Building a Simulation Model for Prediction of the Temperature Distribution in Pulsed Laser Spot Welding of Dissimilar Low Carbon Steel (1010) to AA 7020-T6 Aluminum Alloy

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Abstract. This paper describes the development of a computer model used to analyze the heat flow during pulsed Nd: YAG laser spot welding of dissimilar metals: low carbon steel (1010) to AA 7020-T6 aluminum alloy. The model is built using ANSYS FLUENT 3.6 software where all the environments simulated to be similar to the experimental environments. A simulation analysis based on conduction heat transfer out of the key hole where no melting occurs. The effect of laser power and pulse duration were studied. Three peak powers 1, 1.66 and 2.5 kW where varied during pulsed laser spot welding (in constant pulse energy), also the effect of two pulse durations 4 and 8 msec (in constant peak power) on the transient temperature distribution and weld pool dimension were predicted using the present simulation. It was found that the present simulation model can give an indication for choosing the suitable laser parameters (i.e. pulse durations, peak power and interaction time required) during pulsed laser spot welding of dissimilar metals.

Keywords: Laser Spot Welding, Simulation Model, Dissimilar Metals.

1. Introduction

Laser welding has been studied well for various metals and alloys in different configurations. An understanding of physical processes that take place during welding that affect the weld material properties and the around regions. The analysis of dissimilar metal joint offers a number of challenges arising out of complexities such as dissimilar metal properties, asymmetric weld pool shape, maxing of the molten metals, segregation and formation of intermetallic compound [1]. To stand with some of these challenges it is necessary to know the temperature field in and around the melt pool where the mechanical properties of the weld metal and the around region (HAZ) are highly dependent on the cooling rate of work piece, it is also essential for the understanding and modeling of the welding process [2].

Laser spot welding of dissimilar metallic joints are not well understood in the literature. The present work is concerned with the calculation of temperature fields around the melt pool of laser spot welding only, with the prediction of the weld dimensions using ANSYS FLUENT 3.6 software. Also the interaction time required for the spot welding process can be predicted.

2. Geometry Considered In The Present Simulation

Analysis of the interaction of laser beam with work piece is based on development of 3-D dimensional model for the geometry shown in figure 1.

3. Theoretical Formulation

Based on the first law of thermodynamics the equation for heat flow in three dimensional solid can be written as follow. [7]

$$\frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z}\right] + Q(x,y,z,t) , (1)$$

Where the geometries in the present work are two finite rectangular sheets, the first one is low carbon steel (1020) with the dimensions (30mm x 10mm x 0.8mm) mostly used for automotive applications [3] where placed above aluminum alloy (series 6061) sheet of (30mm x 10mm x 2mm) dimensions with wide range in marine and transportation applications [4]. The materials compositions are given in table 1. The physical properties of the alloys are listed in table 2 [5, 6]. Where the heat source being stationary during laser spot welding.

Table 1. Chemical Composition of The Alloys used in This Study in Wt%

<table>
<thead>
<tr>
<th>Element</th>
<th>Aluminum AA 7020-T6</th>
<th>Steel 1010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>-</td>
<td>0.45</td>
</tr>
<tr>
<td>Cu</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Mg</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Cr</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>-</td>
<td>99.1 min</td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Al</td>
<td>95.85</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Physical Properties of the Alloys

<table>
<thead>
<tr>
<th>Property</th>
<th>Aluminum AA 7020-T6</th>
<th>Steel 1010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (Wm⁻¹k⁻¹)</td>
<td>180</td>
<td>51.9</td>
</tr>
<tr>
<td>Specific Heat (J kg⁻¹k⁻¹)</td>
<td>896</td>
<td>486</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.82</td>
<td>0.17</td>
</tr>
<tr>
<td>Density (g cm⁻³)</td>
<td>2.7</td>
<td>7.85</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>652</td>
<td>1538</td>
</tr>
<tr>
<td>Thermal expansion(°C⁻¹)</td>
<td>23.6 * 10⁻⁶</td>
<td>11.7*10⁻⁶</td>
</tr>
</tbody>
</table>

Fig. 1 Geometry of the Present Work.
Where \( \rho \) is the density of the material, \( C(T) \) is the temperature dependent specific heat of the material, \( K(T) \) is the temperature dependent thermal conductivity \( Q(x,y,z,t) \) is the rate which heat is supplied to the solid per unit time per unit volume, \( T=T(x,y,z,t) \) is the resulting three dimensional time dependent temperature distribution in the material, \( t \) is the time, \( T_0 \) is the initial temperature, \( x, y, z \) is the Cartesian coordinate. For certain application (the present work) it can be assumes that \( k(T) \) and \( c(T) \) do not change dramatically with temperature, so they can be assumed constant for a particular time interval. For the present work the transient heat transfer analysis to be considered along transverse section that is shown in figure 1.

4. Boundary And Initial Conditions

At time \( t=0 \) the work pieces are at room temperatures. At time \( t>0 \) the following boundary conditions are applied.

