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

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Abstract: A model of laser metal deposition with beam oscillation has been developed. The proposed model consists of two coupled sub-models calculating the heat transfer in the deposited part and the free surface of the molten pool, respectively. The heat transfer simulation of the deposited part solves a three-dimensional quasi-stationary heat conduction problem. The free surface of the molten pool are determined by solving the Laplace-Young equation. The developed model enables the layer-by-layer prediction of the shape of the deposited part and the resulting temperature field. It is shown that for an oscillation amplitude equal to the beam radius the peak value of the heat flux decreases by about 53% and 73% in the case of lateral oscillation and circular oscillation, respectively. Lateral oscillating laser beam results in a higher penetration depth due to the higher thermal efficiency. The amplitude of the laser beam oscillation effects the shape of the deposited wall and the deposition rate. A good correlation between the numerically calculated and experimentally observed results is obtained.

1. Introduction

The laser metal deposition (LMD) is an advanced manufacturing technology, which enables the production of complex parts of higher dimensions and partially or completely eliminate the need for the machining and welding [1-4]. The use of the LMD as an everyday industrial tool is still prevented by the high number of process parameters which influence the quality of the deposited parts. A development of an optimal process parameters requires a lot of expensive experimental trials. For this reason, numerical simulation is used to reduce the number of experiments and hence to improve the quality and efficiency of the process. The state of the art numerical models in the field of LMD consider only the physical phenomena during the deposition of a limited number of layers [5-7]. Due to the long computational times, such models are well suited for optimizing the LMD process, by investigating its influencing factors. On the other hand, there are simplified models based on analytical solutions and empirical relations [8, 9]. These models offer lower accuracy and are used for a rough prediction of the temperature field during deposition of the first layer.

Using beam oscillation during welding and brazing a reduction of the porosity, an increase of the gap bridging ability and the process efficiency are obtained [10, 11]. The deposition rate of a LMD process can also be increased by modifying the size and shape of the molten pool through beam



oscillation [12]. Another positive effect is the decrease of the waviness of the surface of the deposited wall. It is especially important in the case of a titanium alloys, which are widely used for the production of thin-walled components. These alloys, e.g. Ti-6Al-4V, offer a high corrosion resistance and find an application in the aerospace industry. Nevertheless their machining is challenging due to the low thermal conductivity and sticking phenomena.

The aim of the present work is to develop a simplified model for the numerical simulation of the laser metal deposition process with beam oscillation. Hereby the precise and fast prediction of the shape of the deposited parts and the temperature field during the process is the focus of this investigation.

2. Mathematical model

2.1.1. Simulation procedure

Since the physics of laser processing are strongly coupled and strongly nonlinear, the equations used for the modelling of the laser metal deposition must be simplified in order to guarantee numerical stability and fast computational time. The thermophysical material properties play a crucial role in the modelling of the temperature field and the fusion zone. The material properties used in the simulation are summarized in Figure 1 [13]. The flowchart of the multi-physics simulation can be seen in Figure 2. Here, the solver sequences used to obtain the solution for a single layer are presented. The sequentially-coupled quasi-stationary heat conduction analysis followed by the calculation of the static free surface problem are performed using the finite difference method (FDM). For this simulation, the developed in-house code is implemented using the commercial programming language MATLAB.

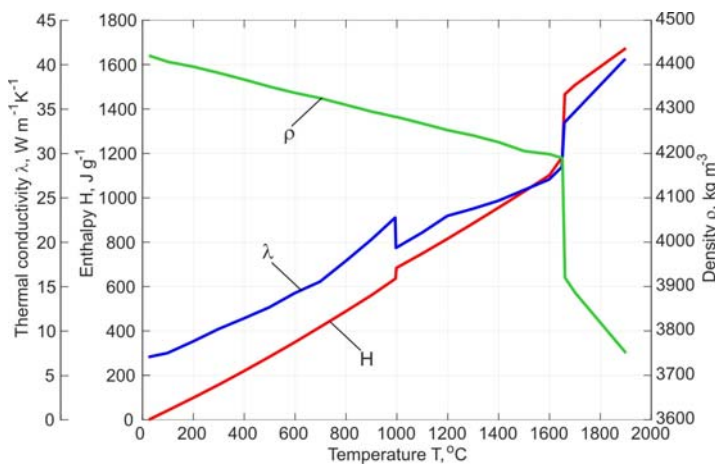


Figure 1. Thermophysical properties of Ti-6Al-4V used in the model.

