Numerical modeling of an autogenous butt joint welding of low carbon ferritic steel sheets using a pulsed Nd: YAG laser beam

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Numerical modeling of an autogenous butt joint welding of low carbon ferritic steel sheets using a pulsed Nd: YAG laser beam

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Abstract

A three dimensional finite element model was developed for a pair of 2 mm thick low carbon ferritic steel sheets that are butt welded using a moving pulsed Nd: YAG laser beam. The incident laser beam modelled as a Hermit-Gaussian heat source and distributed spatially in TEM 00 mode as triangular shaped wave with pulse duration of 12mS. The model was computed to estimate geometry, mesh, surface temperature, isothermal contour, keyhole shape, temperature profile of the butt joint welding. The transient thermal responses across the weld joint and along the penetration depth are predicted and the results are discussed. The simulated keyhole has been compared to the cross section of the keyhole from experiment, predicted keyhole geometry at the top and bottom are almost similar to the experiment.

Keywords: Laser welding, pulsed Nd: YAG laser, Finite Element model, low carbon steel, Moving heat source, Temperature Distribution.

1.1 Introduction

Simulation of any numerical modeling gain great importance both for industrial and for scientific purposes to enable thorough understanding of processes. But, laser welding processes are not yet state of the art especially in the industrial production due to the complexity of parameters where a variety of different physical phenomena are coupled to each other. Usually, laser welding system requires correct value of operating parameters at right place and at right time to ensure successful welding process. So that the numerical modeling and its computation or simulation prior to the laser welding processes are of major importance to reliable extension of the process applicability to modern industrial demanding without enormous cost penalty as experiments are rather expensive [1].

1.2 Brief history about the modeling

The theoretical and experimental study of laser welding began in 1962, Since then, the use of laser welding has grown swiftly, as the new manufacturing possibilities became better understood. Further, many authors have used numerical techniques through Ordinary Differential Equations (ODE)/Partial Differential Equations (PDE) based on control volume method to evaluate the thermal and its related process during various welding methods. The history of most of the heat transfer models using numerical/analytical methods on laser beam welding its related process was briefed up to date [2,3]. Similarly, many important commercial and free coding have been developed and simulated for variety of materials processing including laser welding based on finite difference and finite element or control volume methods in multi dimensions, for instance, SIMPLE, SOLA, FIDAP [4], ABACUS [5], ANSYS [6,7,8,9], SYSWELD [10,11,12], FORTRAN [13], SYSTUS [14], PHOENICS [15], MAPLE software [16], ADINAT [17], ALBERTA [18] and FLUENT software [19]. Apart from the above, newly developed multi physics software’s like LUMET (for laser ultrasonic metallurgy), open FOAM and COSMOL allow to simulate the laser welding process dynamics, for instance, including keyhole oscillations during beam welding, texture of the sample, grain size and growth temperature of the austenite phase in steels [20].

1.3 Previous Models

Many models have been developed and simulated successfully using any one of computing codes as mentioned above, for instance, the effect of thermal cycling assisted void nucleation of Aluminium alloy [21], deformation in fillet-welded joint of ship building steels [22], transformation plasticity in steels [14], TIG and SAW welded thick steel sheets toward ITER TF coil case [9], the effects of turbulence on the transport characteristics associated with typical laser welding process of Cu-Ni dissimilar couples [23], the hardened zone in laser treatment of carbon steel [24], microstructural and mechanical testing of polymer (polyethylene) [25], distortions in chassis components of BMW series [11] and defects are to be expected during fusion welding such as formation of a centre line grain boundary, constitutional liquation at second phases and solidification cracking of super alloy IN718 [26]. Many simple calculations are given for a variety of engineering alloys, including steels, Al, Ti, and Ni based
super alloys [27] to predict the weld cross section in deep penetration [6], to prediction of final distortions of AA5083 thin sheets [5], measures power absorption in the keyhole and in the surface [8], based on keyhole and a coupled transient thermo mechanical analysis for the butt joint specimens of steel [10, 11,12], to evaluate temperature distribution, residual stress and distortion distributions during the welding process of structural components such as of austenitic stainless steel [28], Alloy 690 [7], low carbon steel sheet [29], tensile residual stress of spot welded of AISI 304 Stainless Steel [30], DH36 steel sheets [31], steel and aluminium [32], Zinc coated steel sheets [33], to reduce the possibility of fracture in the process of cutting glass by lasers, in the flat panel display industry [34] and alumina surface [29].

The main objective of this article is to present a three-dimensional finite element model developed using COMSOL multiphysics code for a pair of 2 mm thick low carbon ferritic steel sheets that are butt welded using pulsed Nd: YAG laser beam. The model presents simulated geometry, mesh, isosurface, thermal contour, keyhole shape, transient temperature distribution across the autogenous butt joint welding. The full penetration welding has to estimate based on the simulation results.

