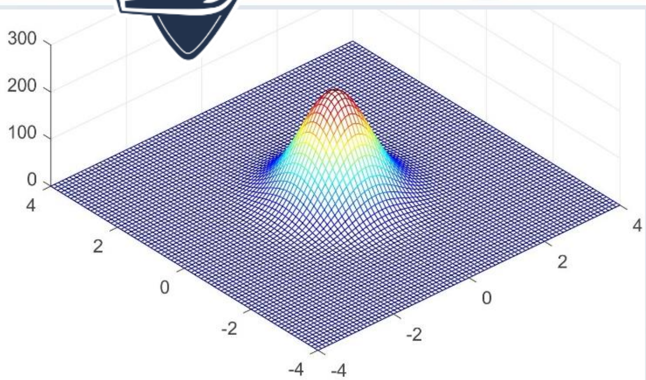
Simplified model for numerical simulation of laser metal deposition process with beam oscillation

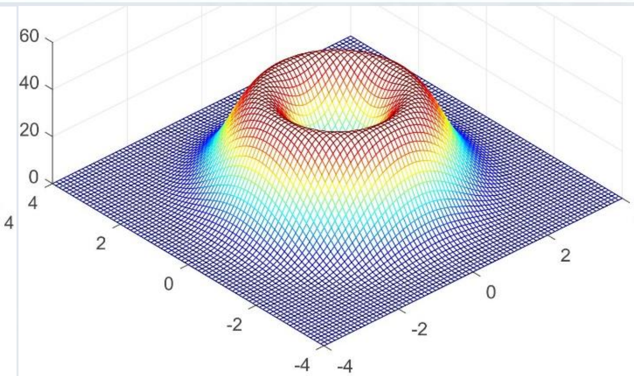
Sergei Ivanov[1], Antoni Artinov[2], Ekaterina Valdaytseva[1]

[1] St. Petersburg State Marine Technical University, Russia
[2] Federal Institute for Materials Research and Testing, Germany

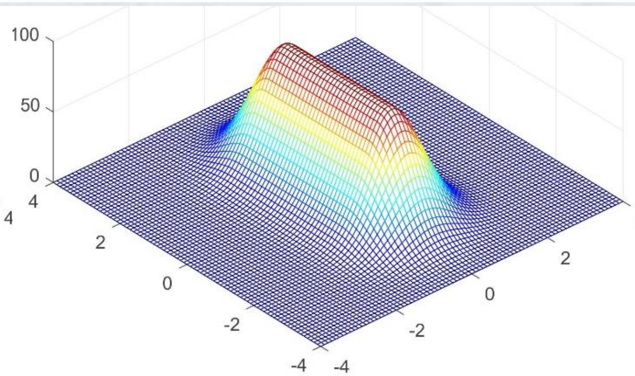
Motivation



No oscillation



Circular oscillation



Lateral oscillation

Beam oscillation in welding allows to:

- reduce porosity;
- increase efficiency of the process;
- Increase gap bridging ability.

