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Original article

Influence of Texture Effects on the Laser-Irradiated Tool Performance

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Abstract

Introduction. Laser surface treatment of mechanical engineering products makes it possible to increase their durability. However, the laser hardening process is not good at the consistency of results, since choosing the irradiation modes and schemes of specific products, texture effects in the zones of laser exposure are not taken into account. This leads to premature wearing and even destructing the working surfaces of irradiated products. Therefore, the work objective is to study the mechanism of influence of the structure of the laser-hardened layer on the operational properties of the tool.

Materials and Methods. The materials for this study were tool steels: R6M5 and R18 (according to the EN 10027 standard tool steels: 1.3355, 1.3343). Pulsed laser irradiation was carried out at the technological device Kvant-16 with a radiation power density of 70–250 MW/m^2. Scanning probe and optical microscopy, X-ray diffraction and durometric methods for analyzing the steels structure were used. The values of steel strength in bending and impact strength were determined before and after laser treatment.

Results. It has been experimentally proven that it is necessary to strengthen the sections of the products working surfaces that are subject to maximum wear and are under the action of compressive stresses during operation. It is shown that textural effects in the laser treatment zones lead to a decrease in the friction coefficients and contribute to an increase in the wear and adhesion resistance of the steels surface layers.

Discussion and Conclusion. The results of the research carried out make it possible to rationally select the surface laser processing modes and schemes of products for various functional purposes and ensure their operability with a guarantee. The possibilities increasing the structural strength and properties of the tool due to laser alloying the surface layers of powder-coated steels and stabilizing tempering after laser irradiation are determined.

Keywords: laser irradiation, alloy steels, structure, properties, wear resistance, adhesion resistance.

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Научная статья

Влияние текстурных эффектов на работоспособность лазерно-облученного инструмента

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Аннотация

Введение. Лазерная поверхностная обработка изделий машиностроения позволяет увеличить их долговечность. Однако процесс лазерного упрочнения не отличается стабильностью получаемых результатов, так как при выборе режимов и схем облучения конкретных изделий не учитываются текстурные эффекты в зонах лазерного воздействия. Это приводит к преждевременному износу и даже разрушению рабочих поверхностей облученных изделий. Поэтому целью работы явилось исследование механизма влияния строения лазерно-закаленного слоя на эксплуатационные свойства инструмента.

Материалы и методы. Материалами для данного исследования послужили инструментальные стали Р6М5 и Р18. Импульсное лазерное облучение проводилось на технологической установке «Квант-16» с плотностью мощности излучения 70–250 МВт/м^2. Использовались сканирующая зондовая и оптическая микроскопия, рентгеноструктурный и дюрометрический методы анализа структуры сталей. Определялись значения прочности сталей на изгиб и ударную вязкость до и после лазерной обработки.

Результаты исследования. Экспериментально доказано, что упрочнять следует участки рабочих поверхностей изделий, подверженные максимальному износу и находящиеся при эксплуатации под действием сжимающих напряжений. Показано, что текстурные эффекты в зонах лазерной обработки приводят к понижению коэффициентов трения и способствуют повышению износо- и адгезионной стойкости поверхностных слоев сталей.

Обсуждение и заключения. Результаты проведенных исследований позволяют осуществлять рациональный выбор режимов и схем поверхностной лазерной обработки изделий различного функционального назначения и гарантированно обеспечивать их работоспособность. Определены возможности повышения конструкционной прочности и свойств инструмента за счет проведения лазерного легирования поверхностных слоев сталей из порошковых покрытий и проведения после лазерного облучения стабилизирующего отпуска.

Ключевые слова: лазерное облучение, легированные стали, структура, свойства, износостойкость, адгезионная стойкость.

Благодарности. Авторы выражают благодарность рецензентам, чья критическая оценка представленных материалов и высказанные предложения по их усовершенствованию способствовали значительному повышению качества настоящей статьи.

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Introduction. Currently, machine-building enterprises pay great attention to improving the performance of tools and technological equipment, especially of high-alloy expensive steels.