On the top surface we use a Gaussian heat flux input and the heat loss from all the surfaces of the two sheets are considered.

The heat flux input on the top surface of the workpiece is given by

\[
Q(r) = \frac{q_0}{\pi q_0^2} \exp \left( -\frac{r^2}{q_0^2} \right),
\]

(2)

Where \( q(r) \) is heat flux at top, \( \eta \) is energy transfer efficiency (absorptive), \( q_0 \) is radius of the laser beam and \( r \) is the radial distance from the beam center. The absorptivity at temperature below the boiling point of steel was set to 50% for high laser powers and 30% for low laser powers [8].

The convective heat loss of the surfaces of the work pieces due to external flow condition can be expressed.

\[
Q_{conv} = \frac{h_{combined} A_s}{T - T_{amb}}.
\]

(3)

Where \( Q \) convective heat flux, \( h \) convective heat transfer coefficient, \( T \) temperature of the work piece, \( T_{amb} \) ambient temperature. The heat flux caused by radiation \( Q_r \) is

\[
Q_r = \varepsilon \sigma (T^4 - T_{amb}^4).
\]

(4)

Where \( \varepsilon \) is the emissivity of the material, and \( \sigma \) is the Stefan-Boltzmann constant.

Radiation heat loss from surface surround by air occurs parallel to convection heat loss between the surface and the air. Thus the total heat transfer is determined by adding the contributions of both heat transfer mechanisms [8, 9].

For simplicity and convenience this is often done by defining a combined heat transfer coefficient \( h_{combined} = h_{rad} + h_{conv} \) that includes the effect of both convection and radiation. Then the total heat transfer rate from the surfaces by convection and radiation is expressed as

\[
Q_{total} = h_{combined} A_s(T - T_{amb}),
\]

(5)

5. Results And Discussion

The present theoretical work aim to predicate the steel to aluminum transient temperature distribution during pulsed laser spot welding. The laser source is a pulsed (IQL-10) laser with a square pulse shape. The repetition rate used is 20 Hz. The laser beam radius \( r_0 = 0.205 \text{mm} \). The time step was used is 0.001 sec to converge the analysis. The mesh type was used is un structural mesh. Figure 2 shows the relation between the temperature and the axis of symmetry (y) for the power (1, 1.66, 2.5) KW respectively, at 6 sec interaction time with constant pulse energy (\( E_p = 10 \text{J} \)). It can be seen from this figure that the power 2.5 KW has no penetration depth on the steel sheet, where melting temperature 1838 K° does not reached. This is considered to be the result of high power beam heating up the top surface for a short pulse duration 4 msec which is insufficient for heat transfer by conduction. As shown in figure 2 powers (1, 1.66) KW have full penetration on both steel and aluminum sheets and this is due to long pulse duration (10, 6) msec respectively which are sufficient for heat transfer by conduction, and low cooling rate in the duty cycles for pulses compared with 2.5 KW, 4 msec pulse duration, where the cooling or dissipation of heat between pulses limits the efficiency of process [10]. Owing to the thermal diffusivity of steel and aluminum heat diffusion in aluminum will be more during the conduction phase during conduction process. Steel which has a lower thermal conductivity shows higher temperature gradient as shown in figure 2 where temperature gradient for 1 KW = 125 K° for steel while 85 K° for aluminum along axial direction (y) also temperature gradient for (1.66, 2.5) KW is 118 & 98 K° for steel respectively and 75 & 70 K° for aluminum respectively.

![Fig. 2 Static Temperature along the Axial Direction (y) at 6 Sec Interaction Time](image327x234 to 534x363)

![Fig. 3 Static Temperature along the Radial Direction (r) at 6 Sec Interaction Time](image327x575 to 533x709)

**Effect Of Pulse Duration.** Figure 4 and figure 5 show the effect of pulse duration in the fusion zone dimensions and contours of static temperature. Figure 4. shows temperature contours at 2.5 KW power, 4 msec pulse duration (\( E_p = 10 \text{J} \))& 4 sec interaction time. Where no formation for melting zone would be occurs. Figure 5 shows the contours of temperature at the same power 2.5 KW, 8 msec pulse duration (\( E_p = 20 \text{J} \)), 4 sec interaction time, where temperature contours show wide and deep melting zone and this due to increase pulse duration at the same power which results increasing of energy per pulse (\( E_p = 20 \text{J} \)) and this causes longer interaction time (during duty cycle) between laser and work piece created larger contours of melting temperature as shown in figure 5.
A computational model to solve heat equations for pulsed laser spot welding of low carbon steel (1010), 0.8 mm thickness to aluminum alloy (AA 7020-T6), 2mm thickness has been developed to provide inside into the process. In spite of some simplifying assumptions the present simulation model is able to capture some of the key features of the process such as differential heating of the two metals by predication of transient heat flow (temperature contours) around the fusion zone (HAZ) for the steel and aluminum sheet during welding process also the interaction time required for the welding process can be predicated. This work lays a strong foundation for future studies of some of complex issues in dissimilar joints.

6. References