is more than 3mm, the gas mixture of Argon and Helium is recommended as a shielding gas. Argon provides arc stability and helium provides deeper penetration [6]. Use of Helium also helps in compensating the heat loss by Cu, due to higher thermal conductivity. Lastly, use of compatible filler metal is necessary, due to low solubility of Cu-Al. It reduces cracking and formation of IMC. Peng et al. [17] used ZnAl for 1mm thick sample of Cu-Al. Maximum tensile strength of 254 MPa was achieved. Feng et al. [18] experimented
on brazing of Cu-Al with the addition of Ti to Zn-22Al filler and resulted in reduction of IMC. Further, IMC layer was lowered with the addition of Ce instead of Ti, which helped to suppress the IMC layer growth. If the third metal is having poor characteristics than base metal, it will deteriorate the joint quality. With the use of Zn, the joint formed may have higher porosity, due to its lower boiling point.

Despite of such rigorous research work, reliable and durable joint is yet to be achieved. There is a strong requirement to develop proper technique of welding Cu-Al, in order to meet the demand of the present time. The present investigation is mainly focused on major parameters of both the processes, to check their feasibility for welding Cu-Al.

### Table 1. Chemical compositions of base metals

<table>
<thead>
<tr>
<th>Elements</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Impurities</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6061-T651</td>
<td>0.56</td>
<td>0.30</td>
<td>0.17</td>
<td>0.12</td>
<td>1.03</td>
<td>0.11</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
<td>Balance</td>
</tr>
<tr>
<td>Cu (Pure)</td>
<td>-</td>
<td>-</td>
<td>&gt;99.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
<td>-</td>
</tr>
</tbody>
</table>

*Fig.1 (a) Fixture used for experiments, (b) GTAW machine setup at PDPU, (c) GTAW Power source at PDPU, (d) LBW setup at ARCI*

## 2. MATERIALS AND METHODS

Experiments were performed using plates of Cu (pure) and AA6061-T651, having sample size of 100mm X 50mm X 1 or 3 mm. Chemical compositions of base metals are shown in Table 1. These samples were machined using milling machine for perfect fit up in case of LBW, and proper edge preparation for GTAW. In order to achieve perfect fit up and prevent distortion, fixture was designed and manufactured as shown in Fig. 1(a).

Initial experiments of LBW were done mainly considering laser power, welding speed, and beam defocus. These experiments were carried out at “Shajanand Laser Technology Ltd”, Gandhinagar, on model YLS-2000 with laser power ranging from 500-1500W using fiber laser having wavelength of 1.068µm. It was performed with variation in beam defocus and welding speed. Initially, Butt joint was used. Due to very small diameter of beam (300µm-900µm), results of lateral shift towards one of the metal were unsatisfactory. Beam shift towards Al, resulted in burn off of Al without affecting the Cu. On the other hand, beam shift towards Cu, resulted in high reflection of laser, providing very less heat for the fusion. Even filler wires of ER-CuAl-A2 and AlSi12 were used. But the power was insufficient to produce molten puddle for coalescence of filler and base metals together. The solutions to these problems were, use of 1mm thick samples higher power, proper welding speed and lap joint with Al on top of Cu instead of Butt joint. Final experiments were performed at “International Advanced Research Centre for Powder Metallurgy & New Materials (ARCI)”, Hyderabad. These trials were done on model Rofin DC305 providing continuous power source of CO₂ laser having Power = 3kW, Beam spot diameter = 180 µm, Argon as a shielding with flow rate of 20 LPM, and keeping other parameters as variable as mentioned in Table 2. Higher welding power is necessary for initiation of welding. As stated by Paolo et al. [19], power density greater than 30 kW/mm² and 10kW/mm² is required to initiate molten pool in Cu and Al respectively. Lap joint with Al on top of Cu was preferred instead of butt joint. Lap joint with Cu on top of Al can’t be used, because of very high reflectivity of Cu. It can damage the optical system of the machine.
In GTAW, mainly, welding current, welding speed, torch offset, and joint geometry were taken into consideration. Experiments were done in manual as well as automatic mode. Feasibility tests were performed autogenously, in order to observe the dynamics of the fusion of both the metals. Initial parameters were selected based on the study of the parameters required by both the metals individually. Initial experiments were performed by trial and error method, on Panasonic Automatic TIG welding Machine of model no: YC-200BR1, at PDPU, Gandhinagar. For manual welding, Thermal arc 250GTSW machine was used at Keepsake Engineering Pvt. Ltd., Ahmedabad. Filler wires such as AlSi12, ER-CuAl-A2, Al-Bro, and Ag-Bro were used for the feasibility tests. In automatic welding, largely, current was varied from 140-200A with welding speed of 50-65mm/min for 3mm thick samples. One of the important parameter is the torch offset. Due to large differences in properties, the torch was kept offset towards Cu side. Torch offset of 2-4mm was experimented. From that, 2mm was best suited. In addition to it, edge preparation on Cu side was beveled at 45°, to increase the heat input. Along these, preheat is also important parameter. It helps to reduce residual stresses and mitigate the need of different heat input. From the literature, recommended preheat temperature for Al and Cu is 200°C and 450-500°C respectively. In order to reduce the heat dissipation rate, stainless steel was used as a backing plate. The main problem during welding was, as the welding starts, Cu demands high heat. By the time of completion of half, the input was so high that, Al affected much and the current is required to be reduced. Continuous change of parameters, and torch movement was required. Depending on the understanding of these tests, final parameters were selected as follows: Power source=AC, Filler wire= ER-CuAl A2, Thickness of materials=3mm, Backing plate=Stainless steel, Joint geometry=45° beveled on Cu side, Electrode size=45°, Shielding gas=Argon, Shielding gas flow rate=13-15LPM, and Filler wire diameter=2.44mm. These parameters were kept constant and other as shown in Table 3 werevariable.

