Досліджено вплив режимів зміцнюючої комбінованої обробки на зміну властивостей поверхневого шару конструкційної сталі. Показано, що товщина зміцненого шару становить 0,18–0,69 мм при поверхневій твердості 10,5–12,5 ГПа. Отримано математичні моделі та номограми товщини зміцненого шару і твердості сталі залежно від технологічних параметрів комбінованої обробки. Знайдені залежності дозволяють визначати конкретні умови зміцнюючої обробки

Ключові слова: конструкційна сталь, поверхневе зміцнення, комбінована обробка, лазерна обробка, азотування, товщина шару, твердість

Исследовано влияние режимов упрочняющей комбинированной обработки на изменение свойств поверхностного слоя конструкционной стали. Показано, что толщина упрочненного слоя составляет 0,18–0,69 мм при поверхностной твердости 10,5–12,5 ГПа. Получены математические модели и номограммы толщины упрочненного слоя и твердости стали в зависимости от технологических параметров комбинированной обработки. позволяют определять конкретные условия упрочняющей обработки

Ключевые слова: конструкционная сталь, поверхностное упрочнение, комбинированная обработка, лазерная обработка, азотирование, толщина слоя, твердость

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DEVELOPMENT OF A COMBINED TECHNOLOGY FOR HARDENING THE SURFACE LAYER OF STEEL 38Cr2MoAl

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1. Introduction

A multitude of steel parts work in conditions of increased surface wear, so there is a need of this surface protection. Surface hardening methods can be divided into two main groups: hardening the product without changing chemical composition of the surface but with a change in structure and hardening the product with a change in chemical composition of the surface layer and its structure [1]. To date, the following methods of hardening steel parts are known:

1. Hardening by changing surface roughness [2].
2. Hardening by changing chemical composition of the metal surface layer [3].
3. Hardening by changing structure of the surface layer [4].
4. Hardening by applying coatings on the surface [5].
5. Hardening by changing energy reserve of the surface layer [6].

Application of this or that method of hardening processing is determined by the requirements imposed on concrete details. In current conditions, loads on machine parts have increased substantially which is connected with a significant growth of power and productivity of machines. This led to the fact that the known methods of rising durability of steel parts are not always able to provide required properties. Therefore, there is a growing interest in using combined hardening methods which are a combination of two or more technological processes. This combination makes it possible to achieve a very high hardening efficiency that cannot be obtained in any single way.

Also, the increased interest in combined strengthening technologies is caused by the need of smaller use of alloyed steels because of high cost of alloying metals [7].

One of the most common technologies for hardening steel surface is nitriding but this is a fairly lengthy and expensive process [8]. Therefore, a rational solution will be development of a combined method for hardening surface layer of steel aimed at acceleration of the nitriding process.

Thus, a topical issue is development of a combined technology for strengthening surface layer of steel consisting in a preliminary laser processing and subsequent nitriding.

2. Literature review and problem statement

One of the methods for accelerating diffusion of atomic nitrogen into the metal interior is a preliminary structural change of the steel surface layers. This state can be achieved by mechanical or thermal means. The greatest interest in accelerating the diffusion processes by the method of local changes in the structure of the surface layer of steel is paid to laser treatment.

Laser treatment of steel in comparison with volumetric methods of heat treatment of materials has many advantages [9], one of which is that laser processing does not require additional temper operations. It is known [10] that hardness of the laser-hardened surface zone exceeds 58–62 HRC due to the formation of martensite in the surface layer. The greatest interest in laser processing of steel for further acceleration of the nitriding process is a significant grain size refinement which results in an acceleration of nitrogen diffusion into the metal interior.

For parts made of 38Cr2MoAl steel, nitriding is the most appropriate method of hardening [11]. There are many nitriding technologies but the most interesting are the innovative technologies that provide a necessary depth of diffusion layer in a small time span of the saturation process. The most common methods of high-speed nitriding are ion-plasma nitriding and nitriding in a finely dispersed powder medium.

As shown in [12], ion-plasma nitriding shortens processing to 2–8 hours. However, this kind of nitriding is associated with the use of special complex equipment. Also, the inability of obtaining sufficiently large depths of the diffusion layer is a serious drawback of ion-plasma nitriding. This factor is connected with technological features of the nitriding process [13].

Another modern direction of high-speed nitriding is nitriding in a powder medium [14]. However not all mixtures meet environmental and technological requirements.