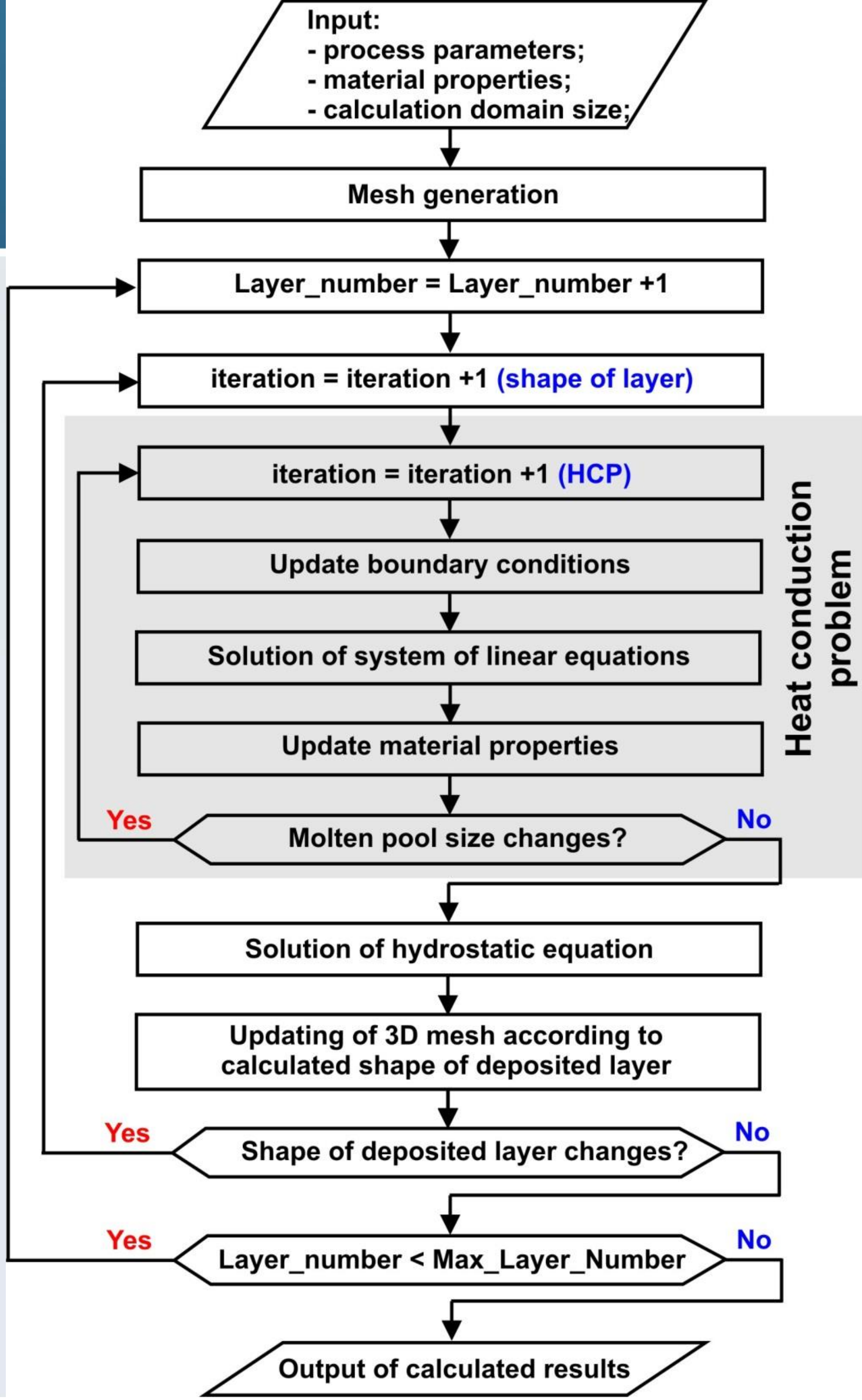
Deposition rate can be improved by the modification of the shape and size of the molten pool through the optimization of laser beam power distribution.

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.

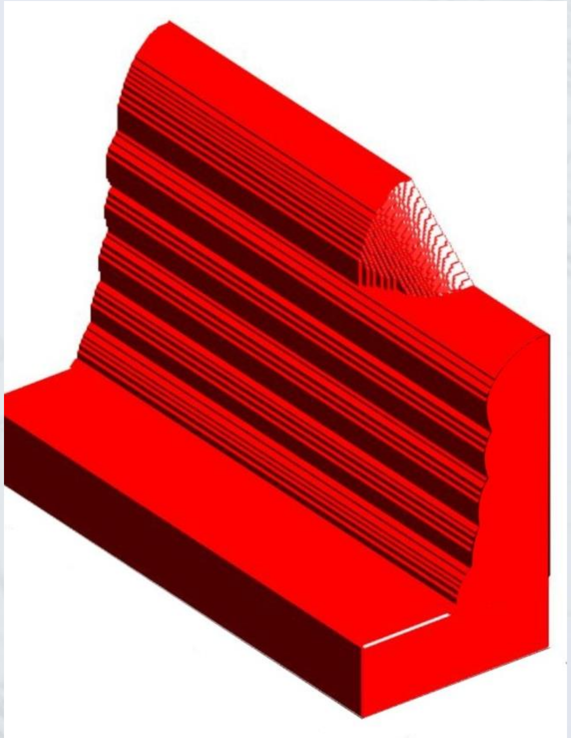
Flowchart of the developed simulation procedure