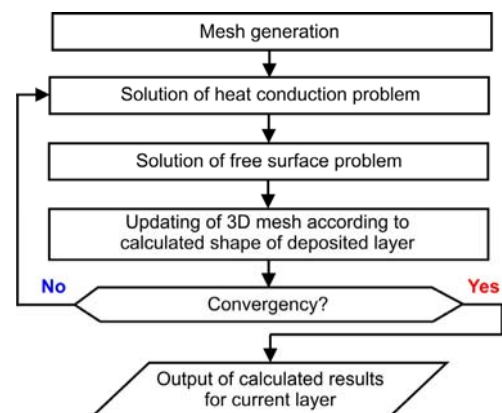


Figure 2. Flowchart of the multi-physics simulation used for the calculation of a single layer.

2.1.2. Heat conduction problem

In order to improve the stability and the computational time of the model, the following assumptions are made:

- non-stationary phenomena at the beginning and the end of a deposited layer are neglected
- vaporization and radiation are not considered
- thermophysical properties are known functions of the temperature, see Figure 1.

Under the assumptions made, the formulation of the nonlinear quasi-stationary in Cartesian coordinates becomes:

$$\frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + \nu c \rho \frac{\partial T}{\partial x} + q_3 = 0, \quad (1)$$

where λ is the thermal conductivity, $c\rho$ is the volumetric heat capacity, ν is the scanning speed and q_3 is the volumetric heat source power.

The boundary conditions at the top surface of the calculation domain are the following:

$$-\lambda \frac{\partial T}{\partial z} = q_{2L}(x, y). \quad (2)$$

Here q_{2L} is the heat flux of the laser beam.

First-order boundary conditions i.e. temperature distribution are applied at the bottom surface and the side surfaces. The temperature field is calculated according to the well-known analytical solution presented in [14].

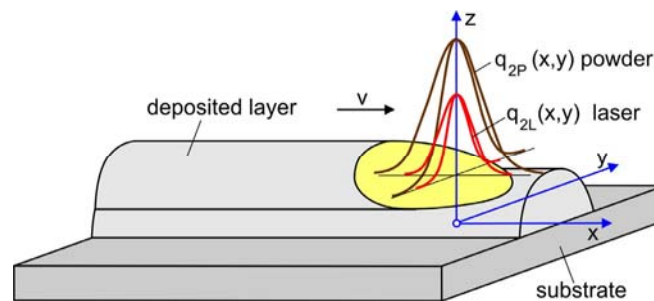


Figure 3. Schematic of the computational domain and the reference frame.

2.1.3. A heat source model for an oscillating laser beam

The normally distributed heat flux of the laser beam without oscillation is defined by the peak value of the heat flux and the laser beam radius:

$$q_2(x, y) = q_{2m\ n} \exp\left(-\frac{x^2 + y^2}{R_b^2}\right), \quad (3)$$

$$q_{2m\ n} = \frac{\eta \cdot q}{\pi \cdot R_b^2},$$

where $q_{2m\ n}$ is the peak value of heat flux and R_b is the normal radius of heat source.