The analysis of literature sources has shown that during its operation the tool experiences high contact stresses and pressures on the working surfaces [1–4]. In addition, the work of products of various functional purposes is accompanied by heating and bending stresses, as well as shock loads or vibrations.

Therefore, steels for the manufacture of tools should have high values not only of hardness, wear and heat resistance, but also strength at a sufficient level of viscosity in order to prevent premature destruction of working surfaces. Laser irradiation of tools and accessories, along with other methods of surface hardening, allows increasing their durability, but the laser treatment process does not differ in the stability of the results obtained [5–9]. This is due to the fact that the criteria for choosing modes and schemes of laser irradiation of products for various purposes are not clearly defined. In particular, the degree of influence of textural effects arising from laser treatment with surface melting on the structural strength of steels has not been considered.

To solve these problems, bending tests, impact strength, wear and adhesion resistance of irradiated samples are required.

The results of such experiments will make it possible to make a rational choice of the parameters of the surface laser treatment process.

The objective of this article is to study the effect of the structure of the laser-hardened layer on the operational properties of the tool.

Materials and Methods. The materials for this study were P6M5 and P18 instrument steels.

Pulsed laser irradiation was carried out at the Kvant-16 process installation with a radiation power density of 70–250 MW/m^2. Identification of the phase composition and the study of the structure of materials after laser treatment were carried out by metallographic, scanning probe, X-ray durometric methods.

Metallographic studies were carried out on MIM-7 and Neophot-21 microscopes. X-ray diffraction analysis was carried out on a DRON-type diffractometer. Microhardness was measured on a PMT-3 device with a load of 0.49 N. The bending strength of the samples was determined using the IM-4A machine, the impact strength of the samples without incision was determined on the KM-5T pendulum copra.

Results. Metal physical studies have established that during laser treatment of steels, a hardened layer is formed on the surface, consisting in general of a melted quenching zone from the liquid state and an underlying quenching zone from the solid (austenitic) state [10–12].

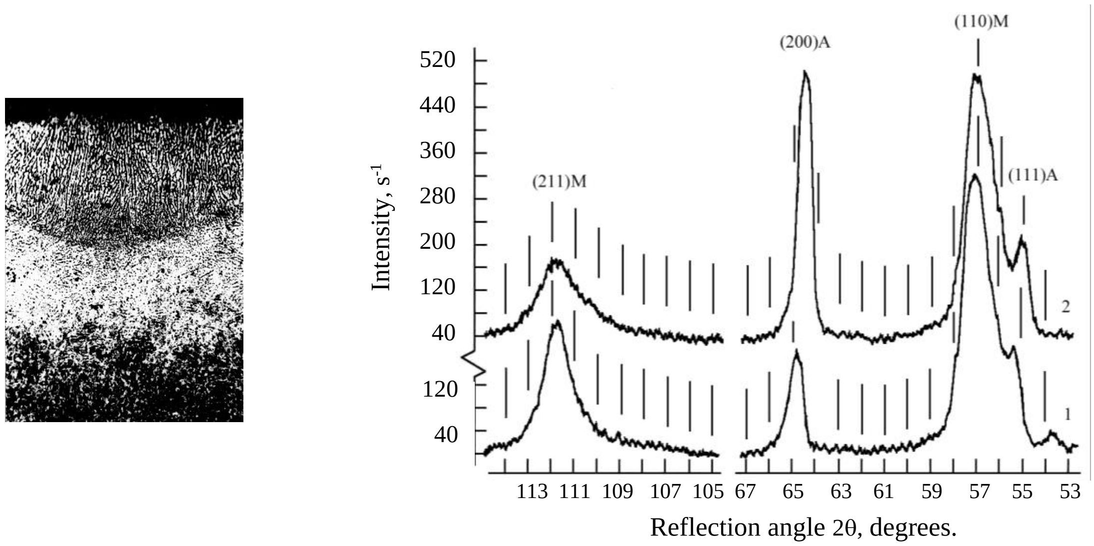
The material is melted to increase the overall depth of the hardened layer or during laser alloying of the irradiated zones. In the latter case, this is caused by the need to melt the alloying coating and a thin surface layer of steel.

Special attention was paid to the study of the features of the structure formation of steels in the zone of laser quenching from the liquid state.

