TRANSMISSION LASER CONTOUR WELDING OF POLYCARBONATES WITH A MOVING LASER BEAM: PROCESS SIMULATION VIA FEM

Misra D.1, Acherjee B.2, Kuar A.S.2, Mitra S.2,
School of Laser Science & Engineering, Jadavpur University, Kolkata – 700 032, India1
Department of Production Engineering, Jadavpur University, Kolkata – 700 032, India2

Abstract: The present research contributes to the development of a three-dimensional transient heat transfer model for laser transmission welding of polycarbonate with a moving laser beam. Temperature dependent physical properties of the materials are taken into account during modeling. The heat input to the model is assumed to be a volumetric Gaussian heat source. Combined heat transfer boundary condition, based on natural convection and radiation, is imposed on model exteriors, which are exposed to surroundings. The commercial finite element code ANSYS® multiphysics is employed to obtain the numerical results. A subroutine is implemented in ANSYS parametric design language for moving the laser beam and changing the boundary conditions, accordingly. The results obtained is verified with experimental results and found in fair agreement.

Keywords: LASER TRANSMISSION WELDING, PLASTIC, FINITE ELEMENT MODELING, TEMPERATURE FIELD SIMULATION

1. Introduction

Laser transmission welding is an innovative plastic joining technology with well-known general advantages in laser material processing, as non-contact, flexible process, easy to control and automate. In this process a laser beam is directed towards two overlapping thermoplastic parts. The laser beam penetrates the top transparent part and is then absorbed and transformed into heat by the underlaying absorbing part. This heat is transferred to the transparent part via thermal conduction between the joining partners; consequently, surface layers of both the parts are heated up such as to produce melt and to be welded [1].

Numerical methods are in widespread use for either modeling or optimizing the performance of the manufacturing technologies. That has been advanced due to the large diffusion of the personal computer and the numerical algorithms. More than a few attempts have been made to simulate the laser transmission welding process by analytical and numerical techniques. An analytical heat transfer model of LTW is established by Kennish et al. [2], to predict the process capabilities and weld characteristics. Their model gives an approximate solution for peak temperature at the weld interface as a function of depth. Becker et al. [3] studied the heating phase of laser transmission welding of polypropylene using finite element method. Russek et al., [4] presented an analytical thermodynamic model of LTW. Ilie et al. [5] presented a study on effects of laser beam scattering phenomena in a semi-transparent polymer induced by their compositions in the LTW process. Mayboudi et al. [6] developed a two-dimensional heat transfer model of LTW of unreinforced nylon 6 in a T-like joint geometry. Van de Ven and Erdman [7] set a two-dimensional heat transfer model to study the LTW process of polyvinyl chloride. A three-dimensional thermal model of LTW solved with FEM is presented by Mayboudi et al. [8] for PA6 with lap joint geometry with a stationary laser beam. Coelho et al. [9] studied the beam spot influence in high speed laser lap welding of thermoplastic films. Acherjee et al. [10] presented a computational model for contour laser transmission plastic to metal welding with a moving heat source.

In this paper, a three-dimensional heat transfer model is developed with finite element code ANSYS® to simulate laser transmission welding of polycarbonates. Heating and cooling phase of welding is successfully modeled. All the major physical phenomena associated with the laser transmission welding process, such as, heat radiation, thermal conduction and convection heat losses are taken into account in the model development. The objective is set to predict the temperature distribution and weld bead profile during the welding process. The model is validated by experimental results and found in good agreement.

2. Process description

Contour welding variant of laser transmission welding process is studied in this paper. Principle of contour laser welding is illustrated in Figure 1. Contour welding involves relative motion between the laser beam and the thermoplastic parts in a direction perpendicular to the beam of the laser. This movement allows a continuously operating laser beam to irradiate a line of specific width, heating the material at the part interface into the melting range. Continuous movement along the weld seam allows the heated polymer to cool and form a joint. The energy delivered by the laser beam is largely governed by conduction into the surrounding material of the thermoplastic parts, for the duration of operation, and a small amount of heat is lost by natural convection and radiation from the parts surfaces.
The thickness and the width of the model in Figure 2 represent the true dimensions of the sample that is used for this study. Due to the presence of loading and material symmetries, only one half of the model is considered. Here, only the overlapped portion is considered as the heat flow to the region away from the bond area can be considered negligible, and hence those areas are not considered in the simulation.

