The laser heat-treatment process control by the non-stationary convective heat exchange modeling

V V Zvezdin, R R Saubanov, R R Rakhimov, R M Khisamutdinov, A V Boldyrev, D L Karelin
Kazan Federal University, Naberezhnye Chelny Institute, Naberezhnye Chelny, Russia
saubanov@mail.ru, rafisih88@mail.ru

Abstract. Various technological processes allow to obtain high quality indicators, such as laser cutting, welding, hardening, etc. The article presents the results of modeling for laser cutting of thick-walled structures. The creation of computational tools for express analysis in a mathematical setting and a quantitative assessment of temperature fields in spatially variable and non-stationary conditions of laser exposure are of undoubted practical interest to minimize experimental costs.

1. Introduction. Nowadays, the laser technological complexes (LTC) with high density of radiation’s power are actively being under development and explored for solving current problems of laser influence in the concentrated flows of energy technology. The exploring dynamics of temperature fields in the zone of laser influence and multifactor optical and thermophysical processes is necessary not only for the quantitative description of phase transition “solid-gas-plasma”, but also for controlled modification of the properties of structural materials. There are complex physical and chemical processes occur in the zone of influencing the laser radiation (LR) by implementation all of development cycles and engineering optimization of the technological parameters, generating system processes by energy, and the systems of control in real-time. For the relatively well explored metals the results of exploring the 3D temperature fields and conjugated with them consumable masses characteristics of irradiated metals, spectral-energy melting of thresholds, evaporation of ionisation, obtained by various theoretical and experimental groups, significantly differ. The creating extension tools of express analysis in mathematical statement and quantification of temperature fields in space-time non-stationary conditions of the laser influence are of undoubted practical interest for the minimizing experimental expenses [1-4, 6].

2. Theoretical and experimental research
The features of the LR process and the results of the research should be taken into account by modeling.

The laser cutting process modeling of 17Г1C steel was implemented using a multiphase liquid model (MMJ) based on the method of fixing the phase interface under the influence of a concentrated energy beam and determining the distribution and movement of immiscible phases. This modeling approach assumes that the grid resolution is sufficient to resolve the position and shape of the interface between phases [3, 5-10].
To determine the phase distribution, the mass conservation equation of the phase bulk part was used:

$$\frac{\partial}{\partial t} \int_V a_i dV + \int_A a_i v dA = \int_V \left( S a_i - \frac{a_i}{\rho_i} \frac{D\rho_i}{Dt} \right) dV - \int_V \frac{1}{\rho_i} \nabla (a_i \rho_i v_{d,i}) dV$$  \hspace{1cm} (1)

where $A$ is the vector to the area of the heat transfer surface, $v$ is the mixture velocity (averaged by mass), and is the diffusion velocity, and is the user-defined initial member of phase $i$ or the Lagrangian derivative of the phase densities.

The total mass for all phases is determined using the continuity equation:

$$\frac{\partial}{\partial t} \int_V \rho dV + \int_A \rho v dA = \int_V S dV$$  \hspace{1cm} (2)

where $S$ – a mass source element associated with a phase source element as follows:

$$S = \sum_i S a_i \cdot \rho_i$$

The dependence on the volume fractions of the mixture substance constituent phases are taken into account through density.

The phase velocity was calculated using the mass momentum equation for the corresponding volume part of the phase:

$$\frac{\partial}{\partial t} \int_V \rho v dV + \int_A \rho v \cdot v dA = -\int_A p I \cdot dA + \int_A T \cdot dA +$$

$$\int_V \rho g dV + \int_A f_b dV - \sum_i \int_A a_i \rho_i v_{d,i} \otimes v_{d,i} \cdot dA$$  \hspace{1cm} (3)

where $p$ – pressure, $I$-the combined tensor, $T$ - stress tensor, $f_b$ - vector mass energy.

The calculation of the temperature field when the material is exposed to concentrated radiation due to the thermal conductivity of the material was performed using the energy equation

$$\frac{\partial}{\partial t} \int_V \rho E dV + \int_A \rho Hv + \sum_i \int_A a_i \rho_i H v_{d,i} \cdot da =$$

$$= \int_A q^* / dA + \int_A T \cdot v dA + \int_V f_b vdV + \int_V S_E dV$$  \hspace{1cm} (4)

where $E$ -total energy, $H$-total enthalpy, - the heat flow vector, - the consumer of the energy source.

Mathematical modeling of laser cutting of 17Г1C steel using the STAR-CCM+ v13 software package was performed using equation 4. The simulation results are shown in figures 1 and 2.
**Figure 1.** Graph of the steam-gas channel depth dependence at the LI power for 6 kW on the exposure time

**Figure 2.** Graph of the steam-gas channel depth dependence at the power of LI for 8 kW on the time of exposure

Based on the results (see Fig. 3-6), the presence of unstable pulsation is noted: for 6kW with a frequency of 17-20 Hz; for 8kW with a frequency of 25-29 Hz.

**Figure 3.** Thermal map of the temperature field distribution and the pulsation frequency in the time interval $t = 0.156$ s in the cross section

**Figure 4.** Heat map of the temperature field distribution and the ripple frequency over a period of time $t = 0.156$ s in the longitudinal section

**Figure 5.** Heat map of the temperature field distribution and the ripple frequency over a period of time $t = 0.156$ s on the front view

**Figure 6.** Heat map of the temperature field distribution and the ripple frequency over a period of time $t = 0.233$ s in cross section
3. Conclusion
From experimental studies, it is known that the spread of the liquid phase from the cutting front occurs in all possible directions: up, sideways, and, if the cut is through, down. As a result of double "support" in this part of the cut, a zone of thermal influence of such a depth can develop, the presence of which, as noted at the beginning of the work, is unacceptable in most cases of using laser cutting in manufacturing technologies for those products in which it is either the most effective or the only possible tool.

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