It has been experimentally established that this zone has a dendritic structure (Fig. 1 *a*). Moreover, the dendrites are directed in a certain way — towards the heat sink from the irradiated surface into the depth of the hardened layer. The total thickness of the hardened layer is 80–100 microns, the average metal hardness of the surface layers is 10-10.5 GPa.

X-ray diffraction analysis showed (Fig. 1 *b*) that the following phases are present in the melting zones: α-phase (martensite), a certain amount of γ-phase (residual austenite) and blurred reflexes of incompletely dissolved carbides.

At the same time, an abnormal ratio is observed of the intensities of the diffraction lines (200) and (111) of austenite in the zones of laser quenching from the liquid state (Fig. 1 *b*, curve 2), compared with the quenching zone from the solid (austenitic) state (Fig. 1 *b*, curve 1).



a) *b)*

Fig. 1. Location of dendrites in the zone of laser quenching from a liquid state on P6M5 steel (a), ×800 and fragments of radiographs (b) of steel after laser treatment without melting (curve 1) and with melting of the surface (curve 2)

This indicates the appearance of texture effects in the surface irradiated layers.

The formation of the austenite texture is probably due to the predominant orientation of its subgrains in the surface layer of materials, which occurs due to the directed crystallization of metal after the end of the laser pulse.

The described effect has a positive effect on the properties of products after laser treatment. In particular, the texture lowers the friction coefficients in the friction pairs, especially if the texture type is consistent with the type of stress state of the hardened products under operating conditions [13].

The paper considers some possibilities of using a texture that causes anisotropy of properties in the surface layers of steels as a factor in improving the technological characteristics of irradiated products.

For this purpose, bending and impact strength tests were carried out on samples made of P6M5 steel irradiated in different modes and according to different schemes, that is, the structural strength of laser-irradiated steels was determined.

When choosing methods of experiments, it was assumed that bending tests create a stress state in the samples close to that arising during the operation of a metalworking tool. Samples with a size of 4×6×55 mm were used.

The use of samples of non-standard cross-section is caused by the need to tighten the degree of influence of a thin hardened layer on the measured properties.

Before irradiation, the steel was subjected to standard heat treatment. To relieve internal stresses after grinding the samples to size, tempering was performed at 400 °C, as well as visual inspection for the absence of cracks or other defects. One face of the samples (6×55 mm) was subjected to laser irradiation with a radiation power density of 70–150 MW/m^2, that is, without melting and with melting of the surface of the samples. Some of the samples were subjected to laser alloying from powder coatings containing dispersed charcoal particles, followed by heating to a temperature of 550 ºC.

It should be noted that during the tests, the laser-hardened layer was under the influence of compressive or tensile stresses, depending on its location relative to the loading element.

As a result of the tests, it was found that in the case of compressive stresses acting on the irradiated layer, the strength of the samples practically does not decrease (Table 1). In case of exposure to tensile stresses, the tendency of samples to brittle fracture increases. This is probably due to the fact that tensile bending loads initiate the nucleation and propagation of cracks in the melted surface layers of steel along the inter-dendritic layers.

Table 1

Mechanical characteristics of P6M5 steel before and after laser treatment

Processing mode	σизг×10, MPa		a×10^{-1}, MJ/m^{2}	
	compression	stretching	compression	stretching
Standard heat treatment (quenching and tempering)	272±7	270±7	3.2±0.2	3.1±0.2
Laser hardening without melting the surface	258±7	32±7	2.8±0.2	0.2±0.2
Laser hardening with surface melting	238±7	30±7	2.7±0.2	0.3±0.2
Laser hardening and tempering at 550 °C	257±7	31±7	2.8±0.2	0.4±0.2
Laser alloying from coal powder	291±7	33±7	2.9±0.2	0.4±0.2
Laser alloying from coal powder and tempering at 550 °C	302±7	32±7	3.0±0.2	0.2±0.2

It can be concluded that in order to stabilize the structural strength of irradiated products, it is necessary to harden the sections of their working part that are exposed to compressive loads during operation.

Of particular interest, from the point of view of improving the operational properties of laser-hardened products, are the results of experiments obtained on laser-alloyed carbon powder samples.

