Numerical Simulation of Laser Welding of Metallic Plates

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Abstract

A new algorithm for numerical simulation of laser welding of thin metallic plates was developed. It is based on the collocations and least squares method and a new 3D model of the laser welding process. Calculations for titanium and steel plates were performed. An influence of the convection on the welding process was investigated.

1. Description of the 3D Model

We consider a stationary process of laser welding of thin metallic plates. The plates are rectangular parallelepipeds tightly adjoined by thin side faces. The laser axis is perpendicular to the plates and lies in the joint plane. The laser beam moves parallel to the plates along the joint. Let us introduce Cartesian coordinate system for which the laser beam is immobile, while the plates move with the welding speed V_w (see Fig. 1).

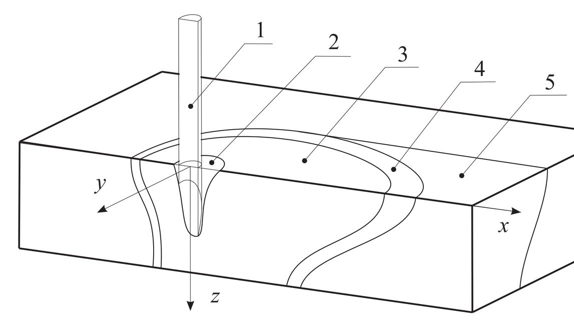

Figure 1. *Layout of the weld zone: 1 — laser beam, 2 — steam channel, 3 — liquid phase zone (welding pool), 4 — two-phase zone, 5 — solid phase.*

Due to the complexity of thermo- and hydrodynamic processes occurred in the welding pool we make some simplifying assumptions:

- we consider the melt solidification in Stefan's approximation,
- we assume that the welding speed is constant and the thermophysical parameters are equal to their average values.

Governing Equations

Heat transfer in the plates is described by heat conduction equation in the model

$$\rho_i c_i\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\frac{\partial}{\partial x}\left(\lambda_i\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_i\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_i\frac{\partial T}{\partial z}\right),$$

where T is the temperature, $\vec{v}=(u,v,w)$ is the velocity vector, ρ_i, λ_i are density and heat conduction coefficient for solid ($i=1$) and liquid ($i=2$) phases, respectively, c_i is the heat capacity of the i-th phase.

At the interphase boundary Stefan condition is written

$$\left(\lambda_2\frac{\partial T}{\partial n}\right)_2-\left(\lambda_1\frac{\partial T}{\partial n}\right)_1=\rho_1\kappa\vec{n}\cdot\vec{V}_w,$$

where $\vec{n}$ is the unit normal with respect to interphase boundary,
κ is the melting heat (crystallization heat).

The liquid metal flow in the welding pool is simulated with the use of Navier-Stokes (N-S) equations

$$\rho_2(\vec{v}\cdot\nabla)\vec{v}=-\nabla p+\mu\Delta\vec{v},$$
$$\operatorname{div}\vec{v}=0,$$

where μ is the coefficient of dynamic viscosity for liquid metal, p is the pressure.

Boundary Conditions

Interaction of the welding zone with the environment is described by corresponding boundary conditions. We take into account

- the presence of the steam channel in the vicinity of the laser beam,
- direct and reflected radiations from the laser beam,
- convective and radiative heat losses through upper and lower surfaces of the plates,
- an influence of surface tension forces and friction forces of the metal vapour escaping from the channel on the liquid metal flow.

2. Description of the Quasi-3D Model

Due to essential difficulty of the 3D model we averaged its equations with respect to variable y Here, averaging operation was defined by the following formula:

$$\bar{f}(x,z)=\frac{1}{L_y}\int_0^{L_y} f(x,y,z)dy,$$

where L_y is the average half-width of the welding pool, f is a physical quantity.

Heat flow in the direction of y axis and viscous friction between orthogonal to axis y layers of liquid metal are approximately estimated and taken into account here.