3. Theoretical background

The transient temperature field generated during the laser welding is determined based on the mechanism of heat conduction:

\[ \rho \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_i, \]

(1)

where \( \rho \) is the material density, \( c \) is the specific heat, \( T \) is the temperature, \( t \) is the time, \( k \) is the thermal conductivity, \( \nabla \) is the gradient operator and \( q_i \) is the rate of internal heat generation per unit volume and is given by:

\[ q_i(x, y, z; t) = \begin{cases} 0 & \text{for transparent part} \\ (1 - R_a) K I_a \exp(-K z_a) & \text{for absorbing part} \end{cases} \]

(2)

where, \( R_a \) is the reflectivity of the absorbing material, \( K \) is the absorption coefficient of the absorbing material, \( z_a \) is the depth within the absorbing materials, and \( I_a \) is the laser intensity after passing through the transparent material, which can be further expressed as:

\[ I_a = \left(1 - R_t \right) P A \]

(3)

where, \( R_t \) is the reflectivity of the transparent material, \( P \) is laser power and \( A \) is area of beam spot.

For the heat transfer between the workpieces and the surrounding medium the boundary condition can be written as:

\[ -k(T) \nabla T = h(T_s - T) + \varepsilon \sigma (T_s^4 - T_i^4) \]

(4)

where, \( \nabla \) is the normal vector of the surface, \( h \) is the convection heat transfer coefficient, \( T_s \) is the surface temperature, \( T_i \) is ambient temperature, \( \varepsilon \) is the material emissivity, \( \sigma \) is the Stefan Boltzmann constant. Convective heat transfer coefficient, \( h \), is assumed to be 5 W/m²K [6]. Emissivity of polycarbonate is taken as 0.95 [11].

4. Finite element simulation

The geometric model is meshed using the SOLID 70 elements. The model is meshed non-uniformly to minimize the simulation time by reducing the total number of nodes. The mesh pattern is shown in Figure 2. Temperature dependent physical properties (thermal conductivity, specific heat and density) of the materials are used for thermal modeling. Polycarbonates, a glasslike polymer, only specularly reflect about 7% of the incident beam intensity [12]. Absorption coefficient of absorbing polycarbonate (containing 0.2 % weight carbon black pigment) is 15,873 m⁻¹. Absorption coefficient for absorbing polycarbonate material is calculated based on the optical penetration depth [4]. The materials are considered to be isotropic.

The heat generation is defined with regards to the laser flux change caused by the absorption of the laser energy by the plastic and is a function of laser power, material absorption properties, laser beam dimensions, welding speed, and laser flux distribution. The heat generation term varies with \( x, y, z \) and time and is calculated using Equation (2). A look-up table is made to create the heat generation input file in the form of a 3-D array and is a function of \( x, y \) and \( z \) coordinates. All the surfaces of the geometry except the symmetry plane are assumed to transfer heat by natural convection and radiation to the environment since they are exposed to the surroundings. The right vertical side is the plane of symmetry and thus insulated.

The moving load is implemented by a subroutine implemented in APDL language. The movement of laser beam is realized by assigning new coordinate values every time along the weld line to apply heat loads as a step. The load moves with time. The resulting effect imitates a continuously moving laser beam with a specified speed and heat flux value. The time is calculated based on the welding speed and heat source location. Thus, nodal temperature history is obtained as function of time steps. Temperature results are offset by 273 to get the temperature values in degree centigrade.

5. Validation of the model

The developed model is validated by the experimental results on the laser transmission welding by Russek et al., [4]. The simulated results of weld dimensions at the specified experimental condition are compared with the reference data in Table 1. The comparisons show that the current simulation results are in good agreement with the results from the experimental results.

