Laser Micro Welding of Dissimilar Material of Aluminum and Copper Alloys

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Abstract. Copper and aluminum are widely used in electronic industries for their excellence in electric and thermal conductivity. Joining these different material in scale of micro is hardly difficult for their obvious different in thermal properties. Melting these materials during welding process will create intermetallic compound which possesses new material properties. The melted zone became extremely brittle thus increase the possibility of failure due to cracks and concentrated loads. To overcome this problem, fundamental study is needed to characterize the material behavior against heat induction under various processing parameters. This study is an attempt to characterize the performance of Nd-YAG laser in micro joining of Al 1100 and Cu 101.

Introduction

Aluminum and copper are widely used in electronic parts for their excellent thermal and electrical properties [1,2,3]. A lot of energy needs to be supplied instantly to the welding region to compensate the heat lost due to conduction. For this reason, laser is suggested to be the best choice to weld high thermal conductive material. Laser system is highly efficient converting electromagnetic light into heat at a small area [4,5,6].

Filler materials such as tin, sliver and zinc had been discovered to improve the strength of joint [1,7]. Silver foil as filler material gives two time enhancement to the joint strength [8]. It reduces the formation of intermetallic phases in joining area and improves the welding quality. However, in micro fabrication, small amount of other elements from filler material could change the behavior to electric conductivity and dimensional accuracy. Thus, it is important to study the technique of welding without filler material.

Applying the correct irradiation parameters is suggested to be effective to secure the welding success rate and improve the joining strength. Mai and Spowage (2004), successfully demonstrate Copper-Aluminum Al 4047 welding by controlling the melting ratio to obtain defect-free welding beads [9]. High peak power and short pulse duration is needed to have a successful welding of these materials. The appropriate welding speed also required to eliminate the problem of excessive heat generation [10].

This study was aimed to identify the allowable range of parameters which could create welding beads that free from cracks and voids problem. Results had shown that the value of pulse repetition rate ($f_p$) and pulse width ($t_p$) give different effect on the molten zone creation.

Experimental Setup

Copper (Cu 101) and aluminum (Al 1100) with thickness 0.8 mm were clamped on a jig to perform butt welding. The most important material properties in welding process are shown in Table 1.
Nd:YAG Laser beam with focusing diameter 0.7 mm was irradiated with angle 90° from workpiece surface. Nitrogen gas was supplied to the heated area as a shielding gas with approximately 45° from workpiece surface using nozzle with 4 mm opening diameter. The nozzle was located as close as possible to the heating area.

Table 1: Material properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Cu 101</th>
<th>Al 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity, (W/m·K)</td>
<td>391.1</td>
<td>220</td>
</tr>
<tr>
<td>Melting points, (°C)</td>
<td>1083</td>
<td>643</td>
</tr>
</tbody>
</table>

Laser irradiation test was conducted to each material using various parameters shown in Table 2 to observe their behavior against laser beam interaction. From this experiment, the applicable range of welding parameters was determined. Observation on the irradiated surface has led to the actual welding parameters as shown in Table 3. Welding processes were performed in two ways; butt welding and side butt welding. The laser beam was focused exactly onto the joining surface line. Observations were done from the top surface and cross sectional direction using measuring microscope.

Table 2: Parameters for blank material irradiation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Laser Power, ( P_{\text{avg}} ) (W)</td>
<td>50, 100, 150</td>
</tr>
<tr>
<td>Pulse repetition rate, ( f_p ) (Hz)</td>
<td>50, 75, 100</td>
</tr>
<tr>
<td>Pulse width, ( t_p ) (ms)</td>
<td>0.7, 1.4</td>
</tr>
</tbody>
</table>

Table 3: Parameters for actual butt welding

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average laser power, ( P_{\text{avg}} ) (W)</td>
<td>150</td>
</tr>
<tr>
<td>Pulse repetition rate, ( f_p ) (Hz)</td>
<td>50, 75, 100</td>
</tr>
<tr>
<td>Pulse width, ( t_p ) (ms)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Results and Discussions

Under various laser irradiation conditions, surface conditions of irradiated surface for both materials were observed. This was to determine roughly the range of parameters applicable to create molten zone with minimum defects such as voids, cracking and oxidations. For copper sheet (Cu 101), almost all parameters created serious voids problem on the top surface. Minimum void appearance was observed from specimens irradiated under 150 W of \( P_{\text{avg}} \), 1.4 ms of \( t_p \) at 50, 75 and 100 Hz of \( f_p \) (Table 4).