In order to obtain shape of deposited layer the following two sequentially-coupled problems was solved:

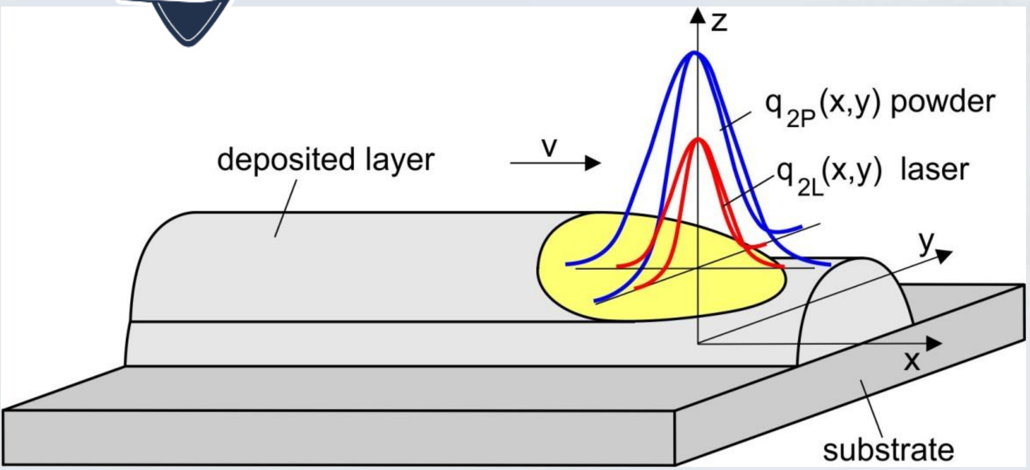
- Heat conduction problem;
- Free surface problem.

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.

Solution of Heat Conduction Problem



Schematic of calculation domain

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

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+vc\rho\frac{\partial T}{\partial x}+q_3=0$$

λ is the thermal conductivity

$c\rho$ is the volumetric heat capacity

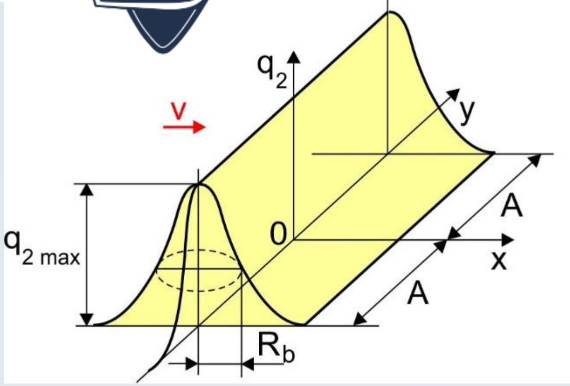
v is the deposition speed

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).

Model for Oscillation Beam Heat Source



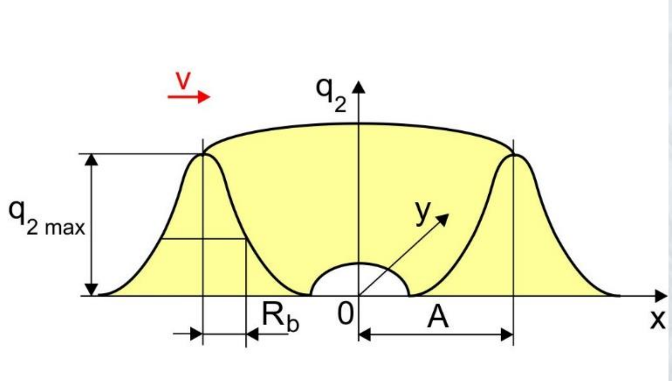
Lateral oscillation

$$A = n \cdot R_b$$

A – amplitude [mm]
R_b – beam radius [mm]

$$q_e = \eta \cdot \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} q_2 dxdy$$

q_2 – heat flux [W m^{-2}]
q_e – effective heat power[W]
η – heat source efficiency