One of the existing methods [15] consisting in gas nitriding and subsequent laser treatment is aimed at rising hardness and modulus of elasticity of the nitride layer. The developed procedure has made it possible to reduce ε-zone porosity and obtain a martensite structure in the diffusion zone. This led to a higher hardness but not to a thicker strengthened layer.

Subsequent laser processing with surface fusion and absence of nitrided layers of alloyed steel was investigated in [16]. It was established that all laser-modified zones with fusion and without it were characterized by an increased wear resistance in comparison with the usual gas-nitrided layer. But this method is aimed only at alteration of modification of the already obtained nitrided layer and does not affect acceleration of the nitriding process.

Thus, the known combined laser processing and nitriding technologies feature a number of unresolved issues. In particular, they do not provide sufficient thickness of the strengthened layer, are difficult to use, labor- and energy-consuming, long-lasting processes.

Therefore, the prospective direction of increasing service life of machine parts consists in creation of an innovative technology for combined hardening the surface layer of steel thru acceleration of the nitriding process.

3. Objective and tasks of the research

The objective of this work was to study influence of conditions of combined strengthening treatment on the change in properties of the surface layer of 38Cr2MoAl steel.

To achieve this objective, it was necessary to solve the following tasks:

– determine thickness of the hardened layer and surface hardness after the combined treatment;

– obtain mathematical models of thickness of the hardened layer and surface hardness depending on variation of velocity of the laser beam travel and duration of steel nitriding following the combined treatment;

– construct nomograms of simultaneous effect of velocity of the laser beam travel and nitriding duration on thickness of the hardened steel layer and surface hardness.

4. Research material used, process conditions for combined treatment and research procedures

4. 1. The test material used in the experiment

The material of this study was structural alloy steel 38Cr2MoAl. Chemical composition of steels and the temperatures of critical points are given in Table 1, 2, respectively.

Table 1

Chemical composition of steels

C	Cr	Si	Mn	Ni	Cu	S	P	Mo	Al
0.35–0.42	1.35–1.65	0.20–0.45	0.30–0.60	0.3	0.3	0.025	0.025	0.15–0.25	0.70–1.10

Table 2

Temperature of critical points

A_{c1}	$A_{c3}(A_{cм})$	$Ar_3(A_{rcc})$	Ar_1	$M_н$
800	865	740	665	330

This steel is a structural alloyed steel. It is most often used for making parts subject to nitriding. Nitrided parts of steel 38Cr2MoAl are corrosion resistant in atmospheric conditions, in water and water vapor. Also, a significant (2 to 3 times) increase in hardness of the part surface layers occurs.

4. 2. Process conditions of combined treatment

The samples were subjected to bettering, namely quenching with high temper.

Laser hardening was carried out using Latus-31 unit (Russia). The laser radiation power was 0.9–1.1 kW, the spot diameter was 5 mm. The velocity of the laser beam travel was varied within 0.5–1.5 m/min.

Nitriding was performed in a medium of finely dispersed nitrogen-containing material with activators at 550 °C for 2–4 hours. This process ran in a closed atmosphere of a sealed container placed in a box furnace.

4. 3. Methods for studying and modeling thickness and microhardness of a hardened steel layer

Thickness of the hardened layer was taken as the distance of microhardness variation from surface to core hardness values.

Microhardness of the samples was measured with the help of PMT-3 device (Russia) at loads of 50, 100 g and an exposure time of 7 to 15 seconds.

Simulation was carried out in the Mathcad program, graphs and nomograms were constructed in the Microsoft Excel program.

5. Experimental data and processing of the results obtained

5. 1. Results of the experiments for determining thickness of the hardened layer and surface hardness following the combined treatment

The effect of preliminary laser treatment and final nitriding on thickness of the hardened layer and microhardness of the surface layers of 38Cr2MoAl steel samples was studied. A detailed description of the preliminary laser treatment was given in [17]. As is well known ([8, 12]), the optimal nitriding temperature is 550 °C. Therefore, variation of nitriding duration was of particular interest for analysis of the effect of nitriding on thickness of the hardened layer and microhardness of the surface layers. The study results are given in Table 3.