2.1 Physics of Heat Conduction during Welding Process

In this simulation work, we can determine temperature distributions in weld specimen in either side of the weldline while it is exposed to a moving laser beam during welding with known parameters. This will increase understanding of laser heat flow during welding which in turn will help in prediction and process improvement. Thus, the heat conduction principle is considered and solved as the main physics for this problem. The speed of heat conduction depends on the material density, specific heat capacity and thermal conductivity, the difference in temperatures, and the shape of the conductor in principle. Hence, the time dependent heat conduction equation is given by

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p U \nabla T = \nabla (K \nabla T) + Q \quad (1)
\]

Boundary condition for thermal insulation

\[
-\mathbf{n} \cdot (-K \nabla T) = 0 \quad (2)
\]

Where, Q-The heat flux or rate of heat flow per unit area across the surface in W/mm², K-A constant, coefficient of thermal conductivity in W/mm K, T-The increase in temperature above the surroundings in Kelvin, \(T_0\) - Ambient temperature in Kelvin, \(\partial T/\partial x\)-Temperature gradient, a function of distance at the point of irradiation in K/m, \(\rho(=m/A \delta x)\)-The density of a medium in kg/mm³, m-Mass of a substance in kg, \(C_p\)-Specific heat capacity of a substance in J/Kg K, \(\nabla(=\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z})\)-Laplacian operator, \(\alpha(=K/\rho s)\)-Thermal diffusivity of a work piece in mm²/sec, \(\partial T/\partial t\)-The time rate of change of temperature in the moving coordinate system in K/sec, x, y, z- Cartesian coordinates of the geometry, \(U_y\) - Welding velocity in y-direction in mm/s.

2.2 Model Definition

Pair of low carbon ferritic steel sheets having the dimension 40 mm (Length) x 10 mm (Breadth) x 2 mm (thickness) is modeled in butt joint configuration. The wavelength of \(\lambda = 1.064 \text{ µm} \) pulsed Nd: YAG laser beam having focused waist diameter of 0.451 mm (spot dia) with an average peak power 2100 Watts is fixed at the point (10, 3, 1). The schematic of the laser welding specimens modeled to move linearly with the translational velocity of 3mm/sec for 10 sec along y-axis to reach butt joint distance along the weldline starting from point (10, 3, 1) towards end point (10, 40, 1) are shown in Figure 1. The entire system is assumed under good thermal isolation from the environment except the proposed boundaries for laser spot area on the specimen across the weld joint. The only source of heat loss is from the welding sheets via radiation to the ambient temperature fixed as 293.15K.

![Figure1. Ferritic steel sheets geometry and focused laser spot position at (10, 3, 1) on work plane.](Image)

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2.3 Laser Beam Profile

The laser beam is modelled as a Hermite-Gaussian pulse spatially distributed at Transverse Electro Magnetic (TEM_{00}) mode heat source. Here, we use the analytical function (an1) to set up the Gaussian Pulse profile model, which enforce that the integral under the curve equals unity. The location of the focal point is assumed as 10 mm in x-axis, 3 mm in y-axis and 0 in z-axis. Hence, the Hermite-Gaussian pulse profile and spatially distributed at TEM_{00} mode are plotted as shown in figure 2. The global parameters used in this model are given table 1. The triangular pulses are generated using analytical function (an2) with the lower limit of half pulse width and upper limit one and half pulse width. The focal point is targeted with the sequences of pulses as shown in figure 3 to define its position along the Y-axis over required simulation time. Pair of low carbon ferritic steel sheet specimens having dimensions 2 mm (Z-thickness) X 10 mm (X-width) and 40 mm (Y-breadth) is assigned in the governing heat transfer equation.

<table>
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<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0</td>
<td>0[mm]</td>
<td>Pulse center x-coordinate</td>
</tr>
<tr>
<td>y0</td>
<td>3[mm]</td>
<td>Pulse center y-coordinate</td>
</tr>
<tr>
<td>sigx</td>
<td>0.225[mm]</td>
<td>Pulse x standard deviation</td>
</tr>
<tr>
<td>sigy</td>
<td>0.225[mm]</td>
<td>Pulse y standard deviation</td>
</tr>
<tr>
<td>Q0</td>
<td>2100[W]</td>
<td>Total laser power</td>
</tr>
<tr>
<td>L1</td>
<td>10[mm]</td>
<td>Sheet size 1</td>
</tr>
<tr>
<td>L2</td>
<td>10[mm]</td>
<td>Sheet size 2</td>
</tr>
<tr>
<td>Lz</td>
<td>2[mm]</td>
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</tr>
<tr>
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<tr>
<td>time_step</td>
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<td>Time to store solution</td>
</tr>
<tr>
<td>end_time</td>
<td>10[s]</td>
<td>Last time step</td>
</tr>
</tbody>
</table>

Figure 2: Profile of Hermite-Gaussian pulse spatially distributed at TEM_{00} mode.

