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INCREASING THE EFFICIENCY OF LASER HEAT TREATMENT OF A LATHE TOOL WITH ALLOWANCE FOR THE INFLUENCE OF THE CUTTING REGIMES

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A complex approach to estimation of the process of cutting with a hardened tool is proposed. The choice of factors having the strongest influence on the durability value of cutting tools upon their laser treatment has been made and the significant influence of their interaction effects has been established. An adequate mathematical model of the cutting process has been constructed. It is shown that to achieve the greatest positive effect, irradiation of cutting tools should be carried out taking into account their particular operating conditions. It is recommended to use this model under working conditions to obtain the required durability of the tool under given operating conditions.

Introduction. In the traditional process of laser heat treatment (LHT) of tools (in particular, lathe tools), the optimum irradiation conditions are found on the basis of the analysis of the structural-phase changes in the laser action zone (LAZ) for each particular material and the standard size of the article being treated. In so doing, one practically does not take into account that the durability of a hardened tool largely depends on the operating conditions. In reality, the number of factors determining, in the final analysis, its workability upon LHT appears to be very large. Therefore, the approach to the estimation of the efficiency of the hardening process currently used in laser technology turns out to be limited. And now the problem of choosing the conditions for irradiating cutting tools under particular operating conditions for obtaining specified operating parameters and optimizing the regime of laser hardening by the wear-resistance criterion is topical. To prolong the life of a tool, it is necessary to consider and take into account, in solving the optimization problem, all factors producing an effect on its durability.

This problem can be solved within the framework of the system approach in a complex study of the influence of the regimes of hardening processes used in production and the operating conditions of a metal-working tool on its durability.

Scheme of Analysis of the Process of Cutting with a Tool Hardened by Laser Radiation. According to the *complex* approach to estimation of the influence of the regimes of pulsed LHT and the operating conditions of irradiated lathe tools on their durability parameters, the laser treatment parameters for specified operating conditions of the tool were determined by the wear-resistance criterion with the use of the method of active multifactor experiment [1]. In so doing, both the quantities characterizing the process of laser hardening and the quantities determining the operation of the lathe tool were varied. As the optimization parameter representing the reaction to the action of the factors under discussion on the process being investigated, the wear resistance of the cutting tool or the width of the wear facet on the rear face at a fixed time of its operation was taken.

With the existing diversity of metal-working tools, their operating conditions, and possible techniques of working surface hardening, the solution of the problem of technological provision of the service properties should be considered in terms of such a methodological approach as the system approach [2]. A model of the process of cutting with a hardened tool based on this principle is given in Fig. 1.

In the technological system (TS) under consideration — "technological process of cutting with a tool hardened by pulsed laser radiation" — one can distinguish two subsystems of technological operations of the first level: (1) LHT (S_1) and (2) cutting (S_2).

At the input of the subsystem S_1 a number of controlled factors characterizing the hardening conditions act: ε, K_{overl}, N, τ_p, etc.

