Modeling of Exposure of Impulse Laser Radiation on Multilayered Instrumental Composition

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In this paper the results of modeling of laser radiation effect of on multilayer instrumental composition are presented. The mathematical model of heat distribution in multi-layer body is described, which allows producing a relatively simple numerical data processing. Analysis of the results of the thermal state of the multilayer composition based on the developed mathematical model of the thermal effect of laser radiation on the material is theoretically allows estimating the parameters of laser treatment within the combined hardening treatment.

Key words: Cutting tools, wear resistant coating, combined treatment, Laser radiation, power density, mathematical model, thermal characteristics.

One of the most effective methods of increasing the efficiency of cutting tools (CT) is the use of wear-resistant coatings. It is known that the deposition of multilayer coatings of different compositions can improve efficiency of cutting tools by several times in comparison with monolayer coatings. Currently there many multilayer structures of wear-resistant coatings are developed, which show significantly less wear in comparison with monolayer coatings (Tabakov and Chihkranov, 2010; Tabakov and Chihkranov, 2009; Tabakov, 2012; Vereschaka *et al*., 2014). Directional change of the microstructure and further improvement the performance of wear resistant coatings in some cases requires the use of several methods of hardening treatment. Consistent application of two or more surface technology in a single technological cycle makes it possible to obtain a combination of properties that can not be achieved by any of these technologies used separately. One of the examples of the combined hardening treatment is a combination of ion-plasma coating by method of CII (cathode ion implantation) with followed laser treatment. In general, the modes of laser processing can be determined on the basis on analysis of the thermal influence zone. Modern wear resistant compositions are multilayer structures, which, together with the locality and the transience of the heat distribution complicates the mathematical description of the process. In this article we attempt to describe the effects of laser radiation on a multi-layer composition (Chia-Han Lai *et al*., 2008; Alami *et al*., 2005; Tabakov and Vereschaka, 2014; Vereschaka *et al*., 2014).

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Methodology

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* (see Figure 1).

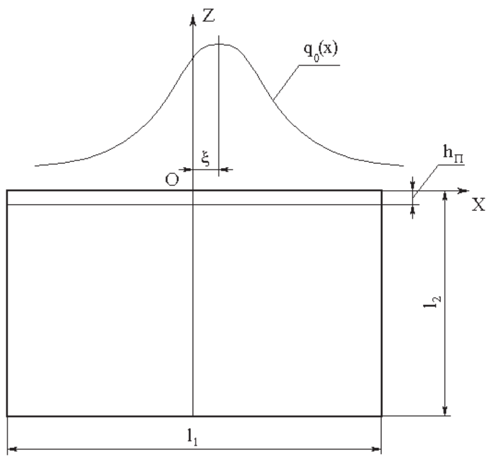

Fig. 1. The scheme of laser radiation exposure on the composition "coating – basis"

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:

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

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

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

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

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

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

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

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

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

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

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

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

$$q=q_0\cdot\exp\left(-k(x-\xi)^2\right);\ -{l_1}/{2}<x<{l_1}/{2};\ z=0,\ 0<t<\tau_I,$$

$$T\left(-{l_1}/{2},z,0\right)=T\left({l_1}/{2},z,0\right)=T(x,l_2,0)=T(x,0,0)=0;\ -{l_1}/{2}<x<{l_1}/{2};\ 0<z<l_2,$$

where c_i, r_i, l_i – specific heat, density and thermal conduction coefficient of i material; h_{L1}, h_{L2}, … $h_{L(k-1)}$ – the width of the first and second … k-1– layer; l_1 and l_2 – body sizes by the axis *OX* è *OZ* respectively; a – thermal efficiency; q_0 – power density in the center of the laser spot ; t – time; t_I – impulse duration; k – radiation concentration coefficient; x – 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):

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

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):