In the case of an oscillating laser beam the heat flux distribution depends not only on the previously discussed parameters but also on additional parameter related to the oscillation amplitude. The heat flux of the oscillating laser beam, see Figure 4 and 5, can be mathematically represented by the following equations:

- for lateral oscillated laser beam:

$$q_2(x, y) = \begin{cases} q_{2\max} \exp\left(-\frac{x^2 + y^2}{R_b^2}\right) & \text{if } |y| \geq A \\ q_{2\max} \exp\left(-\frac{x^2}{R_b^2}\right) & \text{if } |y| < A \end{cases} \quad (4)$$

- for circular oscillated laser beam:

$$q_2(r) = \frac{q_{2\max}}{2} \left\{ \exp\left[-\frac{(A-r)^2}{R_b^2}\right] + \exp\left[-\frac{(A+r)^2}{R_b^2}\right] \right\} \quad (5)$$

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

Here $q_{2\max}$ is the peak value of heat flux and A is the oscillation amplitude.

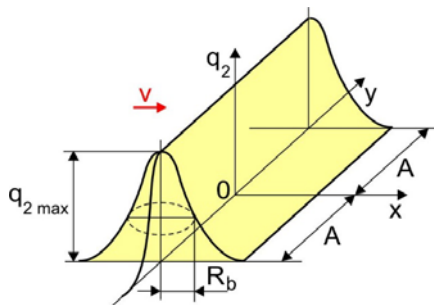


Figure 4. Heat flux distribution of lateral oscillated laser beam.

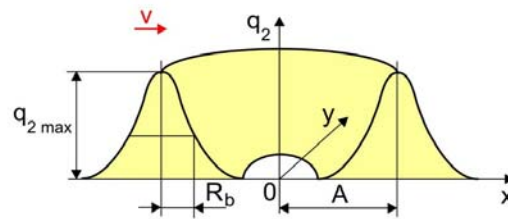


Figure 5. Heat flux distribution of circular oscillated laser beam.

The effective heat power of the heat source q_e can be evaluated as follows:

$$q_e = \eta \cdot q = \eta \cdot \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} q_2(x, y) dx dy \quad (6)$$

where η is the heat source efficiency and q is the heat source power. The process efficiency depends on numerous factors such as material of substrate, surface preparation and local temperature field. The temperature dependent efficiency is used according to experimental data [15].

Substituting equations (4) and (5) into eq. (6) and representing the oscillation amplitude as a function of the laser beam radius $A = n \cdot R_b$, the peak value of the heat flux is obtained:

- for lateral oscillated laser beam:

$$q_{2\max} = q_{2m\ n} \cdot \frac{\sqrt{\pi}}{\sqrt{\pi} + 2 \cdot n} = q_{2m\ n} \cdot k_A \quad (7)$$

- for circular oscillated laser beam:

$$q_{2\max} = q_{2m\ n} \cdot \frac{1}{\exp(-n^2) + n \cdot \sqrt{\pi} \cdot \operatorname{erfc}(-n)} = q_{2m\ n} \cdot k_A \quad (8)$$

The coefficient k_A can be used to analyze the effects of the oscillating amplitude on the heat flux density, see Figure 6. By setting the parameter n to one the amplitude will be equal to the laser beam radius. In this case the peak of the heat flux decreases by about 53% by lateral and 73% by circular oscillation of the laser beam, respectively. An increase of the amplitude leads to an increase of the weld pool width and length and a decrease of the penetration depth, see Figure 7. Note, that the lateral oscillating laser beam has a higher penetration depth due to the higher thermal efficiency.

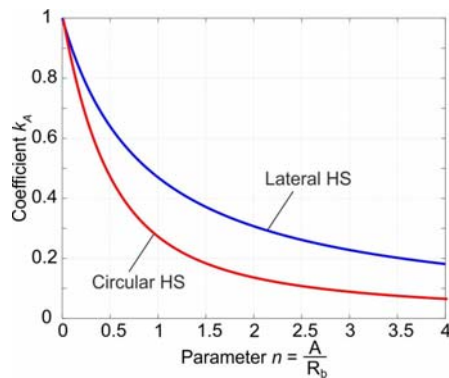


Figure 6. Coefficient k_A as a function of parameter n .