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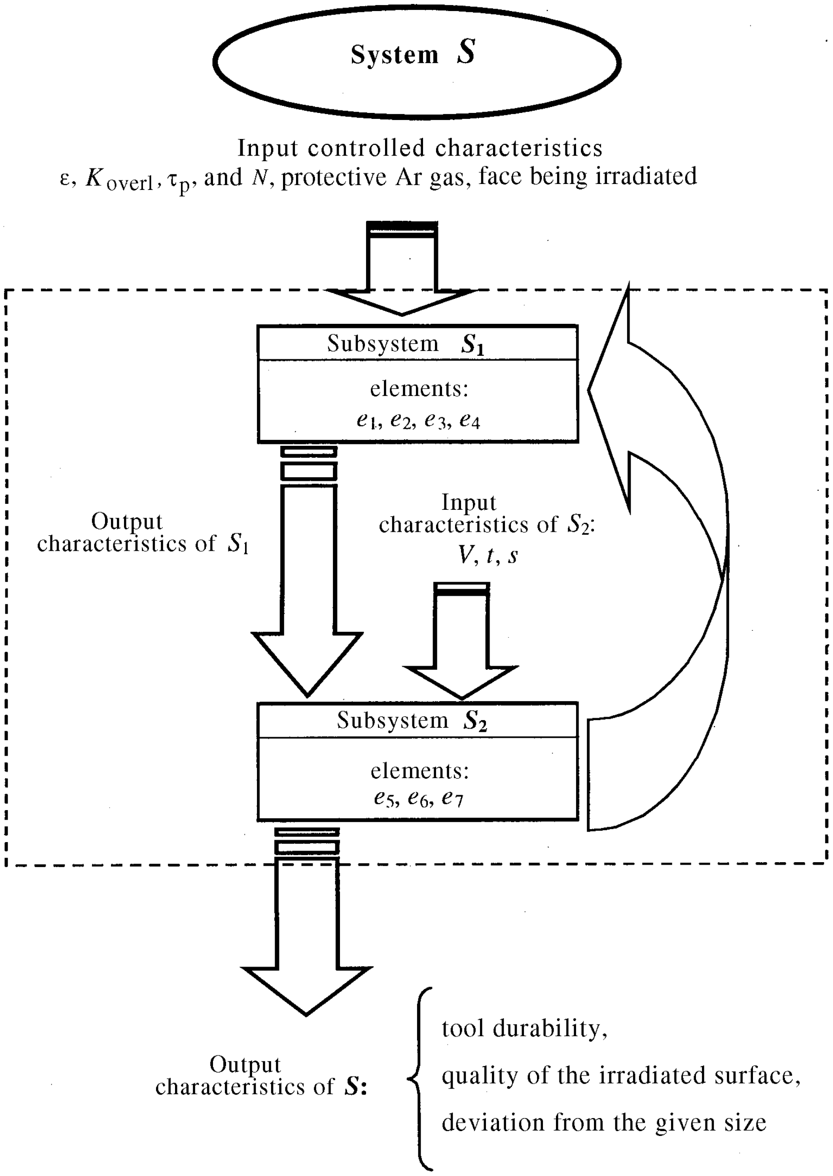

Fig. 1. Technological process of cutting with a hardened tool as a technological system.

The properties of elements e_1, ..., e_4 of the subsystem S_1 are determined by its output parameters. It should be noted that the quality parameters of the surface layer of the material being hardened, primarily the irradiated surface roughness, microhardness, and LAZ depth depend on the combination of properties of particular elements forming the system. The values of a number of factors determining the output characteristics of the subsystem S_1 depend in turn on the properties of elements e_1, ..., e_4. In particular, the laser radiation energy density is chosen proceeding from the properties of the surface layer of the material being hardened and the properties of the medium and the coating in the treatment zone.

The subsystem S_2 has at the input its own number of acting controlled factors characterizing the operating conditions: V, t, and s. Moreover, the output characteristics of S_1 arrive at the input of S_2, and their cooperative action determines the output characteristic of the TS as a whole.

The actions of elements e_5, ..., e_7 of the subsystem S_2 are analogous to the actions of the S_1 elements. Their properties determine the choice of the cutting conditions to provide the required output characteristics of S, in particular, the durability of hardened cutting tools.

Within the framework of the system approach the obtaining of high quality indices of the surface layer in the LAZ (output characteristics of S_1) of an individual tool material is not sufficient for providing maximum durability (i.e., providing the maximum values of the output characteristics of the system S as a whole). The presence of a hardened layer on the working surface of the cutting wedge of the tool upon LHT significantly changes the conditions for the contact interaction in the turning process. Along with the factors characterizing the cutting conditions and arriving at the S_2 input, the output characteristics of S_1 determine the output value of the system as a whole. The cooperative action of these values imparts properties to S_1 which are not inherent in each subsystem taken separately.