During metal physical studies, the microstructure features of laser alloying zones from powder coatings containing activated carbon were revealed (Fig. 2).

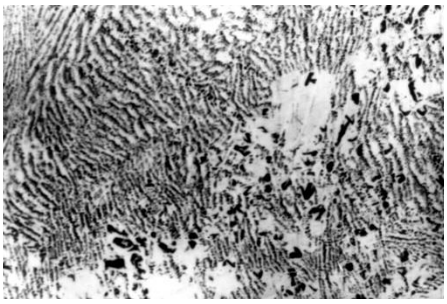


Fig. 2. Structure of the melt in liquid-hardened P6M5 steel under laser alloying from a powder containing coal particles, ×500

In particular, dispersed particles of coal are clearly visible, which are located in the irradiated metal at the boundaries of growing dendrites. Simultaneously with textural effects, the presence of graphite plates in irradiated zones lowers the friction coefficients on the working surfaces of products, acting as a solid lubricant [14]

As it can be seen from the table, under the action of compressive stresses, laser alloying and subsequent tempering at a temperature of 550 °C increase the strength of irradiated products most effectively.

An additional contribution of tempering to improving properties, in particular hardness, of the surface layers of P6M5 steel is associated with the effect of dispersion hardening in irradiated and, especially, alloyed layers of steel. To confirm the effectiveness of the process of laser hardening and alloying of the tool, taking into account textural effects in the surface layers [15, 16], there have been carried out full-scale tests on the wear resistance of cutters made of P18 steel under conditions of cutting parts made of steel 45.

Cutters made of P18 steel were subjected to volumetric quenching and tempering, as well as various surface treatment options: laser quenching with and without melting the surface, laser alloying from powder coatings containing dispersed inclusions of tungsten carbides.

Laser irradiation was carried out along the back face of the working part of the cutter, which is exposed to compressive stresses during cutting. As shown in the article above, this eliminates the brittle destruction of the cutting edges of the tool. The experiments carried out to select the degree of overlap of the irradiated spots showed that the overlap coefficient of the irradiated zones should be at least 0.7–0.8. The depth of the hardened layer was 80-100 microns, the average metal hardness of the surface layers was 11–11.5 GPa.

The degree of wear was estimated by the size of the wear area on the back face of the cutter with the same cutting path for different surface hardening options.

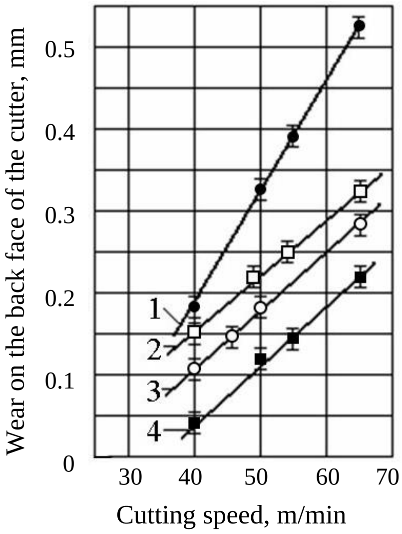
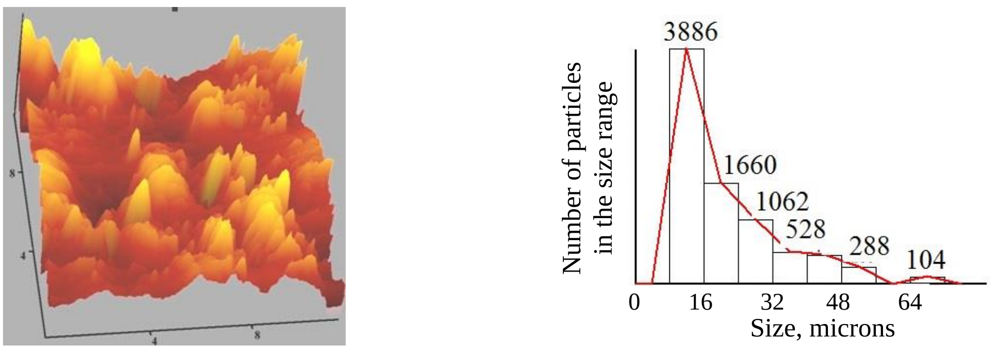


