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# Computer simulation of hydrodynamic and thermal processes in DMD technology

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**Abstract**

The article deals with theoretic basis of melt pool formation during DMD technology, when shape and size of melt bath depend on mutual influence of heat transfer from laser heating, dynamic of melt free surface with consideration of Marangoni effect and spatial distribution of mass flux, coming with gas-powder jet. The model of melt pool has been developed in approximation of boundary layer flow. On the surface the condition of press balance with consideration of Laplace, gravity and thermocapillary forces has been applied. Shape and position of melt pool bottom is given by solution of heat transfer tack with consideration of preheating temperature from previous pass, which is one of model parameters. The model allows to simulate process of wall growing in DMD process in steady-state approximation. Experimental verification of developed model is also discussed.

Keywords: Laser metal deposition; heat transfer; hydridynamics; simulation;

## 1. Introduction

Direct laser deposition now became more and more prospective technology of additive manufacturing for production of parts for aircraft and rocket engines, as mention *Turichin et al*, ship fittings, propellers and water jet propulsion systems, large scale brackets and machinery parts, high pressure vessels and so on. The essence of this technology is a formation of the product from metal powder, feed by gas-powder jet, coaxial or lateral to focused laser beam, directly to the growing area, with controlled heating and melting of the powder particles and substrate. High productivity of DLD process, which reach now 2 and more kg/h according *Boiseller et al*, require use of high laser power and melting speed, as well as appropriate level of powder flow, which can lead to instability appearance, described *Turichin,… et al*. This fact together with large amount of parameters, which are necessary for determination of treatment mode, make experimental choice of technological mode parameters very difficult. Therefore computer simulation on the base of physical adequate and fast mathematical model looks like most convenient way for design of technological

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modes of DLD. Large number of articles from initial results of *Peyre et al*, mainly describe a usage of different numeric schemes for process-simulation in DMD, but such approach don't allow analyze influence of different physical effects, Marangoni convection, for example, and mutual influence of different physical processes, such as hydrodynamics and heat transfer, on shape and size of melt pool. Physical adequate process-model for DMD would include connected solution of several tasks, among them task about powder jet transfer and impingment with substrate, heat transfer in liquid and solid phase and hydrodynamics of melt pool. This paper presents the results of theoretical researches and simulation of the connected heat and hydrodynamic process in steady-state case in melt pool during direct laser deposition, and discussion of usage of this results for choice of technological mode of production of large parts.

## 2. Melt flow model

The steady-state theoretical description of material transfer by gas-powder jet during direct laser deposition described by *Turichin, Valdaytseva at al* with consideration of gas dynamics of gas-powder jet impingement on the substrate.

In the typical conditions of DMD process, it is possible to restrict analysis by the case, when melt pool length "L" is much greater than its width "b" and depth "H". In this case the one dimensional boundary layer approximation, when "longitudinal" velocity $v_x$, directed along axe of laser beam motion, much more than "transverse" velocities $v_y$, $v_z$ , can be used. Therefore a Navier-Stokes equation can be written as:

$$v_x \frac{\partial v_x}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu \frac{\partial^2 v_x}{\partial z^2} \tag{1}$$

The boundary condition at the "bottom" of the melt pool is given as: $v_x\big|_{z=0} = 0$, on the "top" surface – $-\eta \frac{\partial v_x}{\partial z}\Big|_{z=H} = \frac{\partial \sigma}{\partial x}$, requirement of the stress tensor continuity, where σ – surface tension coefficient. Assuming that the temperature changes along melt pool surface much less then average surface temperature, and define $T_t$ as maximum surface temperature, $T_m$ and $T_v$ correspondingly melting and evaporation temperatures, taking a linear law for the temperature drop to the "tail" of the melt pool, one can write:

$$\eta \frac{\partial v_x}{\partial z}\Big|_{z=H} = \frac{\sigma}{L}\frac{T_t - T_m}{T_v - T_m} = \frac{\sigma^*}{L}\ . \tag{2}$$