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

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

$$\left(\lambda_1\sqrt{\frac{c_1\rho_1}{\lambda_1}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}+\alpha\right)\cdot ctg\left(h_{L1}\sqrt{\frac{c_1\rho_1}{\lambda_1}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}\right)=$$
$$=\left(\lambda_2\sqrt{\frac{c_2\rho_2}{\lambda_2}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}+\alpha\right)\cdot ctg\left(h_{L2}\sqrt{\frac{c_2\rho_2}{\lambda_2}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}\right)=\ldots=$$
$$=\left(\lambda_i\sqrt{\frac{c_i\rho_i}{\lambda_i}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}+\alpha\right)\cdot ctg\left(h_{Li}\sqrt{\frac{c_i\rho_i}{\lambda_i}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}\right)=\ldots= \quad ...(7)$$
$$=\left(\lambda_k\sqrt{\frac{c_k\rho_k}{\lambda_k}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}+\alpha\right)\cdot ctg\left((\sum_{j=1}^{k-1}h_{Lj}-l_2)\sqrt{\frac{c_k\rho_k}{\lambda_k}\beta_{m,n}^2-\frac{n^2\pi^2}{l_1^2}}\right)$$

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

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

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

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

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

μ(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;

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

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 (Tabakov, 2012; Faga *et al*., 2007; Kang *et al*., 2003; Castanho and Vieira, 2003; Tabakov and Vereschaka, 2014).

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 (Çalýþkan *et al*., 2013; Fox-Rabinovic *et al*., 2009).

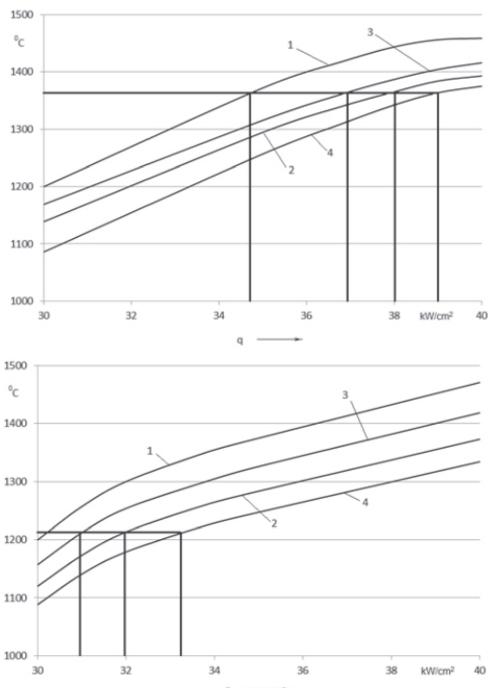

Fig. 2. Influence of laser power density on the temperature in the tool basis on its border with single layer: 1 " at a depth of 6 microns; 2 " TiN; 3 " (TiZr)N; 4 " (TiZr)CN. a " high-speed base R6M5, b – hard-alloyed basis MK8. Coating thickness of 6 microns, τ_1=4 ms

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’”10^4 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’”10^4 W/cm^4 (when this value is exceeded at the interface “cover – basis” the melting temperature of basis is reached), coated with (Ti, Zr)N – 3.68’”10^4 W/cm^2, coated with (Ti,Zr)CN – 3.9’”10^4 W/cm^2 (figure 2, and curves 2-4). The laser power density in the processing of tools made of hard alloy with TiN coating must be equal to 3.2’”10^4 W/cm^2, coated with (Ti,Zr)N – 3.1’”10^4 W/cm^2, coated with (Ti,Zr)CN – 3.38’”10^4 W/cm^2 (figure 2b, curves 2-4 respectively).

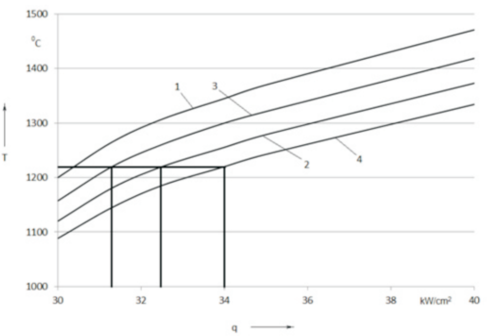

Fig. 3. Influence of power density of laser radiation on the temperature of the hard-alloyed basis of MK8 and on its boundary, with multilayered coating: 1 – basis (at depth of 6 microns); 2 – TiN-(TiZr)N; 3 – (TiZr)N-TiN; 4 – TiCN-TiN; coating thickness 6 microns, τ_I=4 ms

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’”10^4 equal to W/cm^2, coated with the composition of TiN (3.0 microns) “ (Ti,Zr)N (3.0 microns) – 3.25’”10^4 W/cm^2, coated with the composition TiCN (3.0 microns) “ TiN (3.0 microns) – 3.4’”10^4 W/cm^2 (figure 3, 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.