As applied to the technological process of cutting with a hardened tool, the system approach permits using, for constructing a TS model, a regressive analysis that makes it possible to construct a functional model of the relation of its durability to the physicotechnical parameters characterizing both irradiation and cutting conditions.

Analysis of the familiar developments in the field of LHT of metal-working tools [3–5] shows that the joint influence of the regime of laser treatment and its operating conditions on the durability characteristics has not been studied before. Such an approach is undoubtedly expedient, since it permits determining the regimes of laser treatment for particular operating conditions by the wear-resistance criterion and is able to provide a further increase in the existing efficiency of the hardening LHT.

The investigations in accordance with the proposed complex approach to estimation of the efficiency of the process of cutting with a hardened tool were carried out in the following sequence:

1) the significance of the factors influencing the characteristics of irradiated cutting tools was judged;

2) on the basis of the multifactor analysis an adequate functional relation between the durability and the hardening and operating conditions was found;

3) visual interpretation of the results of the natural experiment was made;

4) the wear of hardened cutting tools was predicted and optimization of the LHT regimes for the specified operating conditions of the tool by the wear-resistance criterion was carried out.

Realization of the System Approach to the Process of Cutting with a Tool Hardened by Pulsed Laser Radiation. To choose the factors producing the most significant effect on the efficiency of the process of LHT of a metal-cutting tool, the rank correlation [1] and random balance methods [6] were used.

The application of the rank correlation method did not provide a definite answer about the degree of influence of the factors being analyzed on the durability of hardened cutting tools. The conflicting opinions about their influence on the wear permitted the conclusion that the process has been little studied and it is necessary to include in the natural experiment as many factors as possible.

The choice of the most important factors and their interactions with the use of the random balance method was carried out in several stages on the basis of the experimental data obtained in [6] by conventional methods [7].

As a result of 16 experiments, the factors and pair interactions exerting the strongest influence on the hardened tool wear were determined (Fig. 2).

Upon calculation of the estimates of the regression coefficients, the mathematical model of the process under investigation is of the form

$$T = 33.9 - 12.5X_1 - 18.25X_4 - 15.0X_5 - 14.6X_1X_3 + 10.65X_2X_4 - 8.4X_1X_8 - 11.2X_6X_7 + 6.35X_4X_5 + 4.3X_5X_8\,,$$

where X_1 is the cutting speed, X_2 is the irradiation energy, X_4 is the cutting depth, X_5 is the feed, X_6 is the rear angle of the cutting tool, X_7 is the front angle of the cutting tool, X_8 is the treatment multiplicity, and X_3 is the irradiated face of the cutting tool. In experiments, the presence of a protective Ar gas in the irradiation zone was also taken into account.

Analysis of the experimental results shows that the regime of laser treatment of cutting tools has no direct effect on the tool durability. Its role mainly shows up as interaction effects, for example, "irradiation energy–cutting depth", "cutting speed–irradiated face", etc. (Fig 2). Here the nonlinearity of the response function of the system is pronounced: the regression coefficients for the interaction effects considerably exceed the error in their determination and slightly differ in magnitude from such for linear terms. According to the data obtained, an increase in the durability would be expected in the case of LHT with the largest possible values of energy in the case of cutting with large depth values. It is also expedient to use cutting tools hardened on the rear face, where wear is mainly localized at low turning speeds.