Circular oscillation

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

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

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

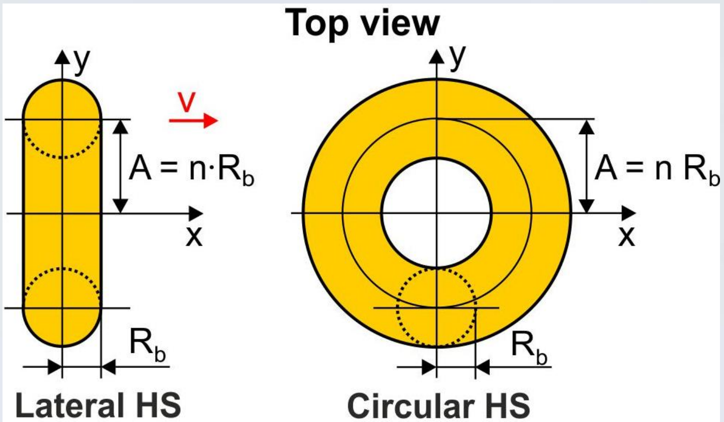
$$q_{2\max} = \frac{\eta \cdot q}{\pi \cdot R_b^2} \cdot \frac{\sqrt{\pi}}{\sqrt{\pi} + 2 \cdot n} = q_{2m\ n} \cdot k_A$$

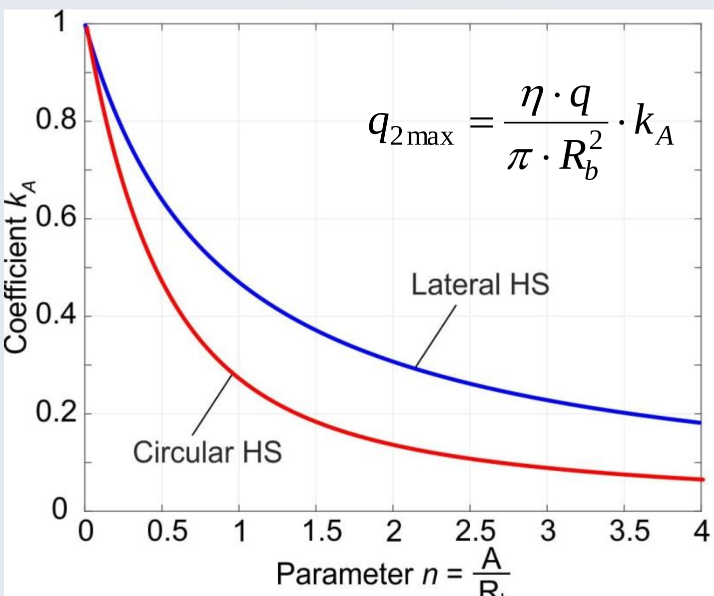
$$q_{2\max} = \frac{\eta \cdot q}{\pi \cdot R_b^2} \cdot \frac{1}{\exp(-n^2) + n \cdot \sqrt{\pi} \cdot erfc(-n)} = q_{2m\ n} \cdot k_A$$