Table 3

The effect of preliminary laser treatment and final nitriding on thickness of the hardened layer and microhardness of the surface layers of 38Cr2MoAl steel samples

Nitriding duration, hours	Laser travel velocity, m/min					
	0.5	1.0	1.5	0.5	1.0	1.5
	Hardened layer thickness, mm			Surface microhardness, GPa		
2	0.59	0.31	0.18	12	11	10.5
3	0.65	0.36	0.21	12.5	11.5	11.0
4	0.69	0.42	0.27	11.0	11.2	10.9

To construct a mathematical model, velocity (x_1^*) of the laser beam travel and nitriding duration (x_2^*) were chosen as input variables. The ranges of variation of these values are given in Table 3. Output variables were the average values of the hardened layer thickness (y_1) and microhardness (y_2) of the surface layers of the steel under study. The mathematical model had the form of a regression equation [18]. For model construction, 10 parallel experiments were conducted to ensure conditions of the experiment homogeneity.

5. 2. Mathematical modeling of experimental results following combined treatment

Mathematical models describing dependence of the hardened layer thickness and surface hardness on the values of velocity of the laser beam travel and duration of steel nitriding were presented in the form of polynomials of the second degree. Methods for estimating the model coefficients, checking its adequacy and statistical accuracy analysis are given in [18].

The obtained model of the hardened layer thickness depending on the normalized values of velocity of the laser beam travel and steel nitriding duration looks like this:

$$y = 0{,}40889 - 0{,}21171 \cdot x_1 + 0{,}05001 \cdot x_2 + \\ +0{,}06827 \cdot x_1^2 + 0{,}003272 \cdot x_2^2 - 0{,}0025 \cdot x_1 \cdot x_2. \quad (1)$$

Adequacy of the model (1) was checked by testing the hypothesis of equality of dispersion of experimental errors and dispersion of inadequacy. Fulfillment of the $F<F_{кр}$ condition has allowed to draw the conclusion of the model adequacy.

Investigation of the response surface described analytically in the form (1) can be performed thru a canonical transformation [19] by a sequential procedure involving the following steps.

1. Determination of the stationary point x* coordinates by solving the system of linear equations:

$$\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1^* \\ . \\ x_n^* \end{pmatrix} = -\begin{pmatrix} a_1 \\ . \\ a_n \end{pmatrix};$$

2. Calculation of the target value at a stationary point

$$y^* = a_0 + 2a' x^* + x^{*\prime} A x^*;$$

3. Definition of n eigenvalues $\lambda_1, \lambda_2, ..., \lambda_n$

$$\begin{vmatrix} a_{11}-\lambda & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22}-\lambda & \dots & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & \dots & a_{nn}-\lambda \end{vmatrix} = (-\lambda)^n + P_1\lambda^{n-1} + \dots P_n = 0;$$

4. Recording the equation of response surface in a canonical form in a general view:

$$y - y^* = \lambda_1\xi_1^2 + \lambda_2\xi_2^2 + \dots + \lambda_n\xi_n^2.$$

In fact, execution of procedures 1–4 is the transfer and rotation of axes and transition from the coordinate system (x_1–x_2) to the coordinate system (ξ_1–ξ_2). The final result of this transformation is transition from the initial equation of the response surface

$$y(x) = a_0 + 2a' x + x' A x$$

to its canonical form

$$y - y^* = \lambda_1\xi_1^2 + \lambda_2\xi_2^2 + \dots + \lambda_n\xi_n^2:$$

$$x = x^* + B\xi, \quad (2)$$

where B is the rotation matrix, $B'B = I$, and the difference between the values of the output variable at an arbitrary and stationary points is described by equation

$$y(\xi) - y^* = \xi' L \xi. \quad (3)$$

As a result of procedures 1–4, the following values of the eigenvalues: λ_1=0.003272, λ_2=0.06827 were obtained, that is, the equation describing the response surface in the canonical form is as follows:

$$y - y^* = 0{,}003272\xi_1^2 + 0{,}06827\xi_2^2. \quad (4)$$

Since the ratio of the eigenvalues in magnitude and sign determines the form of the response surface and

$$|\lambda_1| \neq |\lambda_2|, \lambda_1 > 0, \quad \lambda_2 > 0,$$

the response surface is an ellipsoid.

Estimation of significance of the model coefficients using Student's t-criterion has shown (Table 4) that the final model can look like:

$$y = 0{,}40889 - 0{,}21171 \cdot x_1. \quad (5)$$

Table 4

The results of calculating deviation values of $t_{cr}S_i$ for estimating significance of the model coefficients

Deviation values $t_{cr}S_i$		
For linear coefficients	For quadratic coefficients	For coefficients at pairwise interaction
0.06157	0.10663	0.0754

The mathematical model describing influence of velocity of the laser beam travel and nitriding duration on the values of the surface hardness of the hardened layer is generally represented as follows:

$$y = 11,28889 - 0,51677 \cdot x_1 - 0,06668 \cdot x_2 + \\ +0,08164 \cdot x_1^2 - 0,56836 \cdot x_2^2 + 0,35 \cdot x_1 \cdot x_2. \quad (6)$$