Researches of a working capacity of cutting tools after combined treatment using laser radiation was carried out in a wide range of cutting conditions within turning machining of work parts made of steel 30KhGSA, 12Kh18N10T and titanium alloy VT22. To test the efficiency of the mathematical model and adequacy regimes of a combined treatment the studies of single-element, multi-element and composite types of coatings were performed: TiN, (Ti, Zr)N and (Ti, Zr)CN, which is applied to the tool of high speed steel R6M5K5 and hard alloy MK8. The combined treatment was carried out in two ways: the first variant – the laser radiation treatment and subsequent coating, the second variant – coating and subsequent processing by the laser.

DISCUSSION

Consider the effectiveness of the tool when combined hardening treatment. The results of the research on the effectiveness of the instrument after combined hardening treatment are shown in figures 4-7 and in tables 1 and 2.

When processing of work parts made of steel 30KhGSA by the tool, coated by complex composition, based on nitrides and carbonitrides significantly increases the efficiency of high-speed steel tools (Figure 4). Coefficient of increase in resistance for these coatings in relation to the TiN coating was 1.2-2 and 2-4, respectively, depending on the cutting conditions.

Figure 4 shows that with increasing of cutting speed the effectiveness of the tool made of speed steel with coatings of complex composition, based on nitrides and carbonitrides increases (the coefficient of resistance increase for the coating (Ti, Zr) N compared to TiN coating increases from 1.2 at V = 50 m/min up to 2 at the speed of V = 70 m/min, coating (Ti, Zr)CN – respectively from 2 to 4), within the increasing of feed of the coefficient of resistance increasechanges substantially less (for the tool coated with (Ti, Zr) N) than the resistance change compared to TiN coated tool of the coefficient of resistance increaseincreases from 1.5 when cutting with the feed of S = 0.15 mm/rev to 1.6 when cutting with the feed of S = 0.3 mm/rev; for the tool coated with (Ti, Zr)CN – respectively from 2.8 to 3.1).

Application of the combined hardening treatment can significantly increase the work life of the speed steel compared with the tool with an appropriate coating. The increase resistance period is determined by the variant of the combined hardening treatment, instrumental processed materials, the type of coating and cutting modes. The higher working capacity of speed steel tool after combined hardening treatment is associated with coating microhardness increase, strength of

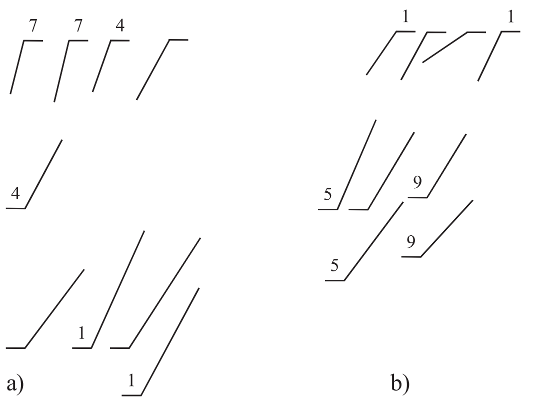

Fig. 4. Effect of cutting speed (a) and feed (b) on the resistance period of the tool made of speed steel R6M5K5 within turning of steel work parts made of 30KhGSA: *S*=0.3 mm/rev, *t*=0.75 mm (**à**); *V*=50 m/min, *t*=0.75 MM (**b**); **1** – TiN; **2** – LT + TiN; **3** – TiN + LT; **4** – (Ti,Zr)N; **5** – LT + (Ti,Zr)N; **6** – (Ti,Zr)N + LT; **7** – (Ti,Zr)CN; **8** – LT + (Ti,Zr)CN; **9** – (Ti,Zr)CN + LT