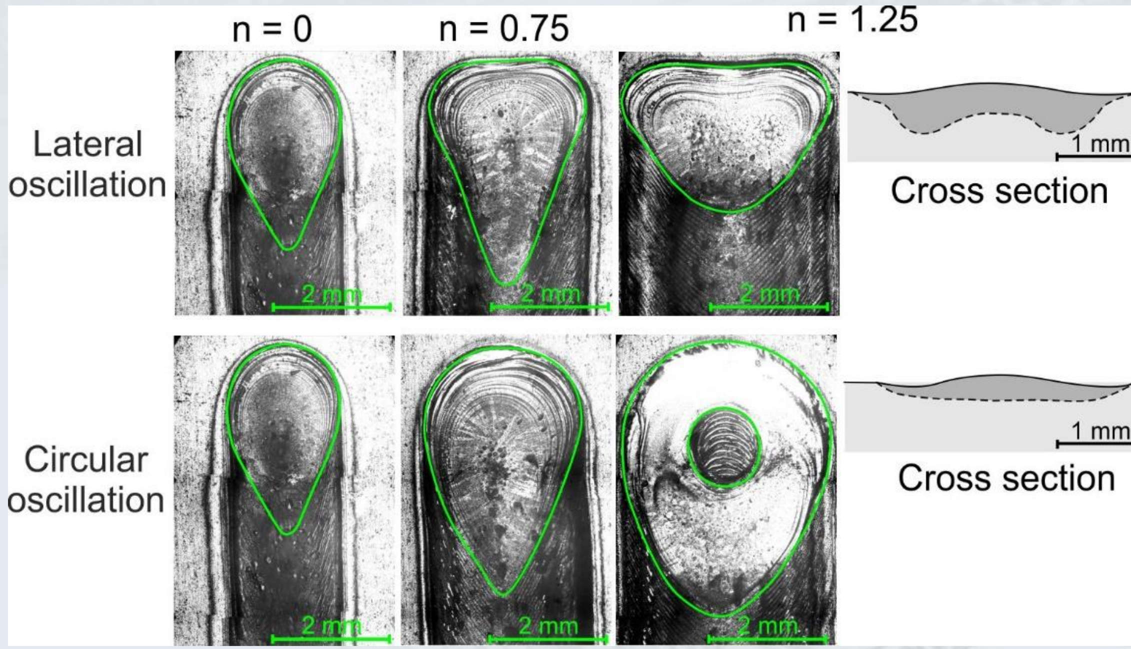
$$q_{2m\ n} = \frac{\eta \cdot q}{\pi \cdot R_b^2}$$ - peak value of heat flux of normally-distributed heat source

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.

Model for Oscillation Beam Heat Source



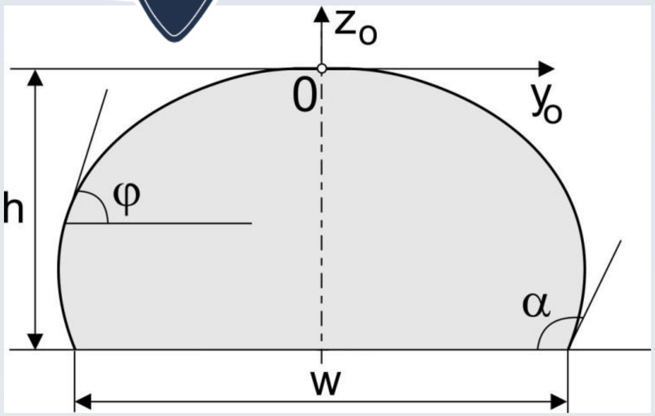




Effect of oscillation amplitude on molten pool

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 decrease rapidly to 53% for the lateral heat source and to 73% for the circular heat source.

Free Surface Problem



Schematic of deposited layer

Cross section shape of deposited layer can be obtained by the solution of the equilibrium equation of the liquid phase in the gravity field: $\sigma\ \kappa = -\rho\ g\ z_o + C$

σ is the surface tension.

κ is the curvature of the free surface of molten metal.

ρ 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:

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

After manipulation the following system of ODE was obtained:

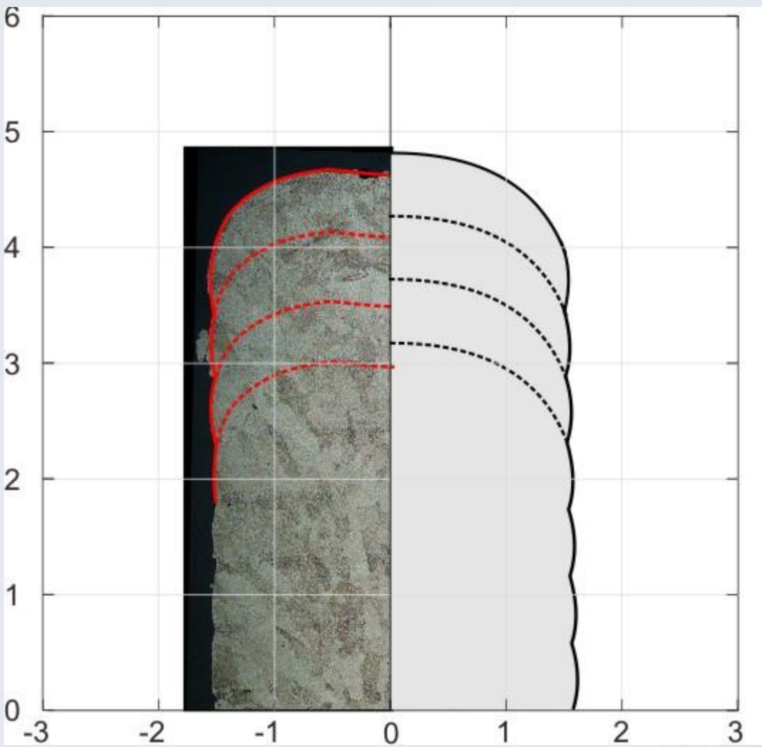
$$\begin{cases} \dfrac{dz_o}{d\varphi} = \dfrac{\sin\varphi}{B} \\ \dfrac{dy_o}{d\varphi} = -\dfrac{\cos\varphi}{B} \end{cases} \qquad B = \frac{\rho\ g\ z_o}{\sigma} + C$$

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

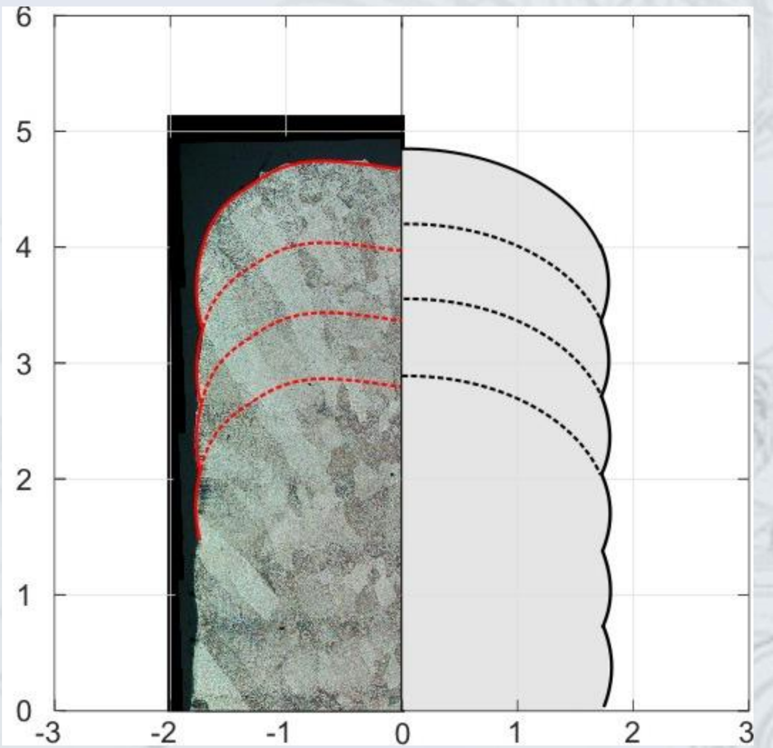
Process parameters :

