Simplified model for numerical simulation of laser metal deposition process with beam oscillation

Sergei Ivanov¹, Antoni Artinov², Ekaterina Valdaytseva¹

¹ St. Petersburg State Marine Technical University, Russia
² Federal Institute for Materials Research and Testing, Germany
No oscillation

Beam oscillation in welding allows to:
- reduce porosity;
- increase efficiency of the process;
- Increase gap bridging ability.

Circular oscillation

Deposition rate can be improved by the modification of the shape and size of the molten pool through the optimization of laser beam power distribution.

Lateral oscillation

Now available mathematical model for simulation of laser metal deposition (LMD) process requires solution of the three-dimensional (3D) coupled hydrodynamic and heat conduction problem which takes much time.

Previously reported simplified model baser on analytical solutions of heat conduction problem and empirical calculation of shape of deposited layers have a weak accuracy.

The aim of the study is to develop simplified model for numerical simulation of temperature field and shape of deposited parts during LMD.
Flowchart of the developed simulation procedure

In order to obtain shape of deposited layer the following two sequentially-coupled problems was solved:
- Heat conduction problem;
- Free surface problem.

MATLAB was used for implementation of the developed simulation procedure.

An average computational time for obtaining shape of single layer is about 400 s using PC with Intel Core i7-2600 processor, 3.4 GHz clock frequency and 12 Gb memory.
The following assumptions were made:

- non-stationary phenomena at the beginning and the end of a deposited layer are not considered;
- laser beam is described as a surface heat source of power density \( q_{2L} \);
- vaporization and radiation are not considered;
- thermophysical properties of the substrate and model metal are known functions of temperature.

Due to thermophysical properties is temperature dependent non-linear heat conduction equation was solved using finite difference method (FDM).

Formulation of the nonlinear quasi-stationary heat conduction problem in Cartesian coordinate system is the following:

\[
0 = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + v c_p \frac{\partial T}{\partial x} + q_3
\]

\( \lambda \) is the thermal conductivity
\( c_p \) is the volumetric heat capacity
\( v \) is the deposition speed
Model for Oscillation Beam Heat Source

A = n \cdot R_b
A – amplitude [mm]
R_b – beam radius [mm]

q_e = \eta \cdot \int_0^{+\infty} \int_{-\infty}^{+\infty} q_2 \, dx \, dy
q_2 – heat flux [W m\(^{-2}\)]
\eta – heat source efficiency

Lateral oscillation

q_2(x, y) = \begin{cases} 
q_{2\text{max}} \exp\left(-\frac{x^2 + y^2}{R_b^2}\right) & \text{if } |y| \geq A \\
q_{2\text{max}} \exp\left(-\frac{x^2}{R_b^2}\right) & \text{if } |y| < A
\end{cases}

q_{2\text{max}} = \frac{\eta \cdot q}{\pi \cdot R_b^2} \cdot \frac{\sqrt{\pi}}{\sqrt{\pi} + 2 \cdot n} = q_{2m \cdot n} \cdot k_A

Circular oscillation

q_2(r) = \frac{q_{2\text{max}}}{2} \left\{ \exp\left(-\frac{(A-r)^2}{R_b^2}\right) + \exp\left(-\frac{(A+r)^2}{R_b^2}\right) \right\}

r = \sqrt{x^2 + y^2}

q_{2\text{max}} = \frac{\eta \cdot q}{\pi \cdot R_b^2} \cdot \frac{1}{\exp(-n^2) + n \cdot \sqrt{\pi} \cdot \text{erfc}(n)} = q_{2m \cdot n} \cdot k_A

Peak heat flux value of the oscillating beam can be represented as a product of the peak heat flux of normally distributed heat source and coefficient \(k_A\) describing the ratio of amplitude to beam radius.
Coefficient $k_A$ shows how the maximum heat flux changes in going from normally distributed heat source to circular or lateral heat source. On increasing the oscillation amplitude from 0 to $R_b$, the heat flux decreases rapidly to 53% for the lateral heat source and to 73% for the circular heat source.

Effect of oscillation amplitude on molten pool
Cross section shape of deposited layer can be obtained by the solution of the equilibrium equation of the liquid phase in the gravity field:

$$\sigma \kappa = -\rho \ g \ z_o + C$$

- $\sigma$ is the surface tension.
- $\kappa$ is the curvature of the free surface of molten metal.
- $\rho$ is the gravity constant.
- $g$ is the density.
- $C$ is the Lagrange multiplier.

Curvature of the deposited layer describing by the curve $y_o = f(z_o)$ can be defined as follows:

$$\kappa = \frac{f''}{\left(1 + f'^2\right)^{3/2}} = \frac{1}{f'} \left(\frac{1}{1 + f'^2}\right)'$$

Represent curve in parametric form:

$$\begin{cases} z_o = z_o(\varphi) & 0 \leq \varphi \leq \alpha \\ y_o = y_o(\varphi) \end{cases}$$

After manipulation the following system of ODE was obtained:

$$\begin{cases} \frac{dz_o}{d\varphi} = \frac{\sin \varphi}{B} \\ \frac{dy_o}{d\varphi} = -\frac{\cos \varphi}{B} \end{cases}$$

$$B = \frac{\rho \ g \ z_o}{\sigma} + C$$

Boundary conditions are defined by the known mass of deposited metal and width of molten pool.
**Example: Laser Metal Deposition of Ti-6Al-4V with Lateral Beam Oscillation**

Process parameters:
- power \( q = 2300 \text{ kW} \);
- speed \( v = 30 \text{ mm s}^{-1} \);
- beam radius \( R_b = 1.5 \text{ mm} \);
- amplitude \( A = 1.25 \text{ mm} \);
- powder flow rate \( m = 0.42 \text{ g/s} \)

Process parameters:
- power \( q = 2100 \text{ kW} \);
- speed \( v = 20 \text{ mm s}^{-1} \);
- beam radius \( R_b = 1.5 \text{ mm} \);
- amplitude \( A = 1.25 \text{ mm} \);
- powder flow rate \( m = 0.33 \text{ g/s} \)
Example: Laser Metal Deposition of Ti-6Al-4V with Lateral Beam Oscillation

Process parameters:
- power $q = 2300 \text{ kW}$;
- speed $v = 30 \text{ mm s}^{-1}$.
- beam radius $R_b = 1.5 \text{ mm}.
- powder flow rate $m = 0.42 \text{ g/s}$.
Example: Laser Metal Deposition of Ti-6Al-4V with Lateral Beam Oscillation

Process parameters:
- power $q = 2300$ kW;
- speed $v = 30$ mm s$^{-1}$;
- beam radius $R_b = 1.5$ mm
- amplitude $A = 1.25$ mm
- powder flow rate $m = 0.42$ g/s

Temperature field at the top surface of deposited part

Thermal cycles at central point of layers № 1 and 5

Temperature field at the top surface of deposited part
Conclusions

1. The proposed models for laser metal deposition allow to determine relationship between process conditions and shape of fabricated part.

2. On increasing the lateral oscillation amplitude up to laser beam radius the heat flux of heat source decrease rapidly to 53%.

3. It is shown that beam oscillation amplitude effects on shape deposited wall. Beam oscillations allow to increase of the molten pool width and therefore increase deposition rate.

4. Shape of molten pool and temperature field changes when distance from the substrate increased.