Fig. 3. Wear resistance of P18 steel cutters after volumetric heat treatment (curve 1), laser hardening without partial melting (curve 2), with surface partial melting (curve 3), laser alloying with tungsten carbides (curve 4)

As it can be seen in Fig. 3, at all cutting speeds, there is a decrease in wear by 1.5–2 times in the cutters subjected to laser hardening. Moreover, minimal wear is achieved in the case of laser alloying of the working surfaces of the cutter with tungsten carbides. At the same time, structures are formed in the surface layers of the cutters, which are a textured matrix with WC tungsten carbides fused with solid particles.

The process of laser alloying of the surface of P18 steel with tungsten carbides having a high hardness (up to 15–17 GPa) is evidenced by the WC reflexes present on the X-ray images, as well as the results of studies of coatings after laser treatment obtained on a scanning probe microscope. In Fig. 4 *a*, the carbide particles protruding above the surface of the sample are clearly distinguishable [17, 18].

Quantitative characteristics of the surface layers of steels after laser melting from coatings of WC particles were obtained in the work. To do this, a computer image processing program (CIP) was used. The results of the analysis are shown in Fig. 4 *b*.



a)　　　　*b*)

Fig. 4. Scanned image of the surface of P18 steel: *a* — after laser melting of tungsten carbides; *b* — histograms of WC particle size distribution

As it can be seen in Fig. 4, inclusions of 5-10 microns are mainly present in the surface layers of steels.

The array of results of experimental determination of the wear resistance of cutters after laser alloying, processed in the program *"Statistica"*, is shown in Fig. 5. From the analysis of the figure, it can be concluded that the minimum wear of the cutters is observed after irradiation with a radiation power density of 110-130 MW/m^2. The white dots in Fig. 5 indicate the results of experimental verification of regression modeling of processes occurring in the zones of laser treatment of steels.

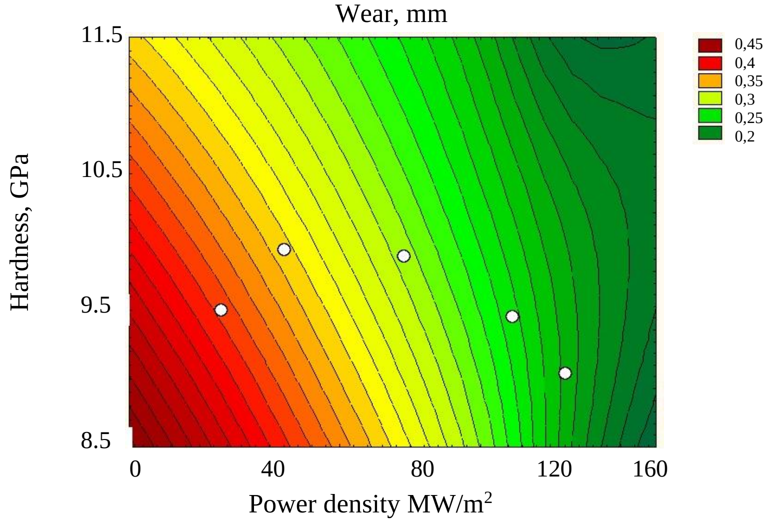


Fig. 5. Regression modeling maps of wear resistance of P18 steel cutters depending on the power density of laser radiation and the hardness of the surface layers of steel

The results obtained are of practical importance, since they allow us to reliably assign laser treatment modes to obtain the required hardness and wear resistance, that is, the operability of the irradiated products.

It should be noted that the adhesive stability of the working surfaces against "sticking" of the processed material is of no small importance for a guaranteed increase in the durability of products, especially tools. This changes the geometric dimensions of the working surfaces, leads to an increase in the loads and stresses acting in the friction pairs, causing the destruction of the surface layers of the products.

The possibilities of improving the operational properties of laser-hardened tool steel in contact with non-ferrous aluminum alloys were determined in the work.