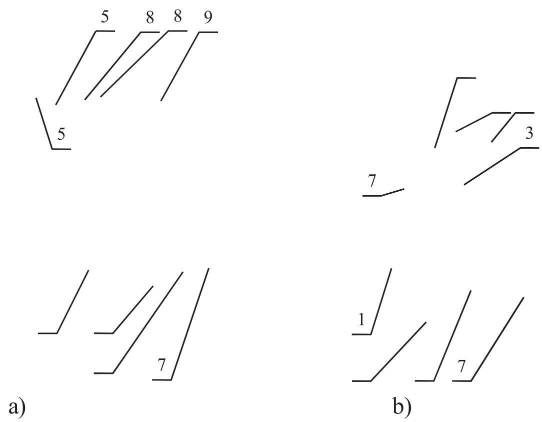

Fig. 5. Effect of cutting speed (a) and feed (b) on the resistance period of the tool made of speed steel R6M5K5 within turning of steel work parts made of 12Kh18N10T: *S*=0.3 mm/rev, *t*=0.75 mm (**a**); *V*=20 m/min, *t*=0.75 mm (**b**); **1** – TiN; **2** – LT + TiN; **3** – TiN + LT; **4** – (Ti,Zr)N; **5** – LT + (Ti,Zr)N; **6** – (Ti,Zr)N + LT; **7** – (Ti,Zr)CN; **8** – LT + (Ti,Zr)CN; **9** – (Ti,Zr)CN + LT

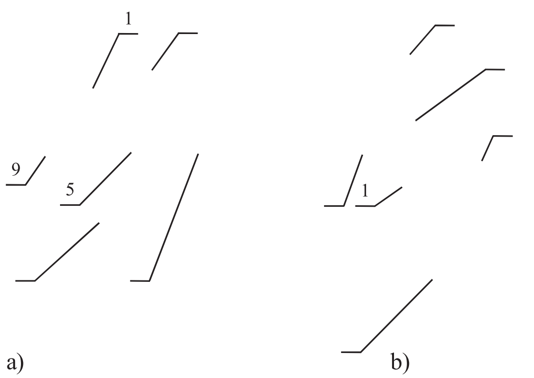

Fig. 6. Effect of cutting speed (a) and feed (b) on the resistance period of the tool made of the hard alloy MK8 within turning of steel work parts made of the steel 30KhGSA: *S*=0.3 mm/rev, *t*=0.5 mm (**à**); *V*=180 m/min, *t*=0.5 mm (**b**); **1** – TiN; **2** – TiN + LT; **3** – (Ti,Zr)N; **4** – (Ti,Zr)N + LT; **5** – (Ti,Zr)CN; **6** – (Ti,Zr)CN + LT

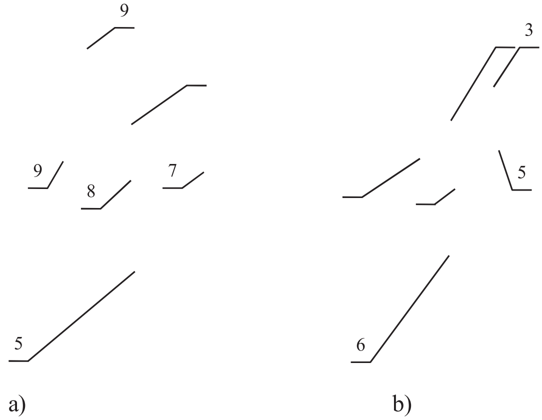

Fig. 7. Effect of cutting speed (a) and feed (b) on the resistance period of the tool made of the hard alloy MK8 within turning of steel work parts made of 12Kh18N10T: *S*=0.3 mm/rev, *t*=0.5 mm (**a**); *V*=160 m/min, *t*=0.5 mm (**b**); **1** – TiN; **2** – TiN + LT; **3** – (Ti,Zr)N; **4** – (Ti,Zr)N + LT; **5** – (Ti,Zr)CN; **6** – (Ti,Zr)CN + LT

