Investigation of the effect of laser radiation on the instrumental composition to determine the modes of combined processing

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Abstract. The paper presents the results of the study of the influence of laser radiation effect on the instrumental composition. The mathematical model of heat distribution in a multilayer body is developed, which allows relatively simple data processing. Analysis of the results of the thermal state of the multilayer composition based of the developed mathematical model of the thermal effect of laser radiation on the material is also presented. The model allows to theoretically estimate the parameters of laser treatment in the framework of combined hardening treatment. The work is executed at support of RFBR project №18-48-730011.

1 Introduction

Improving the performance of the cutting tool by applying wear-resistant coatings to its working surfaces can significantly improve its performance. At the same time, in some cases, the effectiveness of tools with coatings is not sufficient, which necessitates further research in the search for new compositions and designs of wear-resistant coatings and the development of technologies that increase their efficiency. Analysis of scientific and technical literature shows that currently used coatings, single-element, multi-element, single-layer and multi-layer, developed on the basis of titanium nitride or its modifications, the possibilities of which are almost exhausted. This forces us to look for ways to improve the efficiency of already developed coatings.

One of these ways is additional hardening treatment of coated cutting tools, aimed at improving the physical and mechanical properties and adhesion strength of coatings with the tool base [1-3]. As an additional treatment received the use of pulsed laser treatment [4,5].

Despite the significant results obtained by using laser treatment as an additional hardening treatment of coatings applied to the tool, there are many unresolved issues. The existing mathematical models for determining the technological parameters of laser

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processing take into account only the temperature effect on the coated tool, which is quite suitable for high-speed tools. However, for carbide tools it is necessary to assess the stresses that cause cracking. An important point in determining the technological parameters of laser processing are the thermophysical properties of the tool base, which have not been considered in the known works.

2 Methods

The structure of the heat affection zone as a result of exposure to laser radiation on the surface can be investigated by considering the laser treatment as a thermal effect of laser radiation on a multi-layer composition. Using the symmetry of the problem relative to the axis of the laser beam distribution (axis OZ), the temperature distribution will be determined in the plane XOZ, and the real position of the isotherms we will get by the rotation of the corresponding curves around the axis OZ (figure 1).

Fig 1. The scheme of laser radiation exposure on the composition “coating – basis”

Let a body is exposed by an instantaneous distributed heat source at a moment of time $t = 0$, wherein a body has a convective heat transfer with the environment according to the Newton's law. Instrumental composition is composed of k layers: layers from 1 to $k-1$ – rigid wear resistant coatings, k layer – base. Then it is necessary to solve a system of equations:

$$c_1 \rho_1 \frac{\partial T}{\partial t} = \lambda_1 \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right); \quad -l_1/2 < x < l_1/2; \quad 0 < z < h_{L1}; \quad 0 < t < +\infty,$$

$$c_2 \rho_2 \frac{\partial T}{\partial t} = \lambda_2 \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right); \quad -l_1/2 < x < l_1/2; \quad h_{L1} < z < h_{L2}; \quad 0 < t < +\infty,$$

$$c_k \rho_k \frac{\partial T}{\partial t} = \lambda_k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right); \quad -l_1/2 < x < l_1/2; \quad h_{L(k-1)} < z < l_2; \quad 0 < t < +\infty,$$

$$T(x, h_{L1} - 0, t) = T(x, h_{L1} + 0, t); \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty,$$

$$T(x, h_{L2} - 0, t) = T(x, h_{L2} + 0, t); \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty,$$

$$T(x, h_{L(k-1)} - 0, t) = T(x, h_{L(k-1)} + 0, t); \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty,$$

$$\lambda_1 \frac{\partial T(x, h_{L1} - 0, t)}{\partial x} = \lambda_2 \frac{\partial T(x, h_{L1} + 0, t)}{\partial x}; \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty \quad (1)$$

$$\lambda_2 \frac{\partial T(x, h_{L2} - 0, t)}{\partial x} = \lambda_3 \frac{\partial T(x, h_{L2} + 0, t)}{\partial x}; \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty \quad (2)$$

$$\lambda_{k-1} \frac{\partial T(x, h_{L(k-1)} - 0, t)}{\partial x} = \lambda_k \frac{\partial T(x, h_{L(k-1)} + 0, t)}{\partial x}; \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty \quad (3)$$