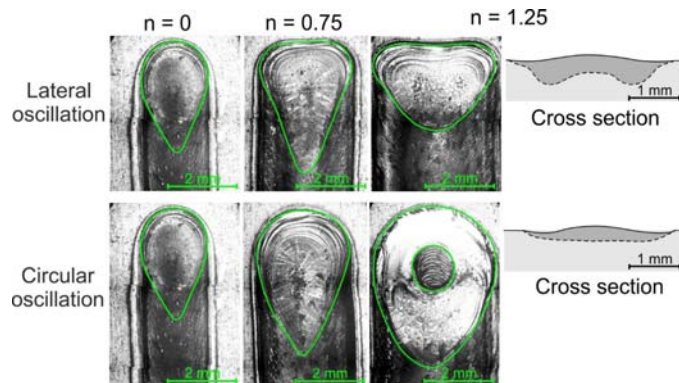


Figure 7. Effect of the oscillation amplitude on the molten pool shape.

2.1.4. Free surface calculation

The equilibrium equation of the liquid phase in the gravity field can be used to predict the cross section of the deposited layer. This equation links the curvature of the free surface of the molten pool and the surface tension by the hydrostatic pressure, see Figure 8 [16]:

$$\sigma \kappa = -\rho g z_o + C \tag{9}$$

where σ is the surface tension, κ is the curvature of the free surface, ρ is the density, g is gravity constant and C is the Lagrange multiplier.

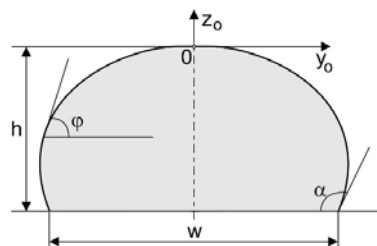


Figure 8. Schematic of the free surface shape of the deposited layer.

The cross-sectional shape of the deposited layer described by the curve $y_o = f(z_o)$ can be defined as follows:

$$\kappa = \frac{f''}{(1+f'^2)^{3/2}} = \frac{1}{f'} \left(\frac{1}{1+f'^2} \right)' \tag{10}$$

A parametric form of the curve can be given as:

$$\begin{cases} z_o = z_o(\varphi) \\ y_o = y_o(\varphi) \end{cases} \quad 0 \leq \varphi \leq \alpha \tag{11}$$

After manipulations, the following system of ordinary differential equations is obtained:

$$\begin{cases} \frac{dz_o}{d\varphi} = \frac{\sin \varphi}{B} \\ \frac{dy_o}{d\varphi} = -\frac{\cos \varphi}{B} \end{cases} \quad (12)$$

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

The boundary conditions for the obtained ODEs is the following:

- 1) $z_o(0) = 0; y_o(0) = 0$
- 2) $y_o(-h) = 0.5w$,

where w is the width of the molten pool.

- 3) $2 \int_{-h}^0 y_o dz_0 = S_{lay}$,

where h is the calculated height of the deposited layer and S_{lay} is the area of the deposited layer.

The area of the deposited layer is the sum of areas of the melted substrate and the deposited per unit time filler material. The latter can be determined by integrating the mass flux of the gas-powder jet over the molten pool surface. The powder flux distribution can be described by the following expression:

$$q_{2P}(x, y) = \frac{q_P}{\pi r_P^2} \exp\left[-\frac{x^2 + y^2}{r_P^2}\right], \quad (13)$$

where q_P is the mass flow of powder and r_P is the effective radius of the gas-powder jet.

The desired shape of the deposited layer is determined by the previously calculated molten pool width, the area of the deposited metal and the Lagrange multiplier satisfying boundary condition. The system of ODEs (12) is solved by the fourth and fifth-order and Runge-Kutta method.