the adhesive bond with the base and higher fracture toughness. As it is seen in Figure 4, at a speed of V = 50 m/min a period of the tool resistance, coated with TiN, (Ti, Zr)N and (Ti, Zr)CN after the first variant of the combined hardening treatment increased for 1.8 times, 2.1 times and 1.9 times as compared with the tool with an appropriate coating; at a speed of V = 70 m/min, the coefficient of resistance increase was 2, 2.7 and 2.1. Thus, as an instrument coated with CIB for the tool after the first variant of the combined hardening treatment, tool efficiency increase takes place together with increase of cutting speed. The feed change has less significant impact on its period of resistance. Thus, when turning with the feed of S = 0.15 mm/rev the coefficient of resistance increase was 2-2.2, when cutting with the feed of S = 0.3 mm/rev tool life period increased for 2.2-2.5 times depending on the composition of the coating.

Application of the second variant of the combined hardening treatment results in a significant increase of resistance period of the tool made of HSS. As it is seen from the Figure 4, the resistance period of the tool, coated with TiN, (Ti, Zr)N and (Ti, Zr)CN after combined hardening treatment of the second variant in comparison with the tool with a corresponding coating increases for 2-3.4 times, 2.5-3.2 times, and 2.1-2.5 times, respectively, depending on cutting speed (higher values of the resistance increase coefficient correspond to velocity V = 70 m/min, lower – velocity V = 50 m/min). With feed increase resistance increase coefficient varies significantly less than the speed changes: the cutting with the feed of S = 0.15 mm/rev by the HSS tool after the combined hardening treatment according to the second variant with coatings TiN, (Ti, Zr)N and (Ti, Zr)CN the coefficient of resistance increase compared with the tool with corresponding CIB was 2.2, 2.3 and 1.7, respectively, when cutting of the HSS after the combined hardening treatment of the second variant in comparison with the tool after the combined treatment of the first variant is associated with high coatings' performance characteristics: microhardness, strength of the connection of coating with the instrumental basis, fracture toughness.

When cutting the work parts made of the steel 12Kh18N10T similar results are obtained. Turning by the tool with coatings of complex composition, based on nitrides and carbonitrides increases the period of resistance, but it is less significant than in the processing of the work parts made of the steel 30KhGSA (Figure 5). The resistance increase coefficient with respect to TiN coating was 1.4-2 and 1.5-2.2 respectively for the tool coated with (Ti, Zr)N and (Ti, Zr)CN. As in the processing of work parts made of the steel 30KhGSA, the efficiency of the HSS tool, coated with complex composition increases with cutting speed increasing and feed, but the change is less significant.

Use of the combined hardening treatment also improves the resistance period of the tool life made of HSS, but the efficacy of the usage of combined treatment is lower than in the processing of work parts made of steel 30KhGSA. This is explained by harder cutting conditions of work parts made of steel 12Kh18N10T: a higher level of plastic deformation, cutting forces, contact loads and temperatures. It is that an instrument, which passed hardening treatment has resistance period (during the processing of work parts made of the steel 12Kh18N10T) 1.2-2.1 times greater than the coated tool CIB (Fig. 6.2). The largest increase of the period of resistance is also the case for the second variant of the combined hardening treatment. Thus, the resistance period of the tool after the first variant of the combined treatment is increased for 1.2-1.6 times compared with the tool with an appropriate coating, and after the second variant – 1.4-2.1 times depending on the speed of cutting.

Similar data were obtained within the machining of work parts made of the titanium alloy VT22. It was found an increase of the resistance period of the tool made of HSS after the combined hardening treatment, the growth of the resistance period is less significant than in machining of work parts made of the steel 30KhGSA 12Kh18N10T. This is because of the fact that machining of titanium alloys is characterized by extremely hard cutting conditions. Resistance increase coefficient after the first variant of the combined hardening treatment was 1.2-1.4, and after the second variant – 1.2-1.7 with respect to the TiN coating according to the cutting conditions. Higher values correspond to the resistance increase coefficient velocity V = 15 m/min, lower – V = velocity of 7 m/min.

The results of research on the effectiveness of the tools made of hard alloy after the combined hardening treatment of the second variant are shown in Figures 6 and 7.