$$\frac{\partial T(-l_1/2, z, t)}{\partial z} = -\alpha T(-l_1/2, z, t); \quad 0 < z < l_2; \quad 0 < t < +\infty,$$

$$\frac{\partial T(l_1/2, z, t)}{\partial z} = -\alpha T(l_1/2, z, t); \quad 0 < z < l_2; \quad 0 < t < +\infty,$$

$$\frac{\partial T(x, 0, t)}{\partial x} = -\alpha T(x, 0, t); \quad -l_1/2 < x < l_1/2; \quad 0 < t < +\infty,$$

$$q = q_0 \cdot \exp(-k(x - \xi)^2); \quad -l_1/2 < x < l_1/2; \quad z = 0, \quad 0 < t < \tau_l,$$

$$T(-l_1/2, z, 0) = T(l_1/2, z, 0) = T(x, l_2, 0) = T(x, 0, 0) = 0; \quad -l_1/2 < x < l_1/2; \quad 0 < z < l_2,$$

where c_i, ρ_i, λ_i – specific heat, density and thermal conduction coefficient of i material;
 $h_{L1}, h_{L2}, \dots, h_{L(k-1)}$ – the width of the first and second ... k -1– layer; l_1 and l_2 – body sizes
 by the axis OX и OZ respectively; α – thermal efficiency; q_0 – power density in the center
 of the laser spot ; t – time; τ_l – impulse duration; k – radiation concentration coefficient; ξ –
 source center coordinate; x, z – variables.

The solution of the equation system is the expression:

$$T(x, z, t) = \sum_{m,n=1}^{+\infty} A_{m,n} \cdot \exp(-\beta_{m,n} \cdot t) \cdot U_{m,n}(x, z) \quad (4)$$

where $A_{m,n}$ – coefficient, depending on the thermal physical properties of the material,
 the geometric dimensions of the body and the technological parameters of the laser
 radiation, which comes from the expression (5):

$$A_{m,n} = \frac{2 \int_{-l_1/2}^{l_1/2} \int_0^{l_2} \sqrt{\mu(x,z)} \cdot q_0 \cdot \exp(-k(x-\xi)^2) \cdot \sqrt{\frac{\tau_u}{\pi}} U_{m,n}(x,z) dx dz}{\|V_{m,n}\|^2} \quad (5)$$

where $U_{m,n}(x,z)$ – coefficient, depending on the geometrical sizes of the body, thermal physical properties of the material and the heat transfer coefficient, which comes from the expression (6):

$$U_{m,n}(x,z) = \begin{cases} \frac{\sin \omega_{m,n,1} z}{\sin \omega_{m,n,1} h_{L1}} \sin \frac{n\pi x}{l_1}, & -l_1/2 \leq x \leq l_1/2; \quad 0 \leq z \leq h_{L1} \\ \frac{\sin \omega_{m,n,2} (z-h_{L1})}{\sin \omega_{m,n,2} (z-h_{L1})} \sin \frac{n\pi x}{l_1}, & -l_1/2 \leq x \leq l_1/2; \quad h_{L1} \leq z \leq h_{L1} + h_{L2} \\ \frac{\sin \omega_{m,n,3} (z-h_{L1}-h_{L2})}{\sin \omega_{m,n,3} (z-h_{L1}-h_{L2})} \sin \frac{n\pi x}{l_1}, & -l_1/2 \leq x \leq l_1/2; \quad h_{L1} + h_{L2} \leq z \leq h_{L1} + h_{L2} + h_{L3} \\ \dots \\ \frac{\sin \omega_{m,n,k} (l_2 - z)}{\sin \omega_{m,n,k} (l_2 - \sum_{i=1}^{k-1} h_{Li})} \sin \frac{n\pi x}{l_1}, & -l_1/2 \leq x \leq l_1/2; \quad \sum_{i=1}^{k-1} h_{Li} \leq z \leq l_2 \end{cases} \quad (6)$$

where $\beta_{m,n}$ – the root of the following transcendent equation ($m=1, 2, 3, \dots; n=1, 2, 3, \dots$):