![Table 1: Comparison of simulation and experimental results](image)

**Table 1: Comparison of simulation and experimental results**

<table>
<thead>
<tr>
<th>Line energy (J/m)</th>
<th>Weld dimensions (µm)</th>
<th>Simulated results</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WW</td>
<td>DT</td>
<td>DA</td>
</tr>
<tr>
<td>60</td>
<td>580</td>
<td>30</td>
<td>130</td>
</tr>
<tr>
<td>80</td>
<td>660</td>
<td>38</td>
<td>144</td>
</tr>
<tr>
<td>100</td>
<td>695</td>
<td>70</td>
<td>186</td>
</tr>
</tbody>
</table>

WW = weld width, DA = molten depth in absorbing part, DT = molten depth in transparent part. Fixed parameters: laser spot diameter = 600 µm, laser power = 10 W.

6. Results and discussion

A three-dimensional thermal model for a lap-joint exposed to a moving heat source is presented. The transient temperature distribution computed with the developed finite element model is presented for a laser power of 5 W with welding speed of 20 mm/s and laser beam diameter of 1 mm. Figure 3 (a) shows the temperature distribution at the symmetry plane of the geometry. It can be seen from the above figure that the temperature reaches to maximum of 493°C at the weld zone, which is greater than the glass transition temperature (150 °C) of polycarbonates. Given the glass transition temperature, the region in the contours plot temperature above 150 °C, shows the molten depth in both the polycarbonate parts from weld interface. It can be noticed that the maximum temperature occurs within the absorbing material. This phenomenon indicates volumetric absorption of the laser energy within the absorbing material. This induces asymmetric weld pool geometries.

On the condition of moving heat flux, the temperature distribution of the workpiece changes quickly with time and space. Figure 3 (b) shows the temperature distribution at weld interface. A preheated zone is observed ahead of the laser beam and a heated trail behind the laser beam. The maximum temperature is attained at the laser beam center and the heat generated at irradiation zone is gradually transferred to surrounding materials. The weld half width can be estimated from the above figure.

The influence of laser power and welding speed on the geometry of the weld bead and temperature field are also studied using the finite element model. Figs. 4-5 show the effect of power
and welding speed on maximum temperature \( \left( T_{\text{max}} \right) \) at weld interface. It is evident from these figures that the temperature increases with power but decreases with welding speed. The attainable temperature is a function of laser power density and irradiation time. That controls the heat input to the weld zone. Surface layers of both the parts start softening, as and when the temperature at weld interface reaches to 150 °C. It indicates the initiation of welding. However, the polycarbonate starts decomposing at 500 °C. The temperature above this range can cause partial degradation of the materials. The effect of power and welding speed on weld bead dimensions (viz. weld width, molten depth in transparent part and molten depth in absorbing part) is presented in Figs. 6-7. It can be noticed that the weld bead dimensions increase with laser power. This is due to the fact that greater volume of base material is melted with increased laser power, and consequently the volume of the weld zone increases.

The result shows that the welding speed has a negative effect on weld bead dimensions. This is due to the fact that with an increase in welding speed, the irradiation time is reduced and less heat is delivered with subsequent reduction in volume of the molten material characterized by a narrow weld.

**Conclusion**

A three-dimensional transient thermal model for a lap-joint exposed to a moving heat source is developed to simulate the laser
transmission welding process. The thermal model accounts for temperature dependent material properties. The materials considered are natural and opaque polycarbonate plaques. This three-dimensional model uses an energy balance method to calculate the temperature at nodes throughout the materials at specified time steps. The numerically computed results of weld pool dimensions are compared with the experimental results. The comparison shows a fair agreement between them, which gives confidence to use the developed model with acceptable accuracy. It is shown that this three-dimensional model is capable of predicting transient temperature distribution along the weld line in three-dimensional space for any combination of process parameters.

References