In the case of aluminum sheet (Al 1100), some of the parameters were performing cutting process rather than melting. This can be observed from specimens irradiated under 100 and 150 W with \( t_p \) 0.7 ms. The specimens were successfully melted with voids covering the top surface when the \( t_p \) was increased to 1.4 ms. Even though the specimens were successfully melted, with the same irradiation parameters used for Cu 101, voids creation and melted metal splattering were observed from all irradiation parameters.

Referring to the Cu 101 results, the applicable value of \( t_p \) was suggested to be 1.4 ms. Since the thermal conductivity of copper is higher than aluminum, the laser irradiation parameters need to be determined by putting the copper laser irradiation results as the first priority to be considered. Using different pulse repetition rate, butt welding was performed and observed.
Table 4: Surface conditions mapping after blank irradiation

<table>
<thead>
<tr>
<th>Average laser power, $P_{\text{avg}}$ (W)</th>
<th>Copper (Cu 101)</th>
<th>Aluminum (Al 1100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width, $t_p$ = 0.7 (ms)</td>
<td>Pulse width, $t_p$ = 1.4 (ms)</td>
<td>Pulse width, $t_p$ = 0.7 (ms)</td>
</tr>
<tr>
<td>Pulse repetition rate, $f_p$ (Hz)</td>
<td>Pulse repetition rate, $f_p$ (Hz)</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>50</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>100</td>
<td>V</td>
<td>sv</td>
</tr>
<tr>
<td>150</td>
<td>sv</td>
<td>V</td>
</tr>
</tbody>
</table>

$C$: cutting, $V$: large voids, $sv$: small voids, $-$: no voids

Fig. 1 shows the conditions of welding beads observed from the top view. The workpiece were melted and mixed more homogeneously for side butt welding. In the case of butt welding, cracks was observed from all $f_p$ values. On the other hands, no crack was observed from side butt welding.

It is suggested that, this phenomenon happened due to melted metals contraction. The metals contracted in horizontal direction and tend to create gap between the joining surfaces. When the two metals were clamped vertically, the metals contained in molten pool and contracted more in vertical direction and blocked by the solid material parts (Fig. 2). The heat conduction direction also gave big influence on the welding pool size and intermetallic material properties.

The succeeded welding joints were observed from cross sectional direction (Fig. 3). Under $P_{\text{avg}}$ and $f_p$ 100 W and 75 Hz, large voids were observed on the top area of melted zone. Bubbles trapped in the melted zone due to solidification occurred between two irradiation pulses. When the welding is performed using low $f_p$, higher laser peak power induced higher heat energy but provides longer chilling period between two irradiation pulses. This is the reason of failure when $f_p$ was 50 Hz. It became better with the existence of large voids when $f_p$ increased to 75 Hz. No void created when the $f_p$ increased to 100 Hz.
Fig. 3: Side butt welding cross section conditions

Under $P_{\text{avg}}$ 100 W, the melted zone shifted more to the Al 1100 side. Even though increasing the $f_p$ value could improve the melted zone conditions, the geometrical problem remains due to lack of heat energy. The heat generated in the Cu 101 sheet conducted instantly, created comparatively small melted zone. On top of that, Al 1100 tends to create larger melted zone due to low melting point and thermal conductivity.

From all parameter combinations, none of them managed to produce successful butt welding joint. Side butt welding was confirmed easier to be accomplished compared to butt welding. The results from those welding test has shown that higher $f_p$ and is effective to counter voids creation. Increasing the $t_p$ has been proven effective for melted zone crack problem. However, the value of $f_p$ and $t_p$ are correlated in inverse proportion. Increasing the $f_p$ will definitely reduce the range of allowable $t_p$ value. Well balanced value need to be identified to obtain voids and cracks free welding joint. Insufficient heat energy supplied will create melted zone with high hardness value. The creation of voids and oxidized particle are suggested to be the reasons of high hardness value.

Fig. 4 shown that the melted zone created using higher $P_{\text{avg}}$ has a lower hardness value which is better for welding joint strength. Lower different in hardness between melted zone and base material will consequently reduce the risk of crack generation at the melted zone boundary line.

![Fig. 3: Side butt welding cross section conditions](image)

![Fig. 4: Hardness comparison of welded region](image)
Conclusions
From the study, the next conclusions were derived.

i. Higher pulse repetition rate is better to reduce the crack generation.

ii. Higher pulse width is better to reduce voids and inhomogeneous intermetallic molten zone.

iii. The hardness of melted zone is higher than the base material. Less hardness increment can be obtained by applying larger average laser power.

iv. Further study need to be done on clamping methods to overcome the shrinkage and swift thermal conduction effect on copper sheet.

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References