<table>
<thead>
<tr>
<th>Sr.no.</th>
<th>Variables</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Welding speed (mm/min)</td>
<td>2000</td>
<td>2000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>2</td>
<td>Thickness (mm)</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Joint configuration</td>
<td>Butt</td>
<td>Butt</td>
<td>Lap</td>
<td>Lap</td>
</tr>
<tr>
<td>4</td>
<td>Remark</td>
<td>No joint obtained</td>
<td>No joint obtained</td>
<td>Al on top of Cu, Best joint achieved</td>
<td>Cu on top of Al, High reflection</td>
</tr>
</tbody>
</table>

Table 2. Experimental parameters of LBW

![Fig2. (a) Experiment 2 and (b)Experiment 3 are welded sample of LBW from Table 2, (c)Experiment 1, (d) Experiment 2, (e) Experiment 3, and (f) Experiment 4 are welded sample of GTAW from Table 3](image)

Table 3. Experimental parameters of GTAW
<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Variables</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mode of welding</td>
<td>Manual</td>
<td>Automatic, Autogenous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Current (A)</td>
<td>50-150</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Torch offset (mm)</td>
<td>Torch waving</td>
<td>1(Cu side)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Welding speed (mm/min)</td>
<td>50-60</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Crater current (A)</td>
<td>0</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Preheat (°C)</td>
<td>350 (both)</td>
<td>350 (Cu)</td>
<td>350 (Cu)</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>Preheat time (min)</td>
<td>5</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Macrostructures of GTAW samples of experiments from Table 3(a) Experiment 2 showing weld zone and HAZ towards Al, (b) Experiment 3 showing lack of fusion on Cu side, (c) Experiment 4 showing weld profile of autogenously welded sample

After performing welding, samples were visually observed for checking weld bead features, presence of surface defects, and effect of various process parameters on weld. Samples were further examined by macrostructure observation of transverse weld cross-section. In order to examine microstructural changes, metallurgy was performed. One sample of LBW, and four samples of GTAW were selected for study of microstructures. Samples were prepared by following standard procedure from ASTM standard E3-11. Etchants solutions (FeCl + HCl + H₂O: for Cu, and 100% H₂O + 1gm NaOH) were applied by swabbing technique. Each sample was properly examined at various locations at 50x, 100x, 200x and 500x magnification as per requirement. Microhardness was measured using Vickers Hardness testing. Load of 1000gm was applied for dwell time of 20 sec. Variation of hardness throughout the cross-section of weld was observed. Tensile test was performed on nine samples with strain rate of 0.1mm/min. Specimens were prepared as per guidelines of ASTM E8. Fracture load, ultimate tensile strength, and % elongation were noted down and used for characterization. Finally, fractography was performed and fracture surfaces were visually examined for the nature of the failure.

3. RESULTS AND DISCUSSION

Macrostructure examinations

Macrostructure examination of transverse cross-section of welded sample was done. It showed various defects such as porosities, lack of fusion on Cu, and burn off of Al. Effect of heat input on both the metals was observed. It also showed the effect of variation of parameters such as laser power, welding current, and welding speed. Lower speed and higher current resulted in huge amount of change in Al. At the back of Al, distortion was observed due to higher heat input from the SS backing plate. In both the processes, heat input was not sufficient enough for Cu. It can be seen from the Fig. 3 (b) and Fig. 4 (a).