Research has established that the processing of work parts made of the steel 30KhGSA the tool resistance period of hard alloy after the second variant of the combined treatment is significantly higher than the tool resistance period of the tool, coated with CIB of the similar composition: 1.8-3 times for 2.1-2.3 times and 1.8-2.1 times, respectively, for the tool coated with TiN, (Ti, Zr)N and (Ti, Zr)CN depending on the cutting speed. As for tools of high-speed steel, the increase of the tool resistance period in this case is associated with a higher microhardness of the coating, the strength of its connection with the instrumental basis, fracture toughness. In addition, it was found that with an increase of feed resistance increase coefficient varies significantly less than when changing the cutting speed (Figure 6).

When processing 12Kh18N10T steel the tool resistance period after the combined treatment increased for 1.7-2 times as compared with the tool with an appropriate coating depending on the cutting speed (higher values correspond to the coefficient of resistance increase corresponds to V = 180 m/min, lower – speed V = 130 m/min; Fig. 7).

Slightly less effectiveness than in turning of work parts of the steel 30KhGSA 12Kh18N10T, show the tools made of hard alloy after the combined hardening treatment within the machining of titanium alloy VT22. It may be noted that the processing of this alloy work parts the tool resistance period of hard alloy after the the second variant of the combined hardening treatment is 1.2-1.4 times as high as the resistant period of the hard alloy tool coated with CIB. As well as for tools of high-speed steel after the combined treatment tool, it was found out that efficiency of the tool of hard alloy after the combined treatment with increasing of cutting speeds. At the same time, the feed has an insignificant effect on the coefficient of the resistance increase: the cutting with the feed S = 0.15 mm/rev coefficient of the resistance increase was 1.2, 1.2 as compared with the tool coated with CIB and 1.1 respectively, cutting feed with S = 0.3 mm/rev – 1.3, 1.25 and 1.2, respectively, for coating TiN, (Ti, Zr)N and (Ti, Zr)CN.

CONCLUSIONS

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.

Efficiency of the combined hardening treatment is considered in this paper, comprising applying a wear-resistant coating and laser treatment, from the viewpoint of operability of the cutting tool. Illustrative is representation of a model resistance period as the mathematical reasoning. Tables 1 and 2 show the mathematical models of the resistance period of HSS and hard alloy after the combined hardening treatment when turning of work parts of 30KhGSA, 12Kh18N10T and alloy VT22.

The analysis of the mathematical models allows mentioning that applying of the wear resistant coatings does not change the nature of dependence of the resistance period by cutting speed and feed. However, the degree of influence of individual factors on the tool resistance period varies depending on the base material and the processed material, and the coating composition and the variant of the combined hardening treatment. In general, it can be noted that the deposition of wear resistant coatings on both the high-speed tool steel and hard alloy, reduces the impact of speed and feed in comparison with the uncoated tool.

REFERENCES

1. Tabakov, V.P., Chihkranov A.V, Method of receiving of multilayer coating for cutting tool: *Russian Engineering Research.* 2010; **30**(1): 2010, Pages 84-89. DOI: 10.3103/S1068798X10010193.
2. Tabakov, V.P., Chihkranov A.V, Multicomponent nitride coatings for improving tool performance: *Russian Engineering Research.* 2009; **29**(10):

2009; 1047-1053. DOI: 10.3103/S1068798X09100190.