Averaged Heat Conduction Equation

Equation for liquid phase:

$$c_2\rho_2\left(u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}\right)=\frac{\partial}{\partial x}\left(\lambda_2\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(\lambda_2\frac{\partial T}{\partial z}\right)-\lambda_2\frac{2(T-T_e)}{L_y^2},$$

equation for solid phase:

$$c_1\rho_1 V_w\frac{\partial T}{\partial x}=\frac{\partial}{\partial x}\left(\lambda_1\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(\lambda_1\frac{\partial T}{\partial z}\right)-\lambda_1\frac{T-T_g}{L_y l_T}.$$

Here, T_e is the crystallization temperature, l_T is the length of the heat wave (time of the wave propagation is equal to $\tau_T=2r_F/V_w$), r_F is the radius of the laser beam.

Averaged Navier-Stokes Equations

$$\rho_2\left(u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right)-2\mu\frac{u-V_w}{L_y^2},$$
$$\rho_2\left(u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right)-2\mu\frac{w}{L_y^2},$$
$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0.$$

3. Numerical Method

- Navier-Stokes and heat conduction equations are solved new versions of the collocations and least squares (CLS) method.
- Computations were performed on nonuniform meshes with a local refinement near the welding pool.
- Numerical simulations on a sequence of grids with decreasing steps were carried out. It is shown that the error of the approximate solution obtained here is equal to $O(h)$, where h is the maximal linear size of grid cells.

4. Computational Results

Titanium Plates

Thickness of the plates is 5 mm, laser beam power is 3 kW, $V_w=1$ m/min.

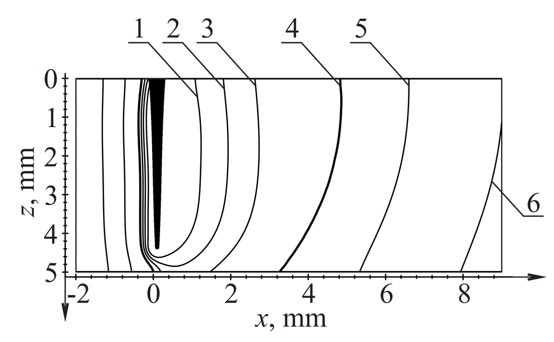

Figure 2. *Temperature field in the welding domain (liquid metal flow in the welding pool is assumed to be plane-parallel). Isotherms: T = 2800 (1), 2400 (2), 2150 (3), 1944 (4) (crystallization temperature), 1200 (5), 1000 (6) K.*

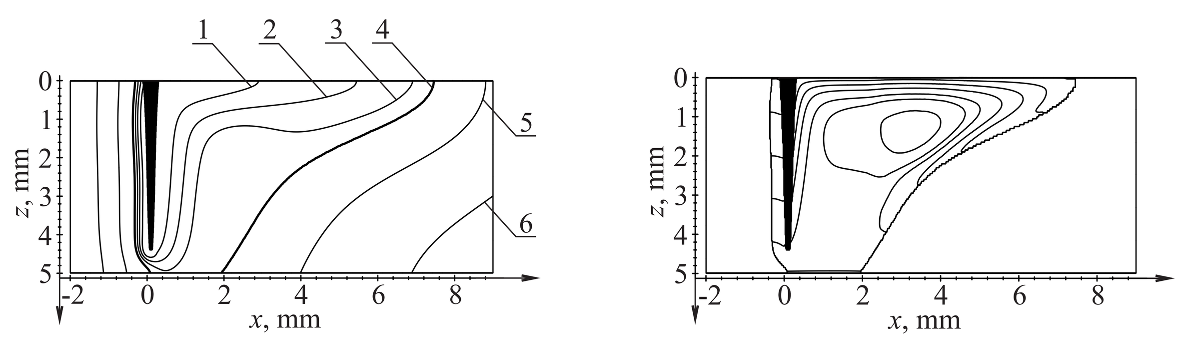

Figure 3. *Temperature field in the welding domain (liquid metal flow in the welding pool is simulated with the use of N-S equations). Pattern of the liquid metal flow in the welding pool.*

Steel Plates

Thickness of the plates is 15 mm, laser beam power is 5.2 kW, $V_w=0.6$ m/min. Liquid metal flow in the welding pool is assumed to be plane-parallel.