- power $q = 2300$ 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



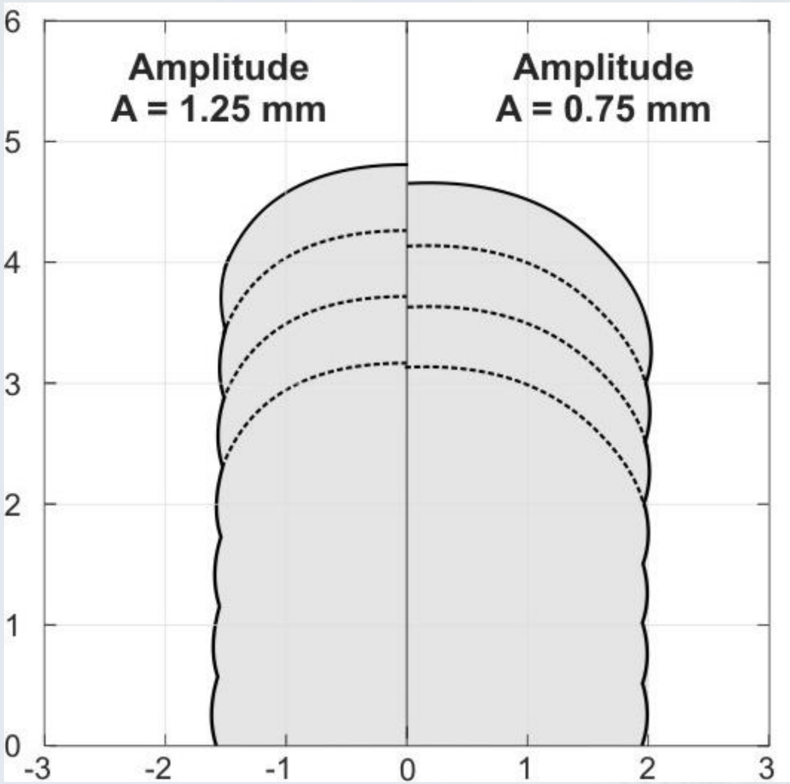
Process parameters :

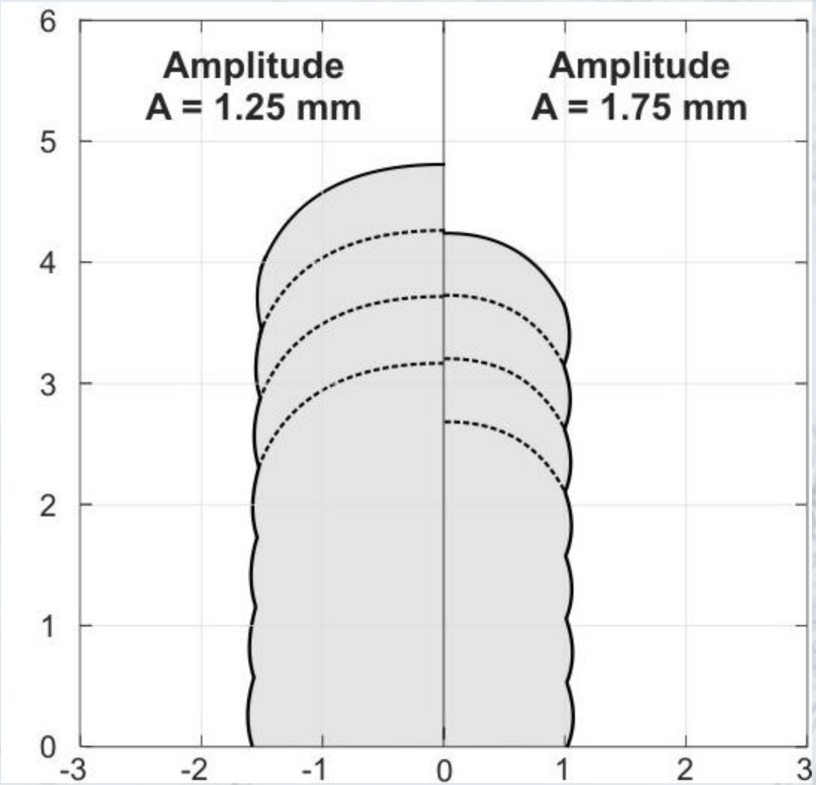
- power $q = 2100$ kW;
- speed $v = 20$ mm s^{-1}.
- beam radius $R_b = 1.5$ mm
- amplitude $A = 1.25$ mm
- powder flow rate $m = 0.33$ g/s



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
- powder flow rate m = 0.42 g/s