The canonical transformation results in a description of the model in the form

$$y - y^* = -0,56836\xi_1^2 + 0,08164\xi_2^2. \quad (7)$$

As can be seen from description (7), the eigenvalues are not equal and have opposite signs (λ_1= =–0.56836, λ_2=0.08164). This is an indication of that the response surface is a hyperboloid and there is a saddle point. However, verification of significance of the coefficients (Table 5) has shown that the model can be transformed to the following form:

$$y = 11,28889 - 0,51677 \cdot x_1 - \\ -0,56836 \cdot x_2^2 + 0,35 \cdot x_1 \cdot x_2. \quad (8)$$

Table 5

The results of calculating values of deviations $t_{cr}S_i$ for estimating significance of the model coefficients

Values of deviations $t_{cr}S_i$		
For linear coefficients	For quadratic coefficients	For coefficients at pairwise interaction
0.25757	0.44607	0.31542

Thus, it can be assumed that the mathematical models of the form (5) and (8) describing thicknesses of the hardened layer and the surface hardness of 38Cr2MoAl steel following the combined treatment depending on the changes in the velocity of the laser beam travel and duration of steel nitriding can be recommended for practical use,

6. Discussion of simulation results and construction of nomograms

As follows from the obtained results, thickness of the hardened layer tends to its maximum values with a decrease in velocity of the laser beam travel and an increase in nitriding duration, however the theoretical optimum is reached beyond the boundaries of the chosen design of experiment. The local optimum is achieved at the boundaries of the experiment design, that is, at r=1.414, and can be determined on the basis of the ridge analysis [20–22] (Fig. 1).

Substantiation of the obtained regularity is connected with the features of formation of the strengthened layer structure under combined treatment. Low velocity of the laser beam travel contributes to the formation of a larger thickness of the hardened layer. This is due to the longer-term influence of high laser temperature on the steel surface, that is, the steel surface is hardened to a greater depth. These changes in the steel surface layer contribute to the accelerated diffusion of atomic nitrogen during subsequent nitriding. An increase in nitriding duration leads to the formation of a larger thickness of the hardened layer. In this case, the surface hardness also increases with a decrease in velocity of the laser beam travel but the effect of the nitriding duration is not unambiguous.

Suboptimal values of the steel surface hardness attained at the boundaries of the experiment design can also be found from the results of the ridge analysis (Fig. 2).

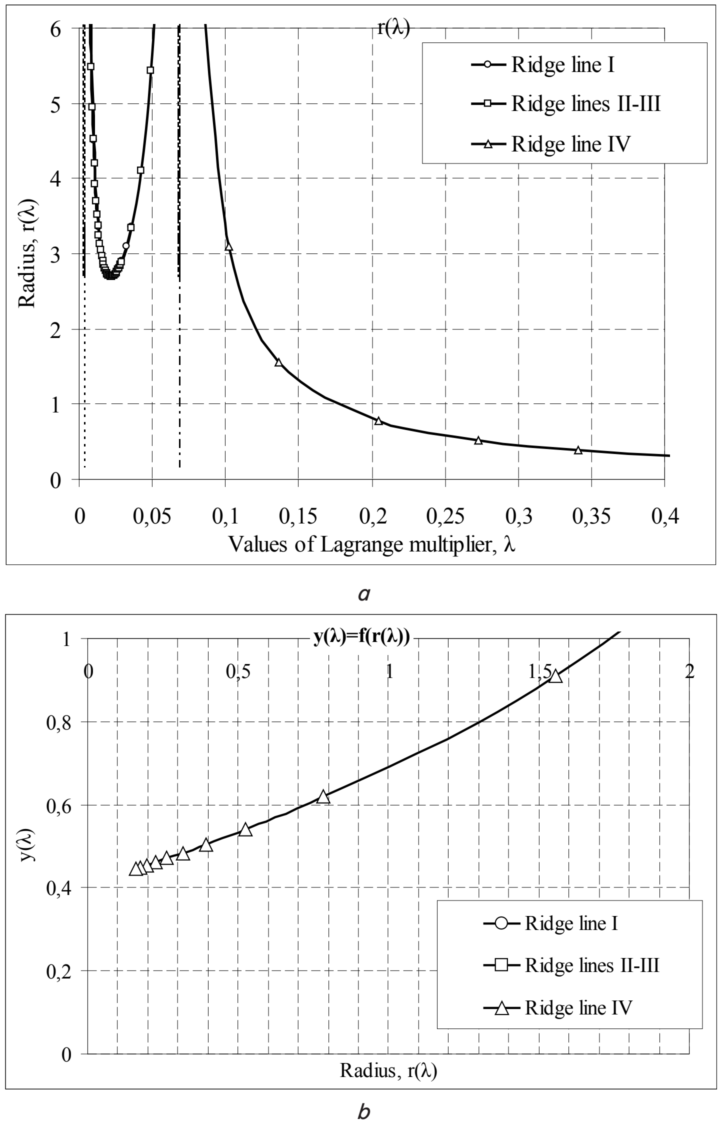
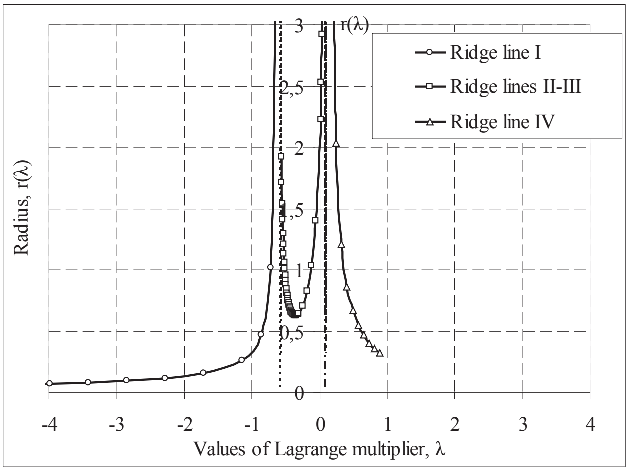