Figure 3: Triangular pulses define its position along translational path in welding direction

2.4 Mesh Model

The low carbon ferritic steel sheets are formed as union in butt joint position at the relative repair tolerance about 1 µm and is meshed using a predefined normal free tetrahedral 1 method that would give slightly more accurate predictions general physics parameter and minimum temperature would not be greatly affected, which has finalized geometry of 2 domains, 11 boundaries, 20 edges, and 16 vertices. Before processing, complete mesh consists of 765 domain elements, 536 boundary elements, and 106 edge elements with maximum element size of 3.5 mm and minimum of 0.63 mm at the growth rate of 1.5 as shown in figure 4.
3. Thermal profile of pulsed laser welding

The simulated profiles of temperature distribution by means of average surface temperature and thermal contours by means of average isosurface temperature onto the entire surface of Low carbon ferritic steel sheets during pulsed laser Nd: YAG welding process at the translational velocity of 3mm/sec with an Average Peak Power (APP) = 2100 Watts are presented as shown in figure 5.

Figure 5: (a) Temperature distribution by means of average surface temperature and (b) thermal contours by means of average isosurface temperature of low carbon ferritic steel sheets simulated for pulsed Nd: YAG laser welding.

Those images presented above are indicating the capability of the proposed numerical modeling to perform a successful prediction of different regions such as keyhole, melt pool and heat affected zone in a weld joint. Estimation of temperature depended thermophysical properties of these regions are mostly concerned to find its effects on the changes on the microstructure and consequent changes in mechanical properties through heat transfer and fluid flow. Though, the thermal profile gives better understanding about the temperature distribution of this welding, it is interesting to see that how the transient thermal responses from pulsed laser welding process. So that the transient thermal responses across butt joint are probed for various probe points by means of average temperature in radial and vertical directions. The probed parameters are recorded and plotted in the form of graphs as shown in figure 6 and 7.

3.1 Temperature distribution in radial directions from weld joint

The locations of the probe points to sense the temperature distributions identified across butt joint welding of Low carbon ferritic steel sheets during pulsed laser welding. Accordingly, the transient thermal responses are plotted for various probe points by means of average temperature across butt joint are recorded in the form of graphs from 1 to 6 as shown in figure 6. It is noted that transient temperature distribution has elevated in different forms and shapes due to the consequences of the energetic laser pulses irradiated on top of the butt joint. This is observed that from the graph 4 the transient temperature profile is wavy and having maximum heat fluctuations due to probe points in and around the region of spot diameter.
On the other hand, very less heat fluctuation are observed in graph 3 and 5 and further reduced in graph 2 while further increase in radial distance as a function of X-axis from the laser spot diameter on both sides where there is no direct irradiation takes place. It may happen due to the phenomenon of destructive interference by overlapping among the transient heat waves which are produced by laser pulsation one after another. Hence, it may reduce the range of subsequent melting of specimens in radial distances due to resistance. In practical, it has observed that the melt pool region is limited to very few millimetres in pulsed laser welding. Next to the melt pool i.e., in heat affected zone, temperature is increased almost linearly as shown in graphs 1 and 6 when the heat is propagated via thermal conduction through free electrons and phonons where no melting occurs. Subsequently, temperature reaches to thermal balance with ambience condition and the laser irradiation does not have any practical effect further beyond heat affected zone. Therefore, it does clearly understand that temperature is spontaneously increased in the region near weldline and decreased gradually around the weldline region towards heat affected zone during welding.

3.2 Temperature Distribution in the direction of Laser Irradiation

There are two probe points along joint edges at the top and bottom of the butt joint in the welding direction. Those probe point values are plotted as time–temperature graphs as shown in figure 7.
Figure 7: Temperature distribution along entire top bead (a) and bottom bead (b) during welding.

It is evident that the transient temperature distribution across the butt joint is symmetric for similar low carbon ferritic steel sheets as discussed above. But, most of the beam energy transferred to the direction of irradiation rather than its conducts radially because of many complexity of phenomena involves during laser material interaction. Since, it is a nonlinear laser–material interaction, assume that all the probe points are individual layers, hence, the difference of heating between the layers are due to the temperature gradient occurs as a function of thickness (Z-axis) i.e., far from the point of laser irradiation. At the top layer where there is direct heat input from the laser, remaining layers are receiving the heat energy by various phenomena such as absorption, heat conduction, melt dynamics, vapour dynamics and phase transition. Figure 7 reveals the full penetration of entire thickness throughout the joint length since the temperature found well above the melting point of the specimen.

Figure 8: (a) Simulated keyhole profile and (b) Experimentally obtained keyhole profile of low carbon ferritic steel joint.

Therefore, we compared simulated keyhole profile with an actual keyhole obtained experimentally as shown in figure 8. Once again, figure 8 also confirms the full penetration of welding that is essential for a perfect welding to ensure the adequate microstructure and mechanical properties required for various working environments.

4. Conclusion
A three dimensional finite element model was developed using comsol multiphysics code for a pair of 2 mm thick low carbon ferritic steel sheets by pulsed Nd: YAG laser beam. The model was computed to estimate geometry, mesh, surface temperature, isothermal contour, keyhole shape, temperature profile of the butt joint. The transient thermal responses across the weld joint and along the penetration depth are predicted and the results are discussed. The simulated keyhole has been compared to the cross section of the keyhole from experiment, predicted keyhole geometry at the top and bottom are almost similar to the experiment. Therefore, full penetration of weld joint is verified and found that has close agreement with experimental result.

5. Acknowledgment
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discussions throughout this work. The figures and data’s used in this paper are from the original work from the author.

6. Reference