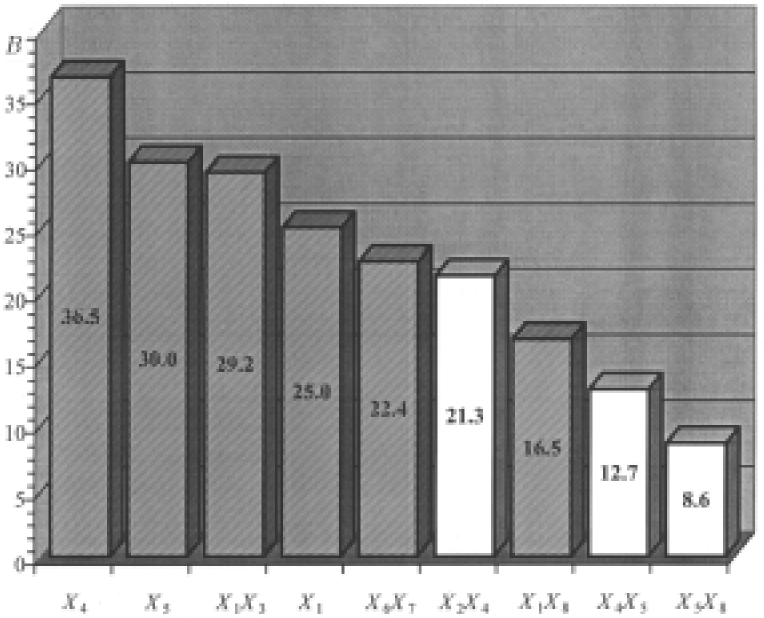

Fig. 2. Diagram of the effects of the selected factors and pair interactions: the light background indicates a positive value, the dark background — a negative value.

The analysis of the effects of the chosen factors belonging to the region of both cutting and hardening conditions and their pair interactions (Fig. 2) enables us to give recommendations on the LHT of a tool and its subsequent application. Taking into account that to increase the turning efficiency high-speed cutting is used, one would expect an increase in the durability in treating cutting tools in air on the front face with small values of irradiation multiplicity and energy. In so doing, cutting should be realized with low feed values at a small thickness of the treated metal layer being cut off. Such a combination of the values of the factors being varied is expedient in finishing turning. Apparently, to increase the efficiency of rough turning, the choice of hardening conditions should be different.

The important role and the appearance of certain interactions among significant ones are associated with the influence of the environment in which the hardening was carried out [6]. For instance, the "face being irradiated–presence of protective gas" interaction with a positive value of the effect shows that to increase the durability of cutting tools, it is necessary to irradiate their rear faces in the protective gas medium and their front faces in air. In the latter case, near the cutting edge of the cutting tool an oxide film is formed. The presence of this film causes, in the cutting process, a decrease in the coefficient of friction between the chips and the working surface, which in turn promotes a decrease in the thermodynamic stress of the cutting process and an increase in the durability of the tool.

Taking into account the results of the selection of factors producing the strongest effects on the efficiency of LHT of the tool, we chose the conditions for performing a multifactor experiment on constructing a mathematical model adequately describing the process of cutting with a hardened tool.

We estimated the durability T of high-speed steel R18 cutters in turning structural alloyed steel 12Kh2N4A with varied V (factor X_1'), t (factor X_3'), E (factor X_2'), and γ (factor X_4'). In so doing, the following levels of changing the factors were chosen: X_1' — 55 m/min at the upper level and 30 m/min at the lower level; X_2' — 62 and 30 J; X_3' — 2 and 1 mm, and X_4' — 10 and 6 deg, respectively. In all experiments, $s = 0.2$ mm/rev and $\alpha = 8$ deg. For a tool subjected to preliminary standard heat treatment, single irradiation in air of the front cutting face was used. It was carried out on a Kvant-16 modernized laser technological facility (LTF) with a pulse energy of up to 60 J. The spot size in the zone of treatment was held constant and equal to a 4.5 × 4.5 mm square due to the use of a focusing prismatic raster. Durability tests of hardened cutters were run on a 1K62 screw-cutting lathe. The bluntness criterion was a 0.4-mm wear on the rear face.

In constructing a linear model of the durability of a hardened tool, as the core of the plan, a 2^{4-1} fractional replica with a lasing relation $X_4' = X_1'X_2'X_3'$ was chosen. The analysis of the experimental results has shown that the obtained model turned out to be inadequate for it.