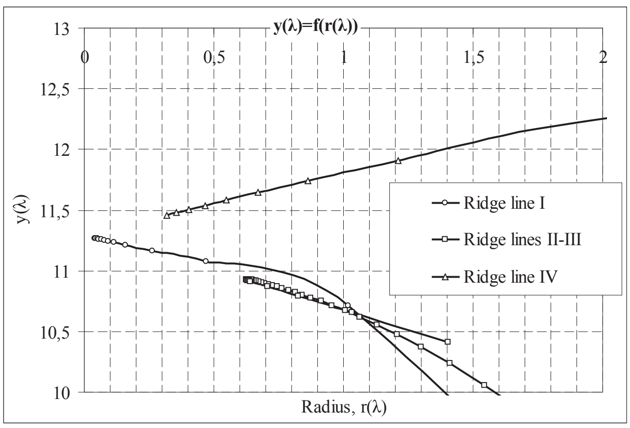
Fig. 1. Results of the ridge analysis for determining the local optima based on the model (1): *a* – r=r(λ), *b* – y=y(r(λ))

The values of the steel surface hardness after the combined treatment corresponded to the range of nitriding durations of 2.69–3.30 hours which can be recognized as rational. The maximum value of the steel surface hardness at a velocity of the laser beam travel of 0.5 m/min corresponded to a nitriding time of 2.69 hours and the respective figures of nitriding time for velocities of the laser beam travel of 1.0 m/min and 1.5 m/min were 3.0 and 3.30 hours.

The obtained mathematical models allow construction of nomograms of simultaneous influence of velocity of the laser beam travel and nitriding duration on thickness of the hardened steel layer and surface hardness (Fig. 3–6).



a



b

Fig. 2. Results of the ridge analysis for determination of local optima based on the model (6): *a* – r=r(λ), *b* – y=y(r(λ))

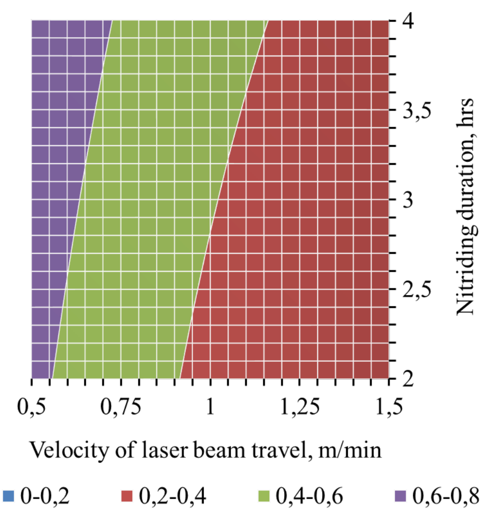


Fig. 3. Nomogram of dependence of hardened layer thickness from velocity of the laser beam travel and nitriding duration

Mathematical description of the relationship between the input and output variables provides a more convenient work for the engineer dealing with the combined treatment processing. Proceeding from the given parameters (thickness and hardness) of the hardened layer of the part, it is possible to find corresponding values of velocity of the laser beam travel and nitriding duration.

