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SIMULATION OF FORCE LOADS OF PISTON RINGS DVZ WITH THE PURPOSE OF CHOOSING OPTIMAL STRENGTHENING TECHNOLOGIES

МОДЕЛЮВАННЯ СИЛОВИХ НАВАНТАЖЕНЬ ПОРШНЕВИХ КІЛЕЦЬ ДВЗ З МЕТОЮ РОЗРОБКИ ОПТИМАЛЬНИХ ЗМІЦНЮЮЧИХ ТЕХНОЛОГІЙ

The service life of motor vehicles depends on many factors, namely the quality of their parts and mechanisms. Quality indicators consist of many factors-from the chemical composition of the material, micro and macrostructure, strengthening technologies, processing modes, etc. to physical and mechanical properties of the surface layer. In the production of world- class parts, the dynamics of the growth of loads (speed, temperature, aggressive environment) on the mechanisms of the destruction of parts operating in extremely difficult conditions are taken into account. In modern production technologies, the share of using differentiated and combined treatments of the surface layer of parts is in-

creasing. This makes it possible to expand the spectrum of occurrence of gradients in the surface layers of the structural-phase state and uneven structure of the material.

With combined and differentiated technologies for strengthening the surface layer, it is necessary to carry out processing in several stages, namely, as an example, preliminary nitriding to obtain the appropriate structures (martensite, carbides, nitrides, borides, etc.) with subsequent laser surface treatment to ensure the specified properties. To assess the condition of the surface layer of parts of piston rings of diesel engines made of 50KHFA steel, the following factors must be taken into account: geometric parameters of dimensions, surface roughness of the part, microstructure and hardness of worn surface layers.

Keywords*: structural-phase composition, piston rings DVZ, combined processing, nitriding, laser processing, modeling.*

Ресурс роботи автотранспортних засобів залежать від багатьох факторів,а саме якості їх деталей та механізмів. Показники якості складаються з багатьох чинників — від хімічного складу матеріалу, мікро і макроструктури, технологій зміцнення, режимів обробки, і т.п. до фізико механічних властивостей поверхневого шару. У виробництві деталей світового рівня враховують динаміку зростання навантажень (швидкість, температура, агресивне середовище) на механізми руйнування деталі, що працюють в над складних умовах.

В сучасних технологіях виробництва збільшується доля використання диференційованих та комбінованих обробок поверхневого шару деталей. Це дозволяє розширити спектр виникнення в поверхневих шарах градієнтів структурно-фазового стану та нерівномірної структури матеріалу. При комбінованих та диференційованих технологіях зміцнення поверхневого шару необхідно проводити обробку в декілька етапів, а саме, як приклад, попередньо проводити азотування для отримання відповідних структур (мартенситу, карбідів, нітридів, боридів та т.ін.) з наступною лазерною обробкою поверхні для забезпечення заданих властивостей.

Для оцінки стану поверхневого шару деталей поршневих кілець ДВЗ із сталі 50ХФА необхідно урахувати наступні фактори: геометричні параметри розмірів, шорсткість поверхні деталі, мікроструктуру і твердість зношених поверхневих шарів.

Ключові слова*: структурно-фазовий склад, поршневі кільця ДВЗ, комбіновані обробки, азотування, лазерна обробка, моделювання.*

Problem's Formulation

Formation of the purpose of the study Internal combustion engine piston rings are the main sealing element in the cylinder-piston group system. Engine power, economy, environmental friendliness and other characteristics of the internal combustion engine depend on the state of the "piston ring — cylinder liner" friction pair. The peculiarity of the load on the piston rings of the internal combustion engine consists in the complex distribution of gas pressure forces, torques of the rotating oils of the rotating bodies and the influence of temperature factors in an aggressive environment. Based on the extremely difficult operating conditions of the piston rings, the requirements that must be met by the materials and coatings of the piston rings also follow, namely to ensure a certain sufficient resource of the internal combustion engine. The material and coating of the piston rings must have sufficient elasticity, strength, wear resistance, heat resistance, and corrosion resistance.