3. Tabakov, V.P., 2012. Crack resistance of tool coatings in continuous cutting: Russian Engineering Research. Volume 32, Issue 5-6, May 2012, Pages 464-468. DOI: 10.3103/S1068798X12040260.
4. Mechanical and tribological properties of multi-element (AlCrTaTiZr)N coatings /Chia-Han Lai, Keng-Hao Cheng, Su-Jein Lin, Jein-Wei Yeh // Surface and Coatings Technology.–2008.–V.202.–P. 3732–3738. DOI: 10.1016/j.surfcoat.2008.01.014.
5. Alami J, Persson P.O.A., Music D, Gudmundsson J.T, Bohlmark J., Helmersson U., 2005. On-assisted Physical Vapor Deposition for Enhanced Film Properties on Nonflat Surfaces // Journal of Vacuum Scienceand Technology A Vacuum Surfaces and Films 23(2):278–280. DOI: 10.1116/1.1861049.
6. Tabakov, V.P., 2012. The influence of machining condition forming multilayer coatings for cutting tools: Key Engineering Materials. 6th International Congress of Precision Machining. Volume 496, 2012, Pages 80-85. DOI: 10.4028/www.scientific.net/KEM.496.80.
7. Faga M.G., Gautier G., Calzavarini R., Perucca M., Boot E.A., Cartasegna F., Settineri L., 2007. AlSiTiN an composite Coatings Developed Via Arc Cathodic PVD: Evaluation of Wear Resistance Via Tribological Analysis and High Speed Machining Operations. Wear 263(7–12):1306–1314. DOI: 10.1016/j.wear.2007.01.109
8. Performance evaluation of AIP-TiAlN coated tool for high speed machining / Kang, M.C.a, Park, I.W.b, Kim, K.H. // Surface and Coatings Technology. Volume 163-164, 30 January 2003, P. 734-738. DOI: 10.1016/S0257-8972(02)00696-5
9. Effect of ductile layers in mechanical behaviour of TiAlN thin coatings / Castanho, J.M., Vieira, M.T. // Journal of Materials Processing Technology Volume 143-144, Issue 1, 20 December 2003, P. 352-357. DOI: 10.1016/S0924-0136(03)00454-0
10. Çalýþkan H., Kurbanoðlu C., Panjan P., Èekada M., Kramar D. Wear behavior and cutting performance of nanostructured hard coatings on cemented carbide cutting tools in hard milling// Tribology International, Vol. 62. 2013. P. 215-222. DOI: 10.1016/j.triboint.2013.02.035
11. Fox-Rabinovich G.S., Kovalev A.I., Aguirre M.N. Disind and performange of AlTiN and TiAlCrN PVD coatings for machining of hart to cut materials//Surface and Coatings Technology. 2009. Vol.204. P.489-496/ . DOI: 10.1016/j.surfcoat.2009.08.021.
12. Vereschaka, A.S., Grigoriev, S.N., Tabakov, V.P., Sotova, E.S., Vereschaka, A.A., Kulikov, M.Y., 2014. Improving the efficiency of the cutting tool made of ceramic when machining hardened steel by applying nano-dispersed multi-layered coatings: Key Engineering Materials, 7th International Congress of Precision Machining, Volume 581, 2014, Pages 68-73. DOI: 10.4028/www.scientific.net/KEM.581.68.
13. Tabakov, V.P., Vereschaka, A.S., 2014. Development of technological means for formation of multilayer composite coatings, providing increased wear resistance of carbide tools, for different machining conditions: Key Engineering Materials, 7th International Congress of Precision Machining, Volume 581, 2014, Pages 55-61. DOI: 10.4028/www.scientific.net/KEM.581.55.
14. Tabakov, V.P., Vereschaka, A.S., 2014. Development of technological means for formation of multilayer composite coatings, providing increased wear resistance of carbide tools, for different machining conditions: Key Engineering Materials, 7th International Congress of Precision Machining, Volume 581, 2014, Pages 55-61. DOI: 10.4028/www.scientific.net/KEM.581.55.
15. Vereschaka, A.S., Vereschaka, A.A., Savushkin, G.J., Sivenkov, A.S., 2014. Multilayer nanostructured coatings for cutting tools: Inorganic Materials: Applied Research. Volume 5, Issue 5, 24 October 2014, Pages 522-529. DOI: 10.1134/S2075113314050220.
16. Vereschaka, A.A., Mokritskii, B.Y., Pustovalov, D.A., Vereschaka, A.S., Bublikov, J.I., Oganyan, M.G., 2014. Improving the efficiency of carbide end mills by deposition of nanoscale multi-layered composition coatings. Applied Mechanics and Materials. International Conference on Mechanics and Mechanical Engineering. Volume 684, 2014, Pages 264-270. DOI: 10.4028/www.scientific.net/AMM.684.264.