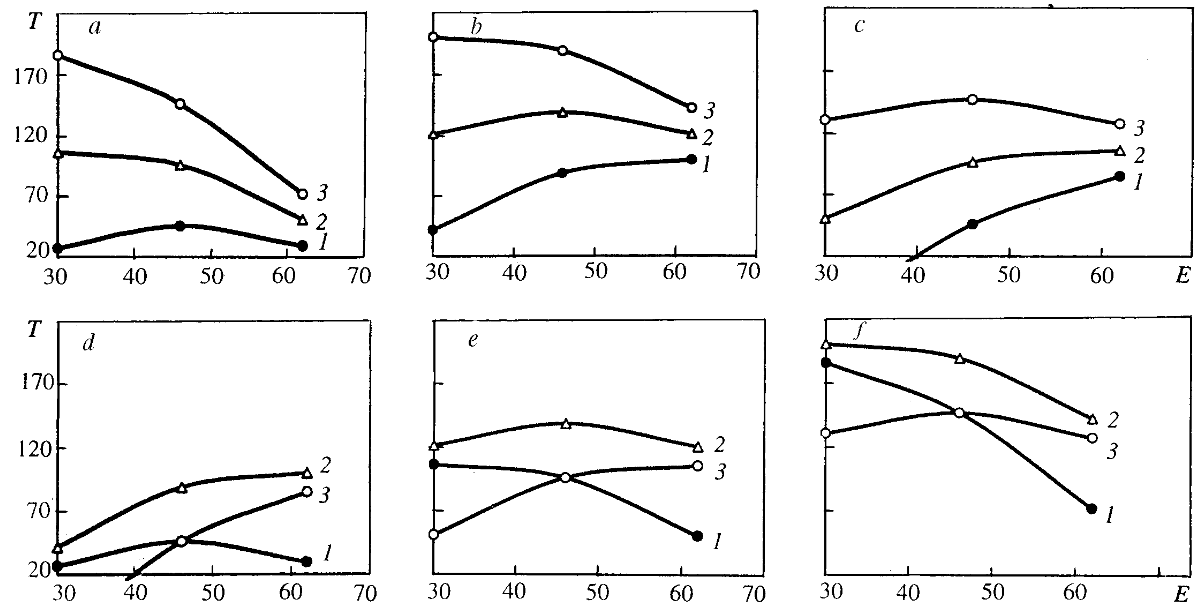

Fig. 3. Durability of the hardened tool in minutes under various conditions of laser treatment (*E*, J): a) t = 2 mm; b) t = 1.5; c) t = 1.0 [1) V = 55 m/min; 2) 42.5; 3) 30]; d) V = 55 m/min; e) V = 42.5; f) V = 30 [1) t = 2.0 mm/rev; 2) 1.5; 3) 1.0].

The transition to a quadratic model of durability was carried out in accordance with the second-order central composition rotatable uniform-design with a "star" shoulder equal to 1.682.

The final equation adequately describing the functional relation of the durability of the hardened tool to the complex of physicotechnological parameters characterizing both the irradiation conditions and the operating conditions of the tool is of the form

$$Y = 139.04 - 50.56X_1' + 29.20X_1'X_2' - 27.74X_2'X_3' - 17.89X_2'^2 - 42.77X_3'^2 . \qquad (1)$$

Replacing the coded values of the factors by the natural ones and performing adequate transformations, we write (1) in the form

$$T = -175.37 - 10.76V + 672.75t + 5.43E + 0.15VE - 3.47Et - 0.07E^2 - 171.1t^2 . \qquad (2)$$