Microstructure Analysis

Microstructural analysis revealed the presence of various defects such as porosity, gross heterogeneity, formation of IMC, cracks, and lack of penetration in Cu as shown in Fig. 4. In LBW, porosities have largely been attributed to instabilities of laser keyhole in the weld pool. Sudden collapsing of keyhole can result into void due to entrapment of gases. Higher porosities, lack of penetration, and cracks towards Cu can be due to higher cooling rate (Fig. 4(f)). Similar analysis of weld zone on Al side showed significant amount of porosities (Fig. 4(b)). These porosities may be because of lower boiling point of magnesium (1091°C). Another reason can be high rate of solidification and higher absorption of hydrogen in liquid Aluminium. Hydrogen diffusion in molten Aluminium could be as high as 1.00 cm³/gm [5]. In case of GTAW, large amount of porosities was observed in autogenously welded sample. It may be due to lack of third compatible filler metal.
Fig. 4. (a) Microstructure of LBW welded sample, points indicate the location of hardness measurement, (b) Weld zone in Al, (c) Interface of weld zone and HAZ, (d) IMC layer at the interface of weld zone and HAZ at higher magnification, (e) Microstructure of Al base metal, (f) Root of weld in Cu, (g) Microstructure of Cu base metal

Fig. 5. (a) Macrostructure of GTAW welded sample, (b) Interface of Cu HAZ and weld zone, (c) Top of weld zone, (d) Interface of Al HAZ and weld zone, (e) Weld zone towards Cu, (f) Cracks at the root of weld, (g) Bottom side of interface of Al HAZ and weld zone showing layer of IMC
Microstructures observed were highly heterogeneous. It is due to heat treatable AA6061-T651 and lower solid solubility of both the metals in each other. Large amount of precipitates starts growing on application of heat in such alloys. IMC layer can also be observed at the interface of weld zone and Heat Affected Zone (HAZ). IMC such as CuAl2, Cu3Al, and Cu9Al4 may have formed. These are very hard and brittle. Such heterogeneity leads to drastic variation in mechanical properties of the joint. Microstructural heterogeneity, difference in coefficient of thermal expansion, and formation of IMC even generated cracks. These cracks act as stress concentrator and result into lower weld strength. In LBW, little microstructural changes were observed, due to lower amount of heat input. Very narrow HAZ was observed. On other hand, samples welded by GTAW showed huge amount of microstructural changes. Large sized HAZ was observed. Within the weld zone, varieties of phases were observed, which had different types of microstructures with varying sizes. Lack of fusion was observed on Cu side as shown in Fig. 3 (b). It may be due to insufficient heat provided on Cu. Despite of preheating at 350°C, application of SS backing plate and torch offset towards Cu, the heat provided was unable to compensate the effect of higher thermal conductivity of Cu. Macrocracks were also observed in weld zone. It can be attributed from the hot cracking of AA6061. All these defects somehow contributed to unsatisfactory weld properties. Prevention of these defects require in depth knowledge of metallurgy, dynamic of process parameters, and sophisticated machines with required precise control and online monitoring.

Mechanical properties

Microhardness measurements

Microhardness was measured using Vickers Hardness testing method. Variation of hardness was observed throughout the cross section of weld, as shown in Fig. 6. Such variation of hardness is due to microstructural heterogeneity, presence of IMC, precipitates and defects. In case of LBW, variation of hardness was less in vertical direction from top to bottom within the weld zone. But, the hardness value is far greater than the base metal. It may be due to small thickness (1mm) of sample, and higher cooling rate. In horizontal direction through the Cu, highest value was observed in the weld zone. It can be because of very high cooling rate and the formation of precipitates of Mg2Si from Al. Hardness in horizontal direction through Al, showed highest value at HAZ. Such specific variation can be because of over aging of Al alloy in HAZ and the interface at the weld zone. This over aging lead to formation of higher amount of brittle and hard precipitates. There is a slight decrease in hardness in weld zone. It is due to large amount of porosities.

![Fig. 6. Variation of hardness throughout weld zone, HAZ and base metals of LBW welded sample at locations shown in Fig. 4(a)](image)

![Fig. 7. GTAW welded sample (a) Locations of hardness measurement, (b) Variation of hardness throughout weld zone, HAZ and base metals](image)
Such huge change can be due to formation of IMC, and precipitates, which are produced in large amount because of heat retained by the SS backing plate. Heat assisted in large amount of atomic diffusion, which resulted into enlargement of precipitates and formation of IMC. But, on the other hand autogenously welded sample showed less value. It may be because of huge amount of porosities observed in the weld zone. From the results of both the processes, it can be inferred that the hardness value at the weld zone, and the HAZ is very high than the hardness of base metals.