$$\begin{aligned} & \left(\lambda_1 \sqrt{\frac{c_1 \rho_1}{\lambda_1} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} + \alpha \right) \cdot \operatorname{ctg} \left(h_{L1} \sqrt{\frac{c_1 \rho_1}{\lambda_1} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} \right) = \\ & = \left(\lambda_2 \sqrt{\frac{c_2 \rho_2}{\lambda_2} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} + \alpha \right) \cdot \operatorname{ctg} \left(h_{L2} \sqrt{\frac{c_2 \rho_2}{\lambda_2} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} \right) = \dots = \\ & = \left(\lambda_i \sqrt{\frac{c_i \rho_i}{\lambda_i} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} + \alpha \right) \cdot \operatorname{ctg} \left(h_{Li} \sqrt{\frac{c_i \rho_i}{\lambda_i} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} \right) = \dots = \\ & = \left(\lambda_k \sqrt{\frac{c_k \rho_k}{\lambda_k} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} + \alpha \right) \cdot \operatorname{ctg} \left(\left(\sum_{j=1}^{k-1} h_{Lj} \right) \sqrt{\frac{c_k \rho_k}{\lambda_k} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} \right) \end{aligned} \quad (7)$$

In formula (8) – (10) the following designations are used:

$$\omega_{m,n,k} = \sqrt{\frac{c_k \rho_k}{\lambda_k} \beta_{m,n}^2 - \frac{n^2 \pi^2}{l_1^2}} \quad (8)$$

$$\mu(x, z) = \begin{cases} c_1 \rho_1 / \lambda_1, & -l_1/2 \leq x \leq l_1/2, 0 \leq z \leq h_{L1} \\ c_2 \rho_2 / \lambda_2, & -l_1/2 \leq x \leq l_1/2, h_{L1} \leq z \leq h_{L1} + h_{L2} \\ \dots \\ c_k \rho_k / \lambda_k, & -l_1/2 \leq x \leq l_1/2, \sum_{j=1}^{k-1} h_{Lj} \leq z \leq l_2 \end{cases} \quad (9)$$

$$\|V_{m,n}\|^2 = \int_{-l_1/2}^{l_1/2} \int_0^{l_2} \mu(x, z) U_{m,n}^2(x, z) dx dz \quad (10)$$

where $\omega_{m,n,k}$ – coefficient, which determines the isotherm form;

$\mu(x, z)$ – coefficient, depending on thermal physical characteristics of the point with coordinates (x, z) ;

$U_{m,n}$ – coefficient, depending on thermal physical properties and geometric characteristics of the treated compositions.

Knowing the distribution of temperatures of the action of a single pulse of laser radiation, using the principle of superposition, the temperature distribution can be obtained from the action of M impulses. Then the solution of the system of equations (1) will have the form:

$$T(x, z, t) = \sum_{m,n=1}^{+\infty} \left[U_{m,n}(x, z) \cdot \exp(-\beta_{m,n}^2 \cdot t) \cdot \sum_{i=1}^M A_{i,m,n} \cdot \exp\left(-\frac{\beta_{m,n}^2 (i-1)}{\nu}\right) \right] \quad (11)$$

where M – number of impulses;

ν – pulse repetition frequency;

$$A_{i,m,n} = \frac{2 \int_{-l_1/2}^{l_1/2} \int_0^{l_2} \sqrt{\mu(x, z)} \cdot q \cdot \exp(-k(x - \xi - (i-1)S_o)^2) \cdot \sqrt{\frac{\tau_u}{\pi}} U_{m,n}(x, z) dx dz}{\|V_{m,n}\|^2} \quad (12)$$

3 Calculation results

As a result of analysis of the mathematical model it is established that the change in thermal characteristics of the layers significantly affects the temperature distribution of the composition. Directionally selecting the thermal physical characteristics of the materials of layers we can control the formation of heat affected zones in the volume of the total composition [6-9].

Determination of the energy characteristics of laser radiation in combined hardening treatment was carried out because of the following reasons: the energy of the laser impulse should provide the maximum size of the hardened zone with the absence of the melted sections for tools, made of high-speed steel, and within the processing of hard-alloyed tools it is necessary to set a temperature limit, at which the destruction of the material of the binder phase begins [10-11].