Since the obtained model (1) contains linear and quadratic terms and the effects of first-order interactions, its physical interpretation is very difficult to make. However, preliminary recommendations on the choice of hardening conditions for given cutting conditions can already be obtained on its basis by plotting $T = f(E)$ at fixed values of the cutting speed (Fig. 3a–c) and depth (Fig. 3d–f). Laser hardening leads to an increase in the durability of a treated tool only in specific cases. This is observed, for example, at small (t = 1.0 mm) and medium (t = 1.5 mm) cutting depths (Fig. 3b, c) in turning at speeds above 42.5 m/min. At t = 2 mm, the decrease in durability is likely to be due to the decrease in the strength of the cutter's cutting wedge. And at small values of depth and cutting speed (t = 1.0 mm, V = 30 m/min and t = 1.5 mm, V = 42.5 m/min) the durability of the hardened tool is independent of its irradiation conditions, and for the nonhardened tool in the regimes corresponding to the center of the design of the experiment it does not exceed 52 min. Comparison of these data with the results presented in Fig. 3 points to the expedience of using the LHT of the tool when it is operated in regimes corresponding to high speeds and medium values of the cutting depth. The necessity of using a hardened tool at higher cutting speeds was also noted in [8], which was associated with the decrease in the efficiency of the softening processes in the initial stage of heating the working edges of the tool. For cutters operating under the most stressed turning conditions (V = 55 m/min, t = 2.0 mm), laser treatment yields no effect. Its influence is also minimum under turning conditions with low values of the cutting speed. Conse-

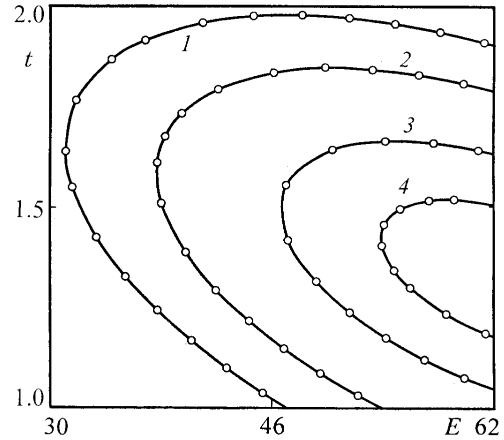

Fig. 4. Durability of the hardened tool under varied cutting (t, mm) and hardening (E, J) conditions at V = 55 m/min: 1) T = 50 min; 2) 70; 3) 90; 4) 100.

quently, it has been established that the durability of a hardened tool strongly depends on the complex action of the factors under investigation, and the presence in regression equation (1) of the interaction effects points to the nonadditive contribution to the change in the durability of individual factors and the necessity of a thorough choice of irradiation conditions in accordance with the specific cutting conditions. The fulfillment of this prerequisite is one of the resources for raising the existing level of durability of the hardened tool.

According to the adequate quadratic model obtained, the durability of a hardened tool is strongly influenced by three factors: V, E, and t. Consequently, in such a formulation the problem of interpreting the results of the investigation is reduced to working out recommendations on the optimum choice of irradiation conditions under given operating conditions, which is done on the basis of constructing two-dimensional sections of the response surface.

To this end, the following procedure was carried out. Two factors were chosen for analysis and the third factor was fixed at a certain level. The new regression equations obtained were reduced to the canonical basis by conventional methods [9].

In particular, the canonical regression equation for the factors determining t (factor X_3') and E (factor X_1') at X_1' = +1 (V = 55 m/min) is of the form

$$-11.70X_2'^2 - 48.96X_3'^2 = Y - 104.71 . \tag{3}$$

Expression (3), which is an elliptic equation, describes the behavior of the efficiency function (hardened-tool durability) with varying energy of laser irradiation of the cutter's working surface and cutting depth at V = 55 m/min. These dependences (Fig. 4) were obtained upon substitution into this equation of various values of durability and represent a family of lines of equal durability T in a given range of variable variations. The durability values of hardened samples are given alongside the curves of equal durability. A departure from the ellipse center in any direction leads to a decrease in the durability of the cutters.

