

**FORMATION OF LOCAL MELTING ZONE
BY LASER ALLOYING OF SURFACE
AND WEAR RESISTANCE UNDER FRETTING CONDITIONS**

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1. INTRODUCTION

The process of interaction of a laser radiation for metals can be described within the framework of analytical and numerical representations by theory of heat conduction. The analysis of heat of various materials by beam of the laser is carried out in a series of works [1, 2]. In most cases the problems of heat was decided in linear statement without the registration of thermal properties of material and was reduced to a solution of heat conduction equations.

The simple analytical expressions are obtained in paper [3]. This is criterions of a choice of optimum parameters and conditions of laser treatment by continuous CO₂ - lasers without melting away of a surface are defined. For a solution of thermal problems the authors use the numerical methods of calculation on heat hardening of steels and cast irons [4, 5], integrated transformations in final and infinite limits [6], Laplace transformation on a temporal variable.

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The flexibility of a numerical model allows easily to take into account a set various thermal conditions on the boundaries and in interior areas of a segment, that in the greater measure corresponds to a reality. The exactitude limits only by amount of the physical effects, discounted by the program, and possibility of the concrete computer. Such flexibility of numerical modeling is the important advantage on a comparison with an analytical method.

We obtain a non-stationary solution permitting to observe on process of heat and melting of metal surface at alloying by Cr, Mo, W, Nb. The solution is three-dimensional, i.e. the geometric form of a laser ray and law of power distribution of is taken into account. The model takes into account also absorption - selection of latent heat of fusion at the moment of phase transition from solid in liquid phase, and also modification thermal parameters in various condition of metal.

The problem was solved by the explicit numerical method of finite differences [7]. Let's consider a low level cell in to volume of a solid body. In a center of each mesh the imaginary node (Fig. 1) is located. We assume, that temperature of element is identical in all volume and equal temperature of a point, where the node is. The heat flux conducts through it lateral faces. It is clear, that these assumptions are fair only in case of enough small-sized siting (on a comparison with a characteristic distance of a modification of temperature). Noting an energy balance for each node the algebraic equation expressing temperature in a node through temperatures in adjacent nodes, geometric sizes of meshes and thermal properties of material we are obtained.

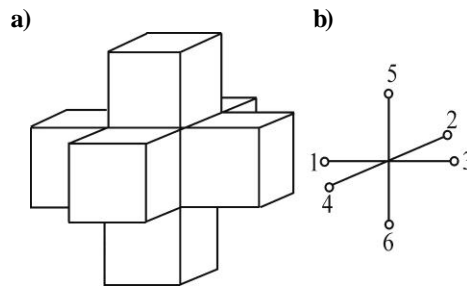


Fig. 1. Three-dimensional problem, cubic mesh (a), internal node (b)

At a solution of a non-stationary problem it is necessary to take into account also energy storage in substance. This energy represents increase of an internal energy in a node, which is determined in thermodynamic performance of a material - specific heat.

2. NUMERICAL MODELING OF HEATING SURFACE

The velocity of transfer of heat quantitatively express by the Fourier law:

$$q_n = -\lambda S \frac{\partial T}{\partial x}, \quad (1)$$

where q_n - heat of flux in normal direction to an isotherm (W);

λ - coefficient of thermal conductivity (W / m·K);

S - the sectional area, through which flows past a heat flux (m²);

x - direction of a heat flux

Law of conservation of energy for a node 0 at an absence of internal heat release:

$$\sum_{i=1}^6 q_{i \rightarrow 0} = \frac{\partial U_0}{\partial t}, \quad (2)$$

where $q_{i \rightarrow 0}$ - heat of flux to direction from i node to 0 node;

$\frac{\partial U}{\partial t}$ - velocity of modification of an internal energy of a zero node.

If to suppose that in moment t density and specific heat are constant:

$$\frac{\partial U}{\partial t} = mc \frac{\Delta T_0}{\Delta t} = \rho \cdot \Delta x^3 \cdot c \cdot \frac{T_o^{t+\Delta t} - T_o^t}{\Delta t}, \quad (3)$$

where ρ - density [kg / m³];

c - specific heat [m²/c²·K].