To satisfy the boundary conditions and the condition of mass flux conservation along the "x" axis it is possible to accept the hypothesis of a "parabolic" distribution of melt speed with respect of depth, accordingly *Turichin, Zemlykov et al*:

$$v_x(z) = v_x\left(\alpha + \beta z + \gamma z^2\right).$$

The boundary conditions give in this case for coefficients:

$$\alpha = 0$$

$$\gamma = -\frac{3}{4H}\left(\frac{2}{H} - \frac{\sigma^*}{L\eta v_x}\right)$$
$$\beta = \frac{2}{H}\left(1 + \frac{H}{4}\left(\frac{2}{H} - \frac{\sigma^*}{L\eta v_x}\right)\right) = \frac{2}{H}\left(\frac{3}{2} - \frac{\sigma^*}{4\eta v_x}\frac{H}{L}\right) = \frac{3}{H} - \frac{\sigma^*}{2\eta v_x L} \quad (3)$$

Accordingly, equation (1) can be written as:

$$v_x \frac{\partial v_x}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - 3\nu \frac{v_x}{H^2} + \frac{3\sigma^*}{2\rho L H}. \quad (4)$$

For linking of melt velocity $v_x$ with the melt pool surface position one can use the continuity equation. In our case, it is necessary to take into account the mass flow coming to the surface of the melt with gas-powder jet. On the surface of the melt, the incident mass flow density can be denote as j(x). Therefore it is possible to write the flow continuity equation as:

$$\frac{\partial}{\partial x}(v_x H) = \frac{j(x)}{\rho}, \quad (5)$$

Let us determine pressure in melt pool "p", taking into account, that $p = \frac{\sigma}{R}$, where R – the surface curvature radius (Fig. 1).

When H<b we have $R \approx b + \frac{H^2}{2b}$, and for pressure it is possible to write: $p \approx \frac{\sigma}{b} - \frac{\sigma H^2}{2b^3}$. Therefore the Navier-Stokes equation term, connected with changes of "transverse" curvature radius of surface can be written as: $\frac{\sigma}{2b^3}\frac{H\partial H}{\partial x}$.

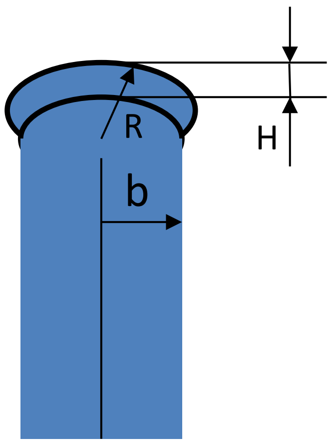


Fig. 1. Scheme of cross-section of growing wall.

Pressure born by changes of the "longitudinal" surface curvature radius can be written as: $\sigma \frac{\partial^2 H}{\partial x^2}$

Then, one can write:

$$v_x \frac{\partial v_x}{\partial x} = \frac{\sigma}{\rho b^3} \frac{H \partial H}{\partial x} - 3\nu \frac{v_x}{H^2} + \frac{3\sigma^*}{2\rho L H} \qquad (6)$$

After integration of continuity equation one can get:

$$H(x) = \frac{1}{\rho v_x} \int_0^x j(x) dx \qquad (7)$$

The initial and boundary conditions for this problem can be represented as:

H = 0 when x = 0, $\left. \frac{\partial H}{\partial x} \right|_{x=0} = 0$, $\left. \frac{\partial H}{\partial x} \right|_{x=L} = 0$.

Substitution of (7) to (6) and numerical solution of this differential equation give a profile of melt pool top surface with consideration of Marangoni effect. Examples of such shapes for different values of powder jet distributions and technological head motion velocity are shown on Fig. 2. It is evident, that surface shape, as well as melt flow speed, depend on melt pool length “L” and depth “H”, which are given by solution of heat transfer problem.

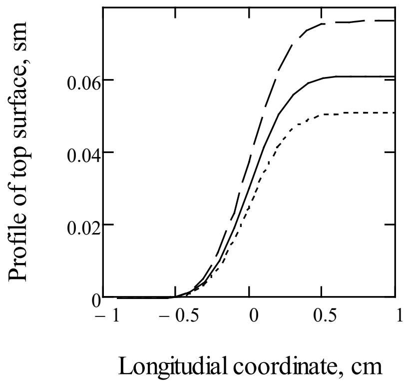


Fig.2. Shape of melt pool top surface for Inconel 625 deposition. Motion velocity 2 cm/c (solid), 2.4 cm/c (dot) and 1.6 cm/c (long dot), laser beam radius on the surface 2 mm, beam power 1770 W, powder jet diameter 3 mm, powder mass rate 3 kg/h, absorption coefficient 0.7.