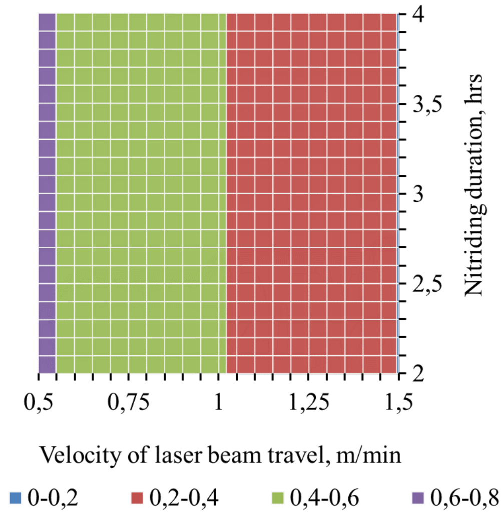


Fig. 4. Nomogram of dependence of thickness of the hardened layer on velocity of the laser beam travel and nitriding duration taking into account the significance of coefficients

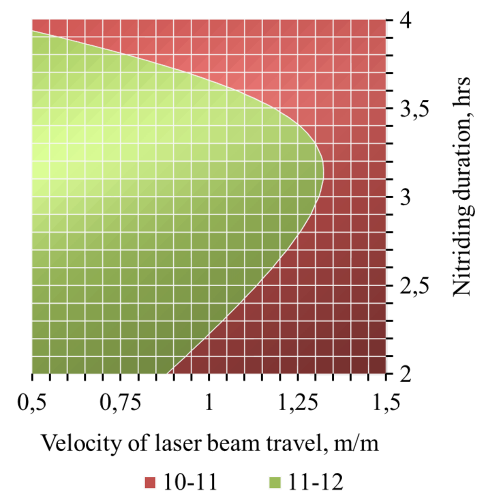


Fig. 5. Nomogram of dependence of surface hardness on velocity of the laser beam travel and nitriding duration

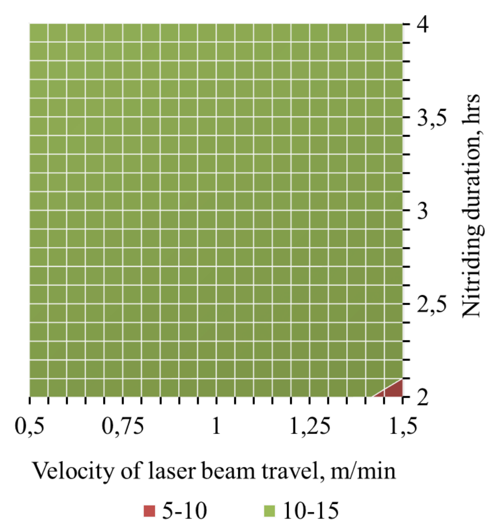


Fig. 6. Nomogram of dependence of surface hardness on velocity of the laser beam travel and nitriding duration taking into account significance of coefficients

Also such description allows solution of the inverse problem, namely, estimation of the assumed thickness of the hardened layer and surface hardness at a simultaneous influence of velocity of the laser beam travel and nitriding duration.

Obtained nomograms ensure determination of concrete conditions of hardening processing proceeding from the specified thickness of the hardened layer or the surface hardness of 38Cr2MoAl steel, respectively.

7. Conclusions

1. Experimental data have shown that depending on the process conditions of combined treatment, thickness of the hardened layer of 38Cr2MoAl steel varies in the range of 0.18 to 0.69 mm at surface hardness of 10.5 to 12.5 GPa.

2. Mathematical models were obtained in the form of regression equations describing dependence of thickness of the hardened layer and surface hardness on the variation of velocity of the laser beam travel and the duration of steel nitriding following the combined treatment. The dependencies found have practical technological value since it is possible to construct nomograms for selection of rational conditions of hardening treatment.

3. Nomograms of simultaneous influence of velocity of the laser beam travel and nitriding duration on thickness of the hardened steel layer and surface hardness were constructed. Nomograms allow determination of concrete conditions of hardening processing proceeding from the specified thickness of the hardened layer or the surface hardness of 38Cr2MoAl steel, respectively, and solution of an inverse problem as well.

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