Samples made of P6M5 steel were subjected to standard volumetric heat treatment and subsequent laser hardening with a radiation power density of 100-120 MW/m^2 to obtain a textured state of the steels on the surface. Coatings containing tungsten carbides were used during laser alloying.

Friction and adhesive stability tests were carried out on the MI-1M machine according to the "disc – pad" scheme. The counterbody was aluminum alloys with different hardness and viscosity. Alloy AD31 had a hardness of HB 2, D16 — HB 70 and AMg6 — HB 90. Damages and signs of setting on the friction surfaces were recorded using an MBS-2 microscope.

The value of the specific load applied to the friction pair and resulting in a significant increase in the coefficient of friction due to the adhesion of the aluminum alloy to the surface of the steel sample, that is, due to the adhesive process, was chosen as a criterion for assessing the tendency to set tool steel and aluminum alloy [19, 20].

As it can be seen in Fig. 6 a and b, when laser-irradiated tool steel comes into contact with aluminum alloys such as AMg6 and D16, the transfer of aluminum alloys to steel is practically absent. The friction coefficients are 0.07–0.09, in comparison with volumetrically hardened samples, for which the friction coefficients reach values of more than 0.10. Moreover, in contact with the D16 alloy, a jump-like increase in friction coefficients is observed for them, starting with specific loads in a friction pair over 6 MPa. This indicates the course of adhesive processes.