The up index in the formula (3) determine a modification of temperature in time, lower - modification of temperature on space.

Let's note the equation for conductive terms $q_{i \rightarrow 0}$ by using the law Fourier of the thermal conduction:

$$q_{i \rightarrow 0} = \lambda S \frac{T_i^t - T_o^t}{\Delta x}, \quad i = 1 \dots 6, \quad (4)$$

The equation (4) is an explicit method of a solution, i.e. each expression determines temperature in moment t . If to take a value of temperatures to a moment $t + \Delta t$ (not an

explicit method), noting difference equations of an energy balance for all nodes, it is necessary to decide a system of the algebraic equations. Both methods have the advantages and shortages. The explicit method should satisfy to a stability criterion, which dictates a very step pitch on time, and it reduces in magnification of volumes of calculation.

Stability criterion for a three-dimensional problem:

$$F_0 = \frac{\lambda \Delta t}{c \rho (\Delta x)^2} \leq \frac{1}{6}, \quad (5)$$

where F_0 - Fourier number.

In an explicit method the step on time is limited, but allows to obtained distribution of temperatures immediately on each step. In view of rapidity of an operation of laser impulse most adapted an explicit method.

Substituting in the formula (2) expressions (3) and (4), we shall receive expression for temperature of a zero node in moment $t + \Delta t$ through temperature of enclosing node for moment t .

$$T_o^{t+\Delta t} = F_0(T_1 + T_2 + T_3 + T_4 + T_5 + T_6) + (1 - 6F_0)T_o^{\Delta t} \quad (6)$$

The similar formulas is obtained and for nodes on a surface and on the boundaries of chosen area. Temperature on the boundaries was determined by linear approximation of temperature field:

$$T_1 - T_0 = T_2 - T_1, \quad (7)$$

where T_0 - temperature boundary volume.

This exact enough approximation, since in this case fineness of separation on space is sufficient that the modification of temperature in limits one volume was replaced by a differential.

3. RESULTS

The purpose of calculations was the definition of geometric performances of zone of laser melting, hardening and tempering for technological conditions of laser treatment.

In Fig. 2-3 the theoretical dependences of heat of model steel (0,45% C).

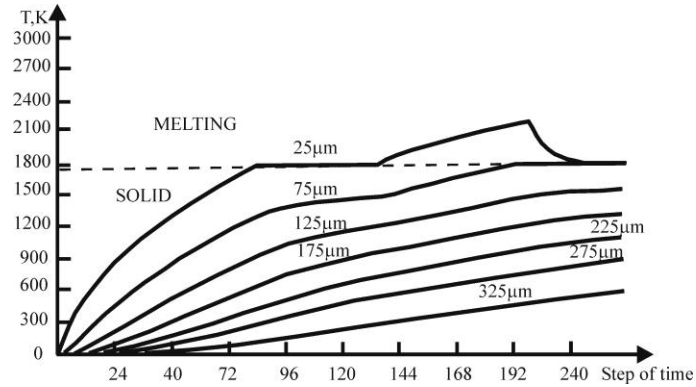


Fig. 2. The heating of under surface layers of steel for laser processing, $E=2 \text{ J/mm}^2$, $t_{\text{imp}}=6 \cdot 10^{-3} \text{ s}$

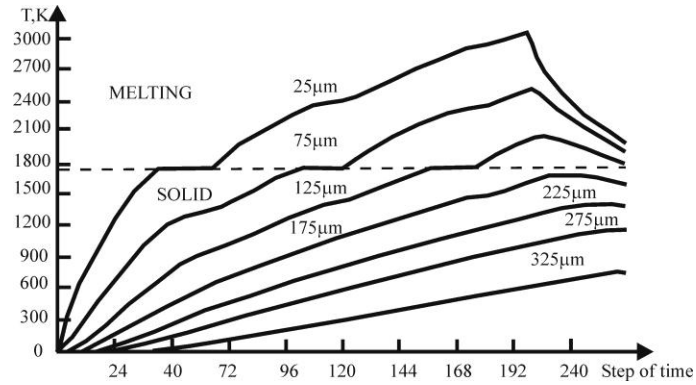


Fig. 3. The heating of under surface layers of steel for laser processing, $E=3 \text{ J/mm}^2$, $t_{\text{imp}}=6 \cdot 10^{-3} \text{ s}$