### 3. Heat transfer model

In steady-state case of heat transfer during DMD process in the zone of laser action on metal the heat transfer equation can be represented as:

$$v_x \frac{\partial T}{\partial x} = \chi \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right)$$

Boundary conditions for this case can be written as:

$$-\lambda \left. \frac{\partial T}{\partial z} \right|_{z=0} = q(x), \quad T|_{z \to \infty} \to 0$$

where $\lambda$ and $\chi$ correspondingly heat transfer and temperature transfer coefficients.
For solution on can, according *Lopota et al*, let's introduce new unknown function $\Theta$, such, as:

$$T(x,z) = \Theta(x,z) \exp\left( \frac{vx}{2\chi} \right).$$

In this case for $\Theta$ one can obtain Helmholz equation:

$$\frac{v}{4\chi^2} \Theta = \frac{\partial^2 \Theta}{\partial x^2} + \frac{\partial^2 \Theta}{\partial z^2},$$

with boundary conditions of second kind: $-\lambda \left. \frac{\partial \Theta}{\partial z} \right|_{z=0} = q(x) \exp(-\frac{vx}{2\chi})$, $\Theta|_{z \to \infty} \to 0$.

For solution of this task for Helmholz type equation it is possible to use, follow, Fourier integral transformation. After a number of calculations one can obtain:

$$T(x,z) = \frac{\exp\left( -\frac{vx}{2\chi} \right)}{\lambda} \int_{-\infty}^{\infty} q(x') \exp\left( -\frac{vx'}{2\chi} \right) K_0 \left( \frac{v}{2\chi} \sqrt{z^2 + (x - x')^2} \right) dx' + T_h, \quad (8)$$

where $T_h$ is a value of initial temperature after previous cladding path. This expression give temperature field in active zone in DMD process with neglect of latent melting heat. Example of calculation with this formula for distribution of superficial temperature along melt pool surface is shown on Fig. 3

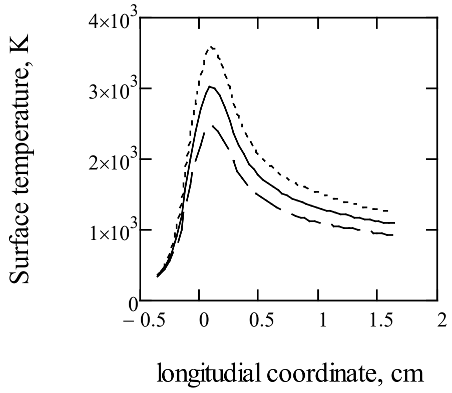


Fig.3. Temperature distribution along melt pool length for Inconel 625 deposition. Motion velocity 2 cm/c, laser beam radius on the surface 2 mm, beam power 1770 W (solid), 2130 W (dot) and 1420 W (long dot).

Calculation show, that relatively small (from 1.7 kW to 2.1 kW increases of beam power lead to overheating of surface to evaporation, that lead to appearance of a cavity on the surface and bed melt pad formation. With determination $T=T_m$ one can transform expression (8) to equation for distribution of melting depth with respect of melt pool length. Results of numerical solution of this equation are shown on Fig. 4.

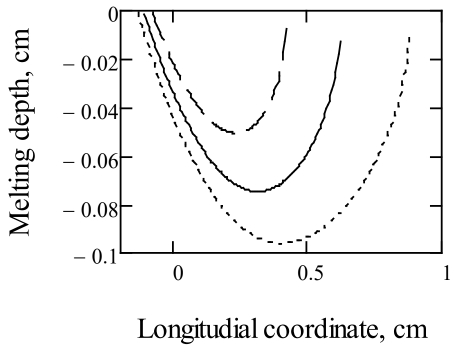


Fig. 4. Melt pool shape for Inconel 625 deposition. Motion velocity 2 cm/c, laser beam radius on the surface 2 mm, beam power 1770 W (solid), 2130 W (dot) and 1420 W (long dot).

This example show, that relatively small (from 1.7 kW to 1.4 kW) decreases of beam power lead to the case, when melting depth became less then melt pad thickness, which was in this experiments equal 0.6 mm, what can lead to appearance of faulty fusion between layers.