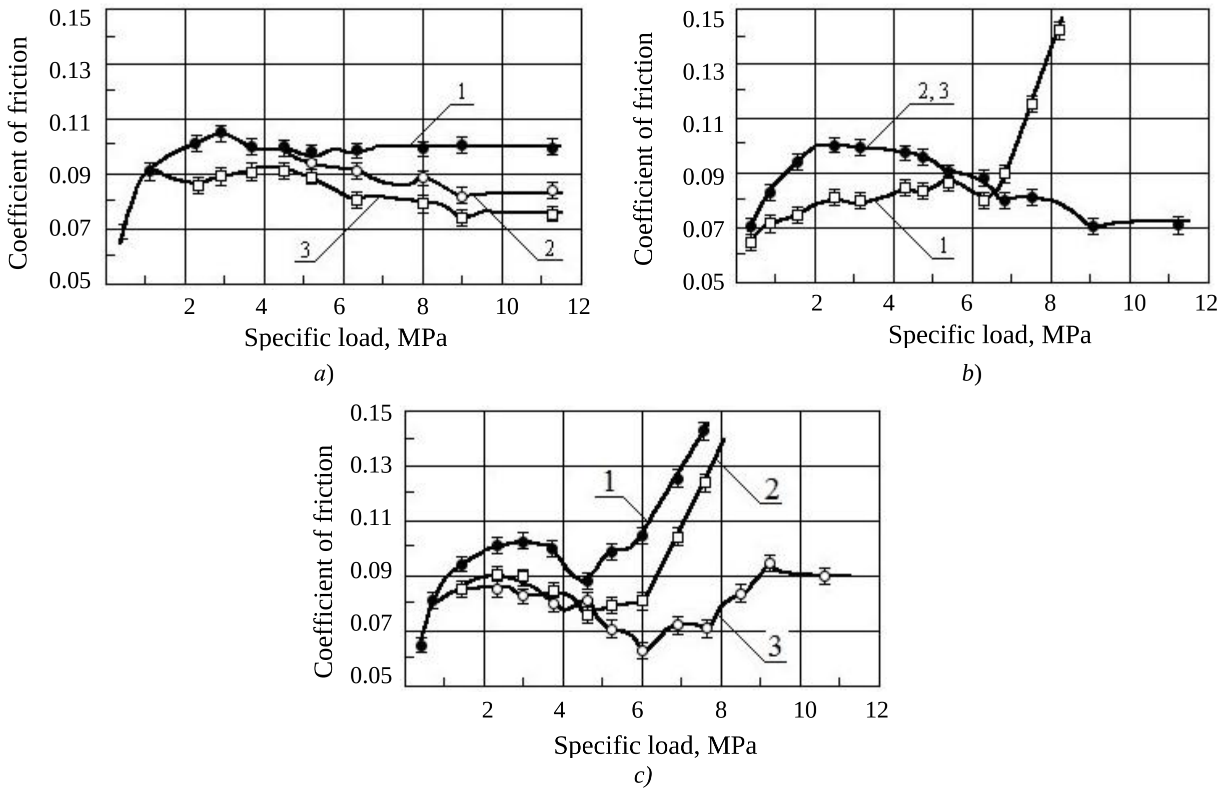


Fig. 6. Friction coefficients at contact of P18 steel with alloys AMg6 (a), D16 (b), AD31 (c) before laser treatment (curves 1), after laser hardening (curves 2), after laser alloying with tungsten carbides (curves 3)

It should be noted that in friction pairs with AD31 alloy, which has the lowest hardness, non-irradiated steel samples have a catastrophic increase in friction coefficients at specific loads of 4.5 MPa, and in laser-hardened steels at higher loads in friction pairs —6 MPa (Fig. 6 c). Only laser-alloyed samples have high adhesion resistance under these conditions [21].

The increase in adhesion resistance under laser irradiation is associated with the achievement not only of high hardness (11-11.5 GPa) of the textured surface layer, but also, as in the case of laser alloying, also with the melting of solid dispersed tungsten carbides from coatings.

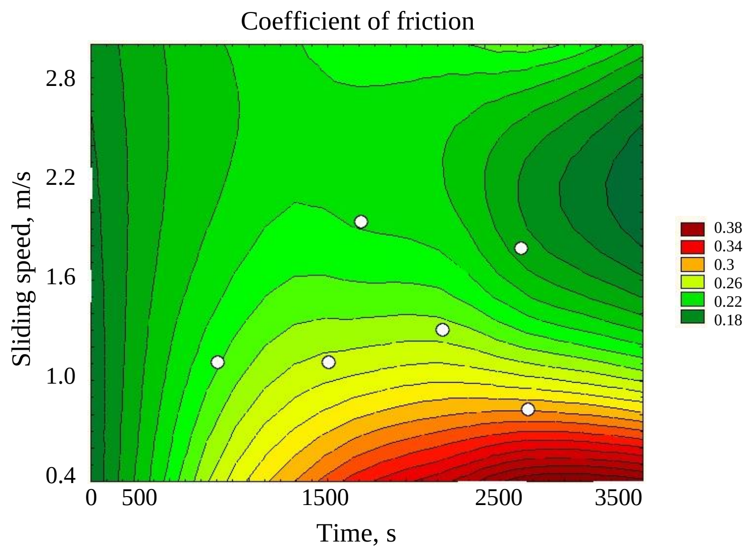


Fig. 7. Regression modeling of friction coefficient values in friction pairs "irradiated tool steel — aluminum alloy"

In order to predict and select the necessary friction coefficients that provide the specified values of wear and adhesion resistance of P18 steel in contact with aluminum alloys after laser irradiation, regression modeling of experimental results using the program *"Statistica"* was carried out (Fig. 7)

Discussion and Conclusion. It has been experimentally established that such features of the structural state of the irradiated surface layers of steels as textural effects in α-and γ-phases contribute to improving the basic properties and improving the performance of irradiated steels. This is especially significant if the texture type is consistent with the type of stress state of the hardened products under operating conditions.

It is established that it is necessary to strengthen the working surfaces of products that are in operation under the influence of compressive loads. The preferred orientation of laser treatment structures reduces the tendency of the surface layers of irradiated products to brittle destruction, reduces the friction coefficients in tribosystems compared to traditional volumetric hardening of steel by 20–30 %. At the same time, the stability of the friction coefficients during the operation of irradiated products also increases. This circumstance is important in ensuring the stationarity of processes in the friction zone, creates prerequisites for the intensification of the modes of operation of friction pairs.

The practical use of the results obtained in the work makes it possible, by purposefully selecting the schemes and parameters of the laser irradiation mode, to obtain structures on the surface that have the specified wear and adhesion resistance under external loading conditions during operation.

The possibility of increasing the structural strength and operational properties of the tool due to laser alloying from powder coatings and tempering after laser irradiation is determined.

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