Analysis of recent research and publications

When comparing the readings of the mass of used and new piston rings, it is obvious that the replacement of the rings, caused by the loss of their initial geometric parameters and service characteristics and, as a result, a decrease in the technical and economic indicators of the engine as a whole, occurred with a loss of up to 10 % of the ring mass during the total mileage car up to 180 thousand kilometers. In addition, used rings have reduced elasticity by 8—9 %, which leads to their loose fit to the cylinder wall and increased gas leakage, increased oil consumption, reduced engine power and increased toxic substances in the exhaust gases. Measurements of the thickness of chrome-plated piston rings with a diameter of 100 mm (ZIL-130) in five sections (Fig. 1) show that the thickness difference in height along the entire contour of the worn ring is 0.1 mm. In new piston rings, the difference in thickness is absorbed in 0.03—0.05 mm [1—4].

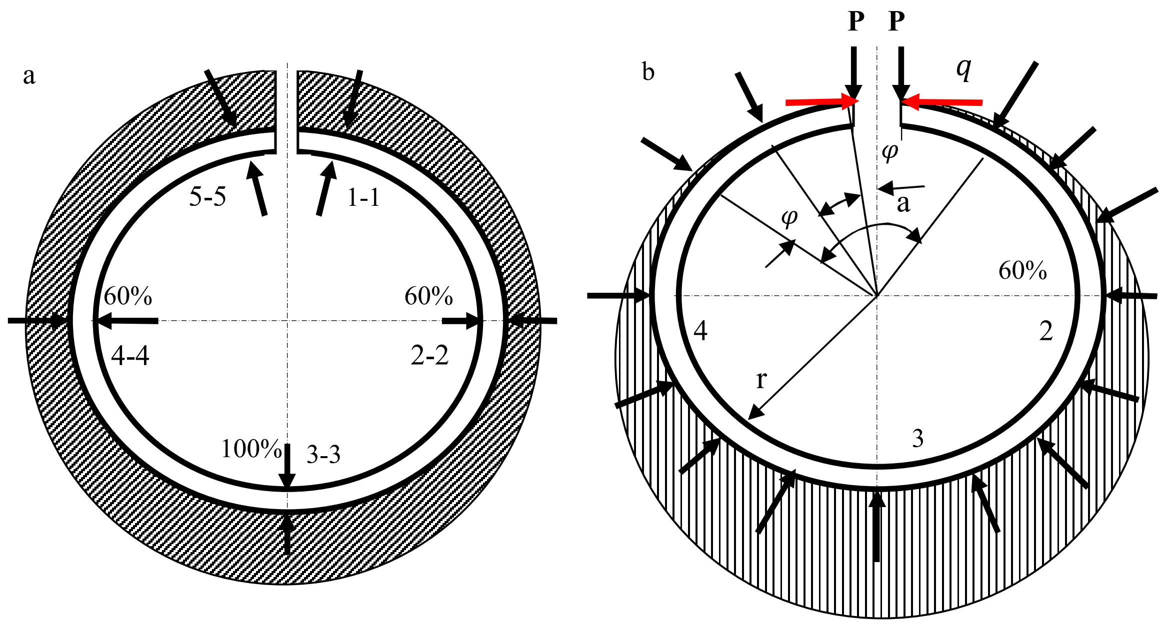

Fig. 1. a — Wear of the piston ring along the contour of the working surface; b — Diagram and chart of the piston ring load