3. Example

A thin Ti-6Al-4V wall was deposited by LMD process in 100% argon atmosphere onto a Ti-6Al-4V substrate. The following process parameters were used: laser power of 2.3 kW, deposition rate of 30 mm s⁻¹, beam radius of 1.5 mm, lateral beam oscillation amplitude of 1.25 mm and powder flow rate of 0.42 g s⁻¹. After the deposition of each layer, the deposited wall was cooled down natural convection and heat conduction to 60-80 °C. The average value of the surface tension of the liquid titanium alloy in the temperature range between 1670 – 1770 °C was constant and equal to 1.55 N m⁻¹ [17].

A comparison of the experimentally measured and numerically calculated width of the deposited wall show good correlation and can be seen in Figure 9. A deviation is observed near the center line of the wall. This is due to the neglected convection in the molten pool and the pressure of the gas-powder stream, which are not considered in the model. The effects of the process parameters on the shape of the deposited wall and the temperature field are analyzed numerically, see Figure 10. An increase of the oscillation amplitude by about 40%, from 1.25 mm to 1.75 mm, leads to a decrease of the width of the deposited material due to the decreasing thermal efficiency of the heat source. Note here, that the deposition rate is also decreasing, due to the decreasing molten pool area and therefore deteriorating powder catchment efficiency. By reducing the oscillation amplitude by 40% practically the opposite effect is observed.

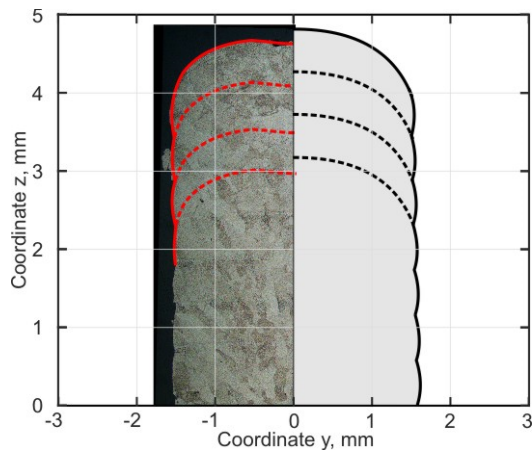


Figure 9. Experimental (left) and calculated (right) cross section of the deposited wall.

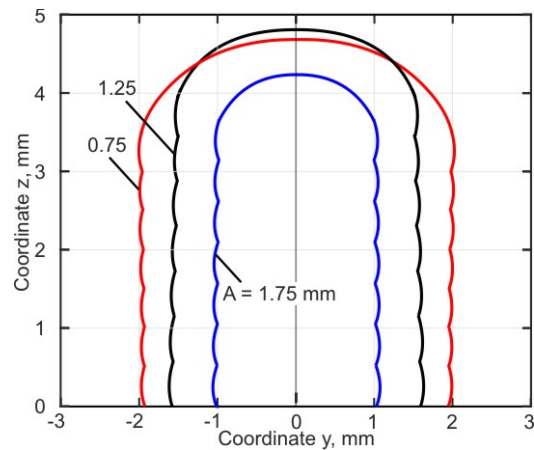


Figure 10. Effect of the amplitude of lateral oscillated laser beam on the cross section of the deposited wall.

4. Conclusions

The aim of the present investigation is to develop a simplified numerical model for the prediction of the shape the temperature field of LMD produced parts. The advantages of this approach are the reduced computation time and good accuracy.

It is shown that the oscillation amplitude has a strong influence on the value of peak heat flux. By setting the amplitude to be equal to the value of the laser beam radius the peak heat flux decreases by 53% for lateral oscillation and by 73% for circular oscillation. Lateral oscillating beam has a higher penetration depth due to higher thermal efficiency. The laser beam oscillation amplitude effects the shape of the deposited wall and the deposition rate in the process. The proposed model is used for the analysis of the effects of the process parameters on the resulted shape of the deposited wall. A good agreement between the numerical results and the experimental measurements is achieved.

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