The analysis of Eq. (3) permits the following conclusions concerning the choice of the irradiation and service conditions of the tool: 1) the durability of the hardened tool strongly depends on the joint action of the regimes of LHT and turning; 2) an increase in the irradiation energy at a given value of the cutting depth leads to an increase in the durability by a factor of more than two, and at the least possible contribution of the irradiation energy the durability practically does not exceed the values attained for the control tool; 3) at an equal level of introduced energy the highest durability is attained with increasing cutting depth.

At the same time, the analysis of the behavior of the obtained curves of equal durability imposes certain limits on the area of effective use of laser treatment. At a fixed irradiation energy with increasing cutting depth an increase in the durability is observed only for values of t not exceeding 1.5 mm, which agrees with the conclusion based on the immediate analysis of the durability model (see above). At $t > 1.5$ mm, the observed decrease in laser hardening efficiency is likely to be due to the increase in the thermodynamic stress in the cutting zone and the development of

TABLE 1. Results of the Experiments on the Estimation of the Applicability of the Proposed Model

Test number	V, m/min	E, J	t, mm	γ, deg	Tool durability		t_{calc}
					T_m, min	T_e, min	
1	30	30	1.0	6	130.71	125.3	0.48
2	55	62	2.0	10	29.59	65.3	3.15
3	55	62	2.0	10	29.59	52.2	1.99
4	30	62	2.0	10	72.31	99.6	2.40
5	55	62	1.0	10	85.07	73.2	1.05
6	42.5	46	1.5	8	139.35	180.1	3.59
7	55	30	2.0	10	26.67	40.2	1.19
8	55	62	2.0	6	29.59	27.2	0.21
9	67.5	46	1.5	8	38.23	33.1	0.45
10	42.5	76	1.5	8	67.79	42.7	2.21
11	42.5	46	1.5	12	139.35	165.9	2.34
12	30	62	1.0	6	127.79	81.3	4.09
13	30	62	1.0	10	127.79	132.6	0.42

softening processes caused by it. The observed effect is the higher, the larger the cutting depth. At t larger than 1.5 mm the tool durability is practically independent of the irradiation energy level and remains almost constant for a given value of the cutting depth, i.e., under these turning conditions the laser treatment has no effect on the workability of the tool. This conclusion agrees with the results obtained in analyzing the canonical regression equation for factors X_1' and X_2' at $X_3' = +1$ ($t = 2$ mm), according to which at large values of the cutting depth ($t = 2$ mm) and a certain value of V the durability is also independent of the applied energy level.

As V is decreased to 42.5 m/min, the tendency for an increase in the durability with increasing values of E and t remains. This statement also holds for values of $t \leq 1.5$ mm.

Such a feature of the change in the hardened-tool durability can be explained if the heating temperature of the material in the irradiation zone in the first approximation is taken to be proportional to the absorbed energy density and the canonical equation is formulated in temperature–cutting depth coordinates.

Analysis shows that at temperatures below 900–1000^{o}C the dominant influence on the wear of the irradiated tool is produced by the oxide film formed by the irradiation. It is reduced to a decrease in the coefficient of friction in the contact zone upon cutting, which decreases, in the end, the run-in time of the tool [10]. With increasing temperature in the hardening zone the process of carbide dissolution and gamma-phase saturation with doping elements is intensified. A further increase in the irradiation energy density leads to an increase in the amount of retained austenite in the structure of the LAZ of high-speed steels [3, 4, 11, 12]. In so doing, for example, according to the data of [11, 12], for R9K5 and R6M5 steels its content can amount to 45% and increases with increasing irradiation energy. Assuming that the wear resistance of the irradiated zone upon friction under the conditions of high contact pressures and temperatures characteristic of machining is determined by the degree of completion of the phase transformations in the metastable structure of the LAZ associated with the ability of retained austenite to turn, upon laser treatment, into deformation martensite upon friction, one can explain the experimental fact that at the same level of applied energy in the adopted range of cutting conditions an increase in the cutting depth is followed by an increase in the durability.