Measurements of the geometric parameters of a batch of compression rings with a diameter of 100 mm, which were replaced as a result of wear when the engine reached critical technical and economic indicators, made it possible to obtain an approximate distribution of piston ring wear in certain zones along the ring contour (Fig. 1a) in sections 2-2, 3-3,4-4,5-5. As can be seen from Fig.1, as a result of the conducted research, the highest wear (up to 100 %) is prone to the zone in section 3-3, located opposite to the ring lock. Zones 1-1 and 5-5 (94—93 %), zones 2-2 and 4-4 (60 %) are less prone to wear. Such unevenness of the degree of wear made it necessary to determine the real contact pressure of the piston ring on the cylinder wall. The pressure on the piston ring from the side of the engine cylinder is the determining force factor for the formation of the load mode in this pair. Thus, within the framework of the one-dimensional contact problem [96], based on the theory of the bending of a beam of small curvature, it is possible to imagine that the ring will not be in close contact with the surface of the cylinder along the entire contour of the circle. In the section 1-2 and 5-4 (Fig. 1.) there is a loose fit of the piston ring to the surface of the cylinder. In sections 2-3 and 4-3 there is a tight fit, which is explained by the impossibility of equalizing the curvature of the ring and the cylinder due to the limited degree of freedom in the ring zones. At points 1' and 1', concentrated forces P act on the side of the cylinder surface, and contact pressure (evenly distributed load with intensity q) acts in parts of the contour 2-3(2'-3). In accordance with the adopted scheme (Fig. 1b), we determine the contact pressure q based on the condition of equality of convergence of the ends of the ring, assuming the cylinder to be absolutely rigid in the radial direction:

$$\Delta = 2\pi(r_k - r_ц), \tag{1}$$

where Δ — is the difference between the gaps of the ring in the free state and in the assembly, m; r_k — outer radius of the ring in the free state, m; $r_ц$ — is the inner radius of the cylinder, m.

$$P = q\, r \sin\alpha, \tag{2}$$

where α — is the angle that determines the length of sections of different curvature, rad.

Next, we determine the convergence of the ends of the ring as a function of q using Mohr's integral

$$\Delta = \sum_{i=1}^{n} \int_{l_i} \frac{M_{zi}(\varphi)\overline{M}_{zi}(\varphi)}{EI_t} r d\varphi, \tag{3}$$

where n — is the number of sections of the ring; i — length of the ith section, m; M_{zi} — is the function of the bending moment at the i-th section, N m; I_t — the function of the bending moment from the unit force, m; E — is the bending stiffness of the ring, N m^2.

$$\Delta = \frac{2}{EI_t}\int_0^{\alpha} Pr\,sin\varphi[r(1-cos\varphi)]rd\varphi + \frac{2}{EI_t}\int_0^{\pi-\alpha}\left[Pr\,sin(\alpha+\varphi)+qr^2(1-cos\varphi)\right]r(1-cos(\alpha+\varphi))rd\varphi\,. \quad (4)$$

After obtaining the mathematical dependence of the definition of bending moments, we reveal the sum. After integrating the expression (4), we obtain

$$\Delta = \frac{qr^4}{EI_t}[sin\,\alpha + (\pi-\alpha)(2+cos\,\alpha)]. \quad (5)$$

From equation (5) we get the value of the contact pressure;

$$q = \frac{EI_t\Delta}{r^4[3\,sin\,\alpha + (\pi-\alpha)(2+cos\,\alpha)]}\,. \quad (6)$$

$$q = \frac{EI_t\Delta}{3\pi r^4}\,. \quad (7)$$

Expression (6) is general. In a separate case, we get a known formula

$$Pr_ц\,sin\,\alpha = EI_t\left(\frac{1}{r_k} - \frac{1}{r_ц}\right), \quad (8)$$

where $\frac{1}{r_k} - \frac{1}{r_ц}$ — is the increase in curvature of the ring.