Taking into account, that on the melt pool surface z=0, it is possible to get equation for determination of melt pool length "L":

$$T(x,z)=\frac{\exp\left(-\frac{vx}{2\chi}\right)}{\lambda}\int_{-\infty}^{\infty}q(x')\exp\left(-\frac{vx'}{2\chi}\right)K_0\left(\frac{v(L-x')}{2\chi}\right)dx'+T_h$$

Numerical solution of this equation allow to find length of melt pool in dependence of material and technological mode parameters. Example of such solution is shown on Fig. 5.

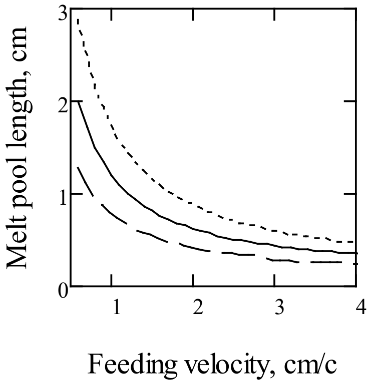


Fig. 5. Melt pool length for Inconel 625 deposition. Motion velocity 2 cm/c, laser beam radius on the surface 2 mm, beam power 1770 W (solid), 2130 W (dot) and 1420 W (long dot).

Now this value together with melting depth “H” can be used in hydrodynamic task as parameters. After that improved value of melt velocity “v” can be used in heat transfer task. Mathcad 15 was used for numeric solutions of model equations. Calculations show, that after 3-4 iterations all values became stable, so that such numeric procedure allow to get self-consistent solution of heat transfer and hydrodynamic tasks for size and shape of melt pool in DMD process.

## 4. Model implementation

The developed model have been used for determination of DMD mode parameters at the Institute of Laser and Welding Technologies SPbMTU (ILWT) during preliminary tests of new large industrial installation for fabrication of fan body ring with diameter 2100 mm and same scale body of turbine support for prospective aircraft engine (Fig. 6). Also the model has been used as a heat source model for simulation of stress distribution for the parts. Comparison of simulation results with experimental data shown mismatch less then 20%, that is quite good for fast semi-analytic process-model.

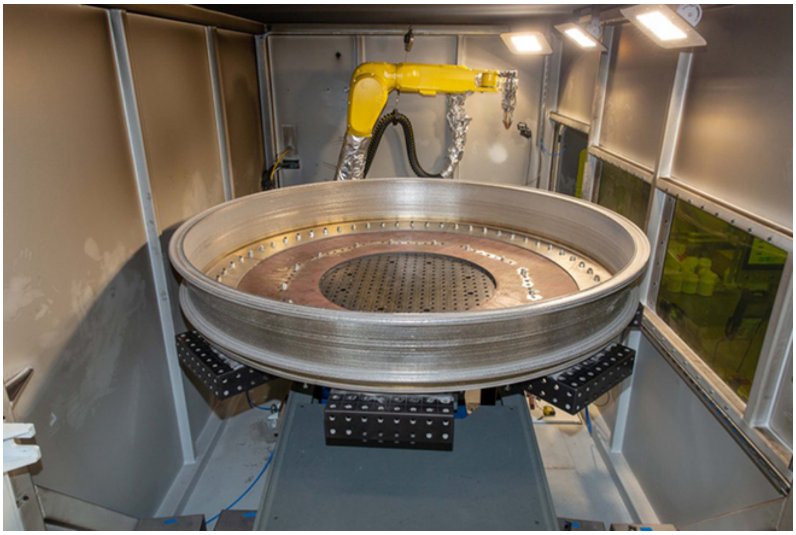

Fig.6. Production of fan body.

## 5. Conclusion

DMD is a complex process with a large number of technological mode parameters, which can dramatically affect the result. Choice of the mode of fabrication is advantageously carried out with the help of mathematical modeling; experimental selection modes can be extremely time consuming.

Semi analytical process-model, which allow to calculate melt pool depth, length and surface profile, based on connected solutions of heat transfer and hydrodynamic tasks have been developed. The model input data include material physical properties, cladding head motion velocity, laser beam power and radius on the deposited surface, powder rate and radius of powder jet. Very short calculation time, less then 1 c, makes this model convenient for technological use.

Simulation results show, that for high productive technological modes the process parameters window is very narrow, parameters changes in the frame 20% can lead to dramatic changes of clad pad formation and defects appearance.

The developed model can be used not only for calculation of active zone parameters, but also as a heat source model for thermo-mechanical simulation.

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