It has been established that the power density of the laser radiation for the treatment of tool, made of high speed steel before coating (to decrease the elastic-plastic deformation of the cutting wedge) should be $3.45 \cdot 10^4 \text{ W/cm}^2$ (if this value is exceeded, on the surface of the tool liquated areas appear). For combined hardening tool treatment, comprising coating and following laser processing, the laser power density is dependent on the base materials and coatings; thus, for the speed-tool with a single layer TiN laser power density should be equal to $3.8 \cdot 10^4 \text{ W/cm}^2$ (when this value is exceeded at the interface "cover – basis" the melting temperature of basis is reached), coated with (Ti, Zr)N – $3.68 \cdot 10^4 \text{ W/cm}^2$, coated with (Ti,Zr)CN – $3.9 \cdot 10^4 \text{ W/cm}^2$. The laser power density in the processing of tools made of hard alloy with TiN coating must be equal to $3.2 \cdot 10^4 \text{ W/cm}^2$, coated with (Ti,Zr)N – $3.1 \cdot 10^4 \text{ W/cm}^2$, coated with (Ti,Zr)CN – $3.38 \cdot 10^4 \text{ W/cm}^2$.

Fig. 2. Influence of power density of laser radiation on the temperature of the hard-alloyed basis of MK8 and on its boundary, with multilayered coating: 1 – basis (at depth of 6 microns); 2 – TiN-(TiZr)N; 3 – (TiZr)N-TiN; 4 – TiCN-TiN; coating thickness 6 microns, $\tau=4 \text{ ms}$

Similar results can be obtained for the multilayer coatings of different composition and thickness. For example, for a combined hardening tool processing, laser power density for the tool of hard alloy MK8, with two-layered coating of composition (Ti,Zr)N (3.0 microns) – TiN (3.0 microns) the laser power density should be $3.13 \cdot 10^4 \text{ W/cm}^2$ equal to W/cm^2 , coated with the composition of TiN (3.0 microns) – (Ti,Zr)N (3.0 microns) – $3.25 \cdot 10^4 \text{ W/cm}^2$, coated with the composition TiCN (3.0 microns) – TiN (3.0 microns) – $3.4 \cdot 10^4 \text{ W/cm}^2$ (figure 2, curves 1-3 respectively). According to the results of studies, the power density of the laser radiation for the combined hardening treatment of tool, depending on the composition, structure and thickness of the coating, the material of the base varies in the range of about 25% of the value, corresponding to the level of power density for a single layer TiN coating of the same thickness.

For compositions "coating-tool base" temperature on the surface of coatings and at the boundary of the coating with a carbide base is higher compared to the same indicator for a

hard alloy without coating. This is due to the lower thermal conductivity of coatings compared to hard alloys. The thermal conductivity of various coatings based on titanium nitride differs slightly, for this reason, the temperature for the compositions "coating-tool base" with different coatings is almost at the same level.

Fig 3. Temperature distribution in the instrumental composition HTi10-TiN (a) and HTi10-TiN-TiZrN (b) during laser beam processing with a power density of 12000 W /cm²

At the same time, increasing the difference in the thermal conductivity of the coating and the carbide base, the temperature difference becomes significant. For example, when exposed to laser radiation on a composition coated with NbN, whose thermal conductivity is 5.1 times lower than TiN, the surface temperature is 16% higher. As seen in (fig. 3), the temperature isotherms for the composition with this coating are shifted towards the laser radiation exposure zone compared to the composition with TiN coating.

Comparison of temperatures on the surface of the composites with single layer and multilayer coatings shows that regardless of the carbide substrate temperature for them is almost indistinguishable, and in the case that the compositions of the single layer coating and the top layer of the multilayer coating are the same. The obtained data are in good

agreement with the results of the mathematical model temperature calculation and confirm the assumption that the surface temperature is determined by the thermal conductivity of the coatings.

4 Conclusion

The analysis of the results of the thermal state of the multilayer composition theoretically allows estimating the parameters of laser treatment within combined hardening treatment. Thus, in the case of piecewise-homogeneous medium for a multilayered body, classical solution for semi-axle was obtained by the analytical method, which can be used to estimate temperatures, obtained as a result of thermal effect on the composition and for selection of parameters of technological regimes combined hardening treatment, ensuring the necessary properties of cutting tools, made of high-speed steel and hard alloy.

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