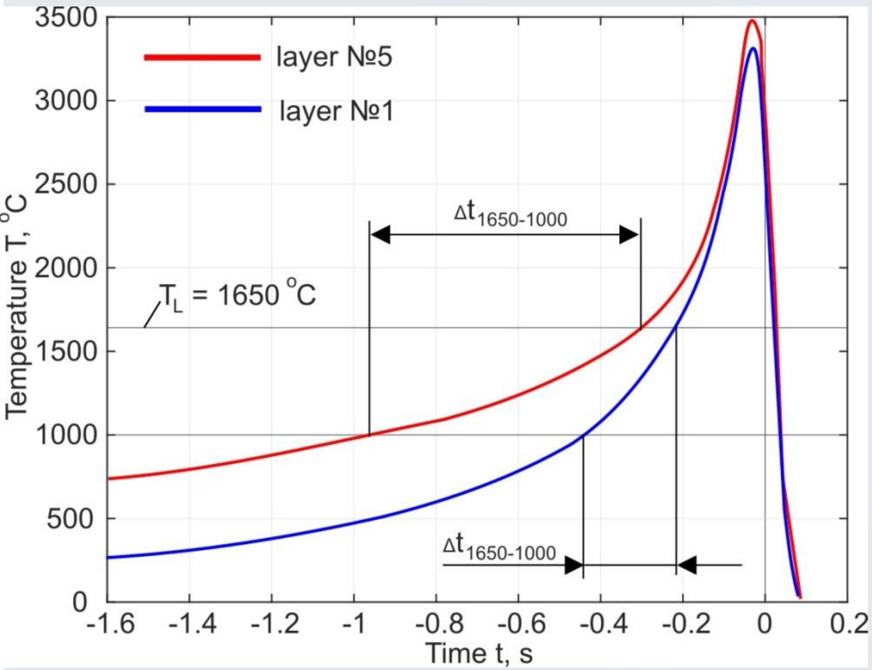




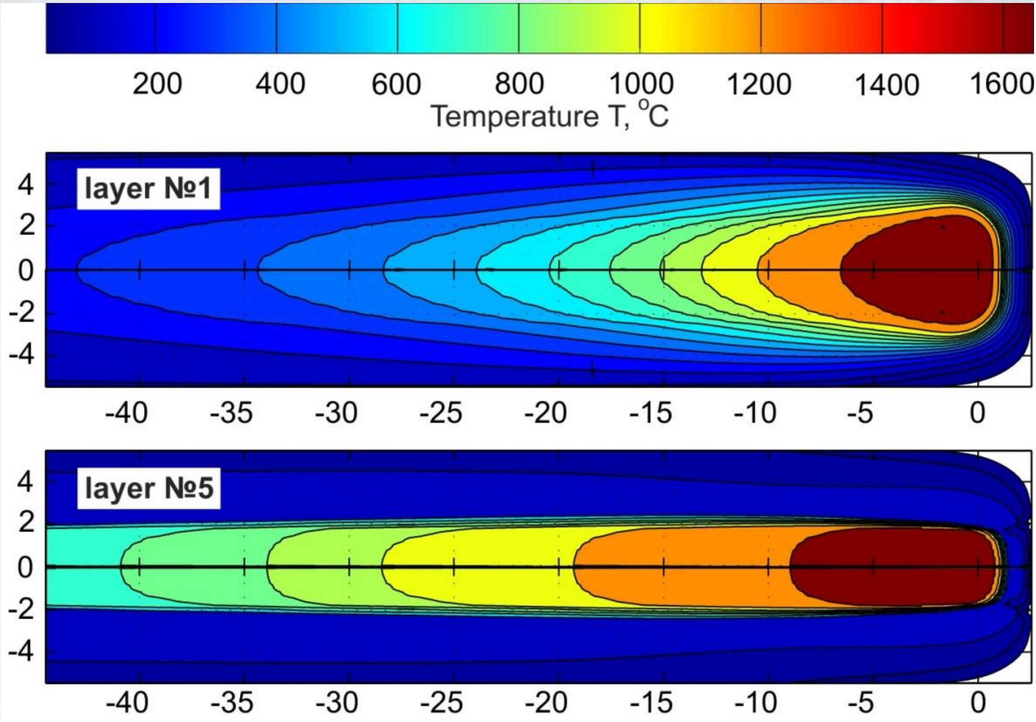
Example: Laser Metal Deposition of Ti-6Al-4V with Lateral Beam Oscillation

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



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.