Tensile test

![Image of tensile test specimen](image1)

Fig. 8. Broken specimen of experiment 1, 2, and 3 after Tensile test

Tensile test was performed on manually welded samples with ER-CuAl-A2. The results are as shown in Table 4. The strength of the welded sample is far lower than the base metals. The highest strength of 25.2 MPa was observed with 1.5% elongation. Such a less strength can be because of large number of various types of defects in the weld zone. Sudden failure of the joint near Al interface was observed, in spite of presence of lack of fusion on Cu side and macro-voids. The reason can be the formation of brittle and hard IMC. Ductility of the sample was very less and can be seen from the values of the %elongation. In spite of application of very small strain rate of 0.1mm/min, the sample failed in highly brittle manner. The amount of hard precipitates and IMC can be imagined from such results.

Table 4. Tensile test results of 3 samples of Experiment 1 from Table 3

<table>
<thead>
<tr>
<th>Sr. no.</th>
<th>Ultimate Tensile strength (MPa)</th>
<th>% Elongation</th>
<th>Failure location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.2</td>
<td>1.8</td>
<td>Near Al interface</td>
</tr>
<tr>
<td>2</td>
<td>25.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>17.3</td>
<td>2.7</td>
<td></td>
</tr>
</tbody>
</table>

Fractography

Surfaces of the failed samples from the tensile test were analyzed. On the failed surface, sharp and shiny features were observed. It can be seen from the Fig.9. It is a clear indication of the brittle failure. One of the sample showed failure from the weld zone towards Al. It can be inferred that the brittleness of weld zone was high enough that, despite of presence of lack of fusion on Cu side, it failed from the weld zone on Al side. Failed surface showed indications of cleavage failure.

![Fracture surface images](image2)

Fig. 9. Fracture surface of failed samples in tensile test (a)Al side of sample 1, (b) Cu side of sample 1, (c) Al side of sample 2, (d) Cu side of sample 2, (e) Al side of sample 3, (f) Cu side of sample 3
Results of the microstructure investigations, tensile test, hardness test, and fractography gave clear idea of feasibility of the application of fusion based processes for welding Cu-Al. Due to application of heat, there will always be metallurgical changes in the base metals. Specifically, in the Al alloys these changes are detrimental. Formation of IMC, precipitates, and other defects such as porosities, cracks, and lack of fusion lead to lower strength of the weld. From the present investigation and the literature survey, it can be concluded that the use of LBW is still possible with further investigations, but the use of GTAW is not recommended, because of the complexity of the process and the high amount of heat input. In order to get the reliable and durable Cu-Al joint, rigorous research work is still required to be done, with deeper understanding of dynamic characteristics of the processes and the combine metallurgy of both the metals.

4. ACKNOWLEDGEMENT

Authors want to express sincere gratitude to ARCI, Hyderabad; Keepsake Engineering Pvt. Ltd., Ahmedabad; and Shajanand Laser Technology Ltd., Gandhinagar; Pandit Deendayal Petroleum University (PDPU), Gandhinagar for providing their facilities for experimental work. Authors are thankful to Office of Research and Sponsored Project, PDPU for funding the project work. The authors wish to thank Indian National Academy of Engineering for providing student mentorship during this project work.

5. CONCLUSIONS

From the present investigation following concluding remarks can be made:

1) The major challenges in welding Cu-Al are the difference in melting temperature, lower solubility of Cu and Al in each other, higher thermal conductivity of Cu, and coefficient of thermal expansion. All these lead to formation of IMC, microstructural heterogeneity, porosities, cracking, thermal distortion, and residual stresses. Presence of large number of defects, lowers the tensile strength of the joint. Formation of IMC and precipitates leads to very high increment in the hardness value in the weld zone.

2) Maximum tensile strength of 25.2 MPa with 1.5% elongation was achieved in this investigation. Maximum hardness value of 269.8 VHN at Al HAZ and weld interface in LBW, and 633 VHN in HAZ and 595.8 VHN in weld zone in GTAW was observed. Investigation of surfaces of failed components showed features of cleavage and complete brittle failure. Formation of IMC, precipitates from AA6061-T651, porosities and cracks resulted in highly brittle weld.

3) In LBW, beam power density and the welding speed played significant role. Due to high reflectivity, and thermal conductivity of Cu, higher power density is necessary. In future, parameters such as higher laser power, beam power density, use of lower wavelength laser and effective means to reduce the reflectivity should be focused.

4) Due to large amount of heat input, GTAW is not recommended for Cu-Al welding. Due to less concentrated and high heat input, various metallurgical changes were observed in the base metals, which resulted into brittle, hard and very low strength joint. For the future investigations, better compatible filler metal, stringent control of dynamics of process and heat input is required to be concentrated. But, from the present investigation GTAW is not suitable as other processes such as Solid state welding processes (Friction stir welding [1,20], Friction welding and Diffusion bonding).

6. REFERENCES