Thus, the preferable area of using a hardened cutting tool can be defined as follows:

a) turning at a cutting depth close to 1.5 mm;

b) turning at high cutting speeds (at a maximum value of the applied energy).

In the natural experiment performed, the ranges of variations of the factors characterizing the cutting conditions for a given tool–part pair cover practically the entire area of actually used turning conditions specified in the standards of cutting conditions for structural steels [13]. Likewise, the laser radiation energy levels (factor X_2') realized in the experiment cover the range of energy values corresponding to the hardening conditions of LHT of high-speed steels. Therefore, Eq. (1) can be used to forecast the durability of a hardened tool when the factors under investigation are varied over the range chosen for consideration.

To confirm the applicability of the proposed technique and the obtained interpolation model to the calculation of the hardened cutting tool durability, a set of experiments was performed with various combinations of the factors being varied. The results of these experiments are given in Table 1.

The test with the Student criterion has shown that the difference between the observed and calculated values of the response is statistically insignificant for the overwhelming majority of the check experiments performed. The table value of the criterion $t_{\text{tabl}} = 3.18$ was chosen for $P = 0.95$ and $f = 3$ corresponding to the values at which the dispersion of the reproducibility of tests of the multifactor experiment was determined. The results of the test point to a good agreement between the calculated durability values and the experimental results, which permits recommending the obtained model (1) for predicting the workability of the laser-radiation-hardened tool.

CONCLUSIONS

1. On the basis of tests of the cutting tool hardened by pulsed laser radiation an adequate mathematical model of the functional relation of the durability of irradiated turning tools to the cutting and laser treatment conditions has been obtained. The quantitative characteristics describing the change in the durability of the hardened tool have been determined.

2. For the first time it has been established that the durability value of irradiated cutters is strongly influenced, along with the linear effects of the factors, by the effects of their interaction that are comparable to the linear effects and determine the nonadditive contribution of the cutting and hardening conditions to the change in the durability.

3. Two-dimensional cross sections of the obtained response surfaces have been constructed. The regions of cutting conditions where the use of laser treatment provides the maximum durability of the tool have been established.

4. It has been shown that to attain the highest possible effect in hardening, it is necessary to carry out LHT of cutters taking into account their specific operating conditions.

5. The evaluation of the model has shown that there is agreement between the calculated and experimental values of the durability of the hardened tool. It is recommended to use the proposed model under operating conditions to choose the conditions for irradiating the cutting tool on a laser heat-treatment facility of the type of Kvant-16 or Kvant-18 in order to obtain the required durability under given operating conditions of the tool.

NOTATION

S, technological system ("technological process of cutting with a tool hardened by pulsed laser radiation"); S_1, subsystem of the technological operation of LHT with the following elements: e_1, material being hardened; e_2, laser radiation; e_3, environment; e_4, absorbing coating; S_2, subsystem of the technological operation of cutting with the following elements: e_5, tool; e_6, part; e_7, environment; K_{overl}, coefficient of overlapping of treated spots; N, multiplicity of treatment; τ_{p}, pulse duration; ε, laser radiation energy density; V, cutting speed; t, cutting depth; s, feed; X_1, X_2, ..., X_8, varied factors in the experiment with the use of the random balance method (V corresponds to X_1, E to X_2, the face being irradiated to X_3, t to X_4, s to X_5, α to X_6, γ to X_7, and N to X_8); B, magnitude of the effect; T, tool durability; E, laser radiation energy; α and γ, rear and front angles of the cutter; X_1', X_2', X_3', X_4', varied factors in the multifactor experiment (V corresponds to X_1', E to X_2', t to X_3', and γ to X_4'); Y, optimization parameter; t, Student criterion; P, confidence level; f, number of degrees of freedom. Subscripts: m, model; e, experiment; p, pulse; calc, calculated value; tabl, table value; overl, overlap.

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