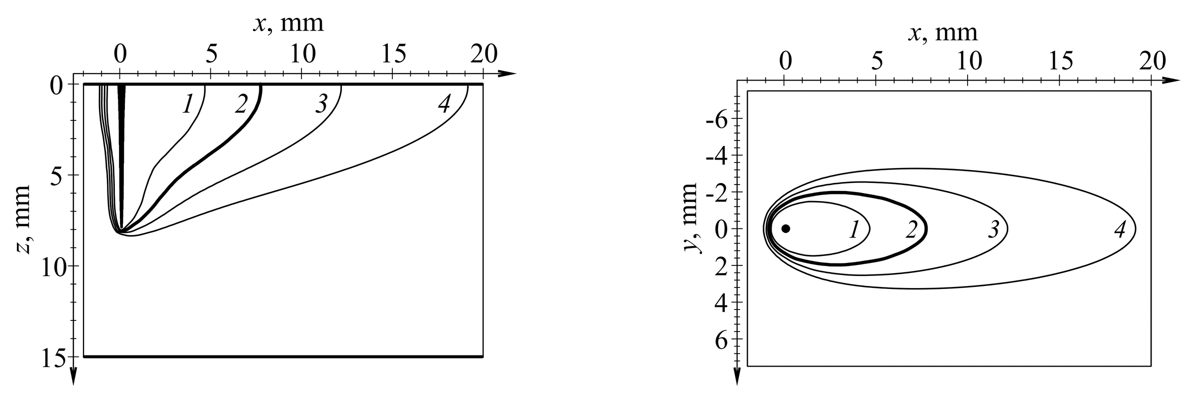

Figure 4. *Temperature field in the welding domain: sections y = 0 (left), z = 0 (right). Isotherms: 2100 (1), 1760 (2) (crystallization temperature), 1400 (3), 1100 (4) K.*

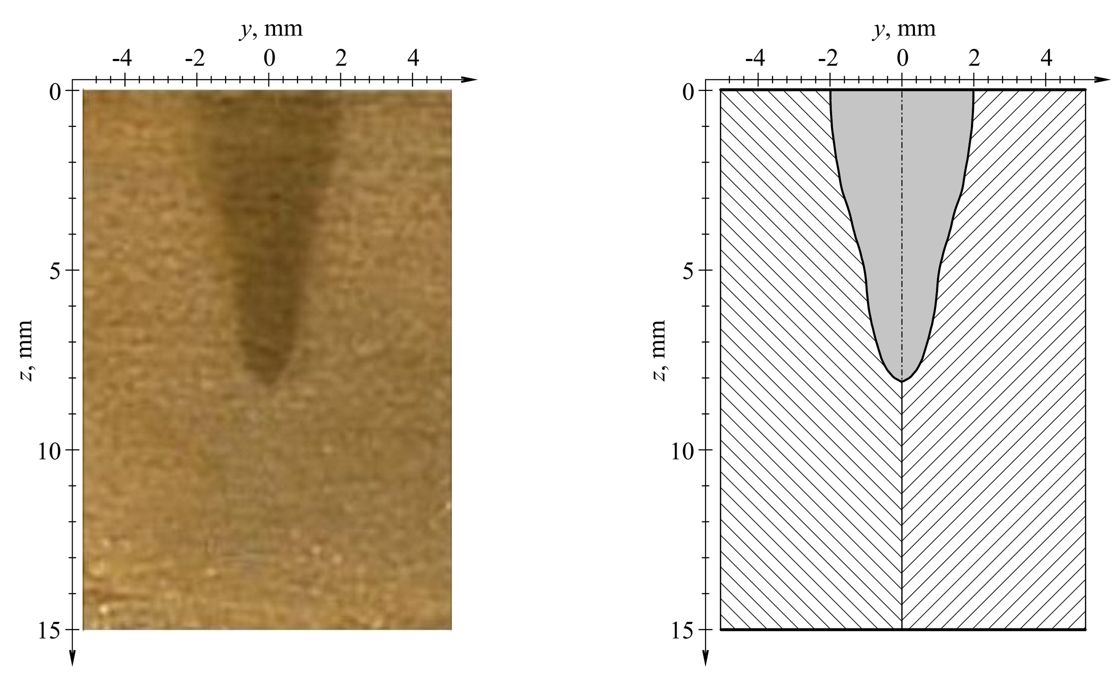

Figure 5. *Weld joint section: experiment (left) and simulated (right).*

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References

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