We write down the condition for equalizing the curvature of the ring and the cylinder at point 2 or, after expressing the force P in terms of q, we obtain the dependence;

$$qr_ц^2\,sin^2\,\alpha = EI_t\left(\frac{1}{r_k} - \frac{1}{r_ц}\right). \quad (9)$$

We express the increase in curvature of the ring due to the difference in clearances from the formula (1):

$$\frac{1}{r_k} - \frac{1}{r_ц} = -\frac{1}{r_ц\left(1+\frac{2\pi r_ц}{\Delta}\right)}\,. \quad (10)$$

We rewrite the expression (9) taking into account (6) and (10):

$$\frac{EI_t\Delta r_ц^2\,sin^2\,\alpha}{r_ц^2[3\,sin\,\alpha + (\pi-\alpha)(2+cos\,\alpha)]} = \frac{EI_t}{r_ц\left(1+\frac{2\pi r_ц}{\Delta}\right)}\,. \quad (11)$$

After reduction, we get the expression

$$\frac{sin^2\,\alpha}{r_ц[3\,sin\,\alpha + (\pi-\alpha)(2+cos\,\alpha)]} = \frac{1}{\Delta + 2\pi r_ц}\,. \quad (12)$$

Where do we get such a trigonometric expression

$$(\Delta + 2\pi r_ц)sin^2\,\alpha - 3r_ц\,sin\,\alpha - 2\pi r_ц + 3r_ц\alpha + r_ц\alpha\,cos\,\alpha - \pi r_ц cos\alpha = 0\,. \quad (13)$$

The analytical solution of equation (13) is difficult. Due to the constancy of the curvature of the ring, a constant (calculated) bending moment acts on the section 2-3-2', which, taking into account the expression (2), takes the following form: (14) where the contact pressure q is determined by the formula (6). Then you can write down the formula for determining the maximum normal stress

$$M_z = qr_ц^2\,sin^2\,\alpha\,; \quad (14)$$

$$\sigma_н = \frac{6EI_t\Delta sin^2\,\alpha}{r_ц^2[3\,sin\,a + (\pi - a)(2+cos\,a)]h\delta^2}, \quad (15)$$

where $\sigma_н$ — is the maximum normal stress, Pa; h-axial height of the ring, m; δ — radial thickness of the ring, m.

Calculations performed for the studied engines of a number of basic cars using formulas (14) and (15).

Formulation of the study purpose

As it follows from the above results, the angle of alignment of the curvature of the ring and the cylinder is significant and is within the limits — and practically does not depend on the dimensions of the piston group. This can explain the presence of an area of loose fit and the prevailing wear in the areas adjacent to the ring gap.

In this way, a new, more accurate mathematical model of the contact interaction between the piston ring and the cylinder wall was developed, which, unlike the existing load models, takes into account the unevenness of the contact interaction of the tribological coupling of the "piston ring-cylinder liner" pair, its change depending on the angle of the position of the local points of the ring and removing them by radius from the lock.

Presenting main material

Structure and properties of 50HFA steel subjected to nitridation. Study of the structural-phase state and properties of the nitrided surface of the piston ring. Two types of samples were chosen for the study: rings made of profiled tape with a diameter of 100 mm and 120 mm, plates with a barrel-shaped working surface, intended for tests with a radius of curvature of the barrel-shaped surface 5 and 6. Nitriding was performed samples from 50HFA steel according to the method given in section 1. The initial microstructure of 50ХФА steel subjected to nitriding in the cross section at a distance of about 1 mm from the surface is ferrite with dispersed inclusions of cementite Fig. 3. Initial microstructure of steel 50HFA, subjected to nitriding, ×1000.

Analysis of the microstructure of the nitrided surface layers of samples No. 11, 12, 13, etc. showed that the structure consists of long sections of the light component with veins extending deep into the samples (Fig. 2). X-ray diffractometric analysis of the nitrided surface of sample No. 11, shows that the intensity of the (110) a-Fe (ferrite) line, which is the most intense in the diffraction spectrum of pure iron, is weakly expressed in the nitrided sample. The diffraction lines of the high-nitrogen Fe_3N phase have the highest intensity (Fig. 4). The intensity of the lines corresponding to the Fe_4N phase indicate its smaller volume fraction in the surface layer. It follows from this that nitriding ensures the formation of two high-nitrogen phases in the surface layer of 50ХФА steel: Fe_3N and Fe_4N, which in the form of solid fields and massive veins cause the high hardness of