From the graphs it is visible how the process of heat surface of metal and moment of beginning of formation a melting bath. The calculations have shown, that the melting of matrix begins at energy density $E_{\text{min}}=1,5 \text{ J/mm}^2$. The tangent of angle of slope on the graphs corresponds to heat rate. And the following picture is traced: at reaching of fusing temperature by high layers, they absorbed an energy, which goes only on fusing of given metal volume. In this moment heat of under layer is sharply decelerated. So at laser

treatment in a condition $E = 3 \text{ J/mm}^2$ and pulse duration $6 \cdot 10^{-3}$ seconds, the heat rate on depth $75 \text{ }\mu\text{m}$ prior to the beginning melting away uplayer was $10,2 \times 10^5 \text{ K/s}$, and after of the beginning of melting away - $3 \cdot 10^5 \text{ K/s}$. The data on of cooling on various depths of a fusing bath (Fig.5,a) were obtained. The high gradient of temperatures on depth on a stage of cooling reduces in zonal liquation inside a fusing bath and to high stress temperature with formation of cracks (Fig.5,b).

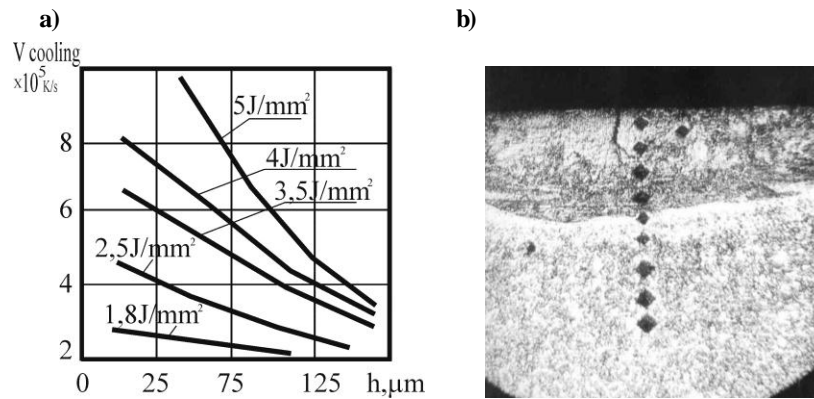


Fig. 5. Variation of cooling rate of a melt on depth at various conditions of laser exposure (a), microstructure of steel by laser chrome alloying, $E=3,5 \text{ J/mm}^2$ (b)

As basic technology factors for laser processing are duration of laser action and density energy, absorbed at it. The conditions of an exposures necessary for a realization on a surface of those or other physical processes were calculated. As a beginning from phase transition of steel to austenite condition and finishing active surface evaporation.

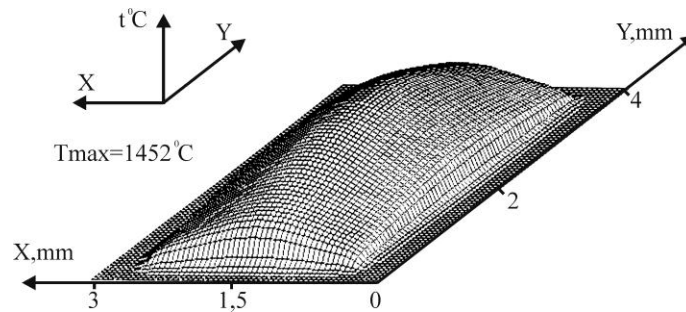


Fig. 6. Temperature field in section of laser beam on surface steel for moment $0,6 \cdot 10^{-3}\text{s}$, $E=2 \text{ J/mm}^2$, $t_{\text{imp}}=3 \cdot 10^{-3}\text{s}$.

In a fig. 6-8 the results of calculation of temperature fields on section of an irradiated surface at various stages of laser action are shown. It is visible, that the fusing bath is formed not on all square of a spot laser exposure

The important moment in laser melting is the definition of depth of alloying and sizes of zones hardening. The investigation is shown, that the defining factor, as density energy is duration of laser exposure. And, the melting consists not only of receiving maximum homogeneity of layers, but also to save defined homogeneity, level of internal stress and hardness of structure. If first is achieved at duration of action $8-10 \mu\text{s}$, by second more short impulse ($2-3 \mu\text{s}$). The depth of melting of layer practically is identical, however gradients of temperatures rather differ, and in the greater measure in fusing bath. In further with a decrease of pulse duration, the depth of zone of laser alloying decreases also.

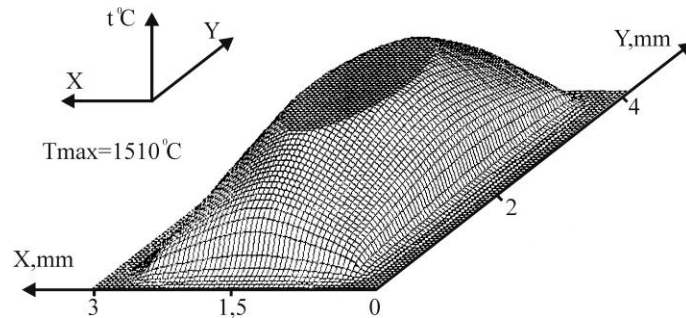


Fig. 7. Temperature field in section of laser beam on surface steel for moment $1 \cdot 10^{-3}\text{s}$, $E=2 \text{ J/mm}^2$, $t_{\text{imp}}=3 \cdot 10^{-3}\text{s}$.

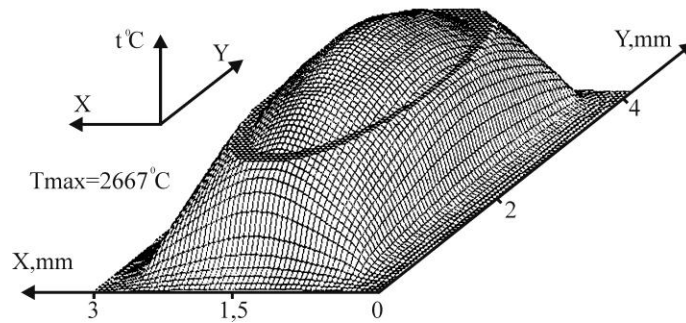


Fig. 8. Temperature field in section of laser beam on surface steel for an extremity of impulse $E=2 \text{ J/mm}^2$, $t_{\text{imp}}=3 \cdot 10^{-3} \text{ s}$.

By results of calculations the diagrams permitting to define depths of zones of laser influence at various conditions of laser exposure were constructed. For this purpose fixed maximum temperature was determined at a specific density of an energy and duration of laser impulse. The maximum depth of zone of laser influence was simultaneously determined.

The ordinates of cross points give values of maximum depth of zone of laser influence. The difference between isotherms T_s and T_l gives magnitude of maximum melting away. As have shown further experimental researches on cross-sectional the depth zone of melting corresponded calculated as the zone hardening from austenite is a little underestimated in the field of small values of an energy density.

In calculations the absorption coefficient and thermal properties is taken into account, but it does not show that complicated influence, which renders process of burn-out on interaction of laser ray with metal surface. The calculation of temperature fields allows to inspect a warm-up of a surface at an exposure and on this basis to predict a degree alloyable.

4. FRETTING WEAR CONDITIONS

It is known, that the laser melting away is applied to improving frictional properties of surfaces of details of machines [8,9]. An impulse exposure lead to not only to a variation of properties because of the localization, but to a

variation of properties in the boundaries of separate impulse. Discretely fretting-resistance of a local zone of melting away was investigated. The scheme of fretting loading

is a balla plane, amplitude of relative movement $50\mu\text{m}$, normal pressure in contact $2,5\text{ MPa}$ number of a cycle $5 \cdot 10^5$. (Fig. 9).

In (Fig.10) the distribution of depth of fretting-wear on a surface after laser processing is shown. As well as it was supposed deep meting of hardened steel reduces of fretting-resistance in a zone of melting away. To ensure a sufficient wear resistance in zone of melting it is possible alloying by Cr, W, Mo, Nb. High fretting-resistance has of doping by niobium with formation of zones of carbides of inculcate carbides NbC.

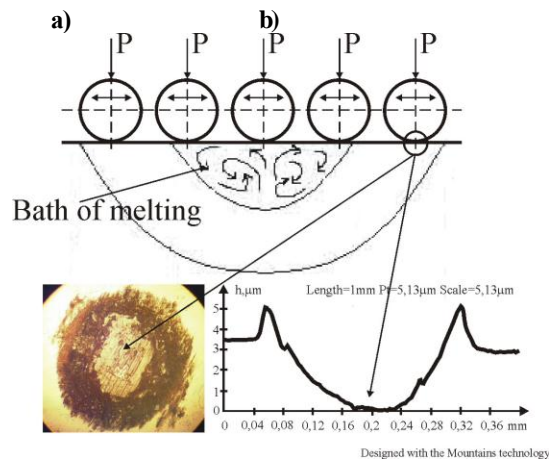


Fig. 9. The scheme of fretting loading of melting and hardening zone (a) and depth of fretting-wear in ball-plane contact.

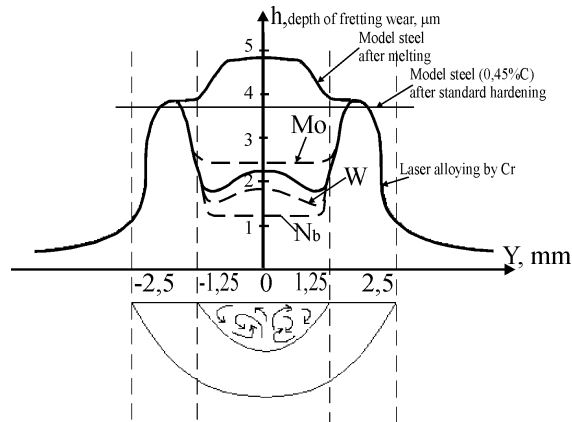


Fig.10 The depth of fretting-failure in depending on the place of ball on a treated surface

5. CONCLUSIONS

1. Temperature gradients in are some times different on depth of zones of laser influence, as on a stage of cooling and heat. And, in a liquid phase this difference is more, than in a solid phase. It reduces in a various degree of a supercooling on depth of a fusing bath and origin of internal liquation. The solid phase is heated up to fusing temperature in time, much smaller pulse on-time. Temperature of fluid is increased faster, than temperature of a solid body, owing to its smaller heat conduction.

2. The temperature fields on a section of laser ray having the rectangular form are calculated. It has allowed to calculate efficiency of alloying with reference to geometry of a ray and normal law of distribution of an energy.

3. The fusing metal is not a sufficient condition for formation of solid solution. Because of greater fusing temperature of alloying elements mechanical and convectional intermixing a liquid matrix with solid particles is possible.

4. The high fretting-resistance of middle carbon steel in conditions local melting is reached by doping by transitional metals Cr, W, Mo, Nb.

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**KSZTAŁTOWANIE LOKALNYCH STREF TOPIENIA LASEROWYM
WPROWADZANIEM DODATKÓW STOPOWYCH W WARSTWĘ WIERZCHNIĄ
ODPORNĄ NA FRETING**

STRESZCZENIE

Laseroowa obróbka impulsowa jest przeznaczona dla obróbki lokalnych miejsc części, które przenoszą znaczne naprężenia kontaktowe. Obszar obróbki ma złożoną budowę zarówno w głębi, jak i na samej powierzchni. Metodą różnic skończonych opracowano model procesu nagrzewania i topienia impulsem laserowym. Wyznaczono parametry geometryczne przestrzeni topienia i wpływu ciepła, gradienty temperaturowe w fazie stałej i płynnej w okresie nagrzewania oraz naturalnego ochładzania. Przeprowadzono próby porównawcze zużycia podczas frettingu różnych fragmentów przestrzeni obróbki stali konstrukcyjnej z dodatkami stopowymi Cr, Mo, W, Nb w czasie działania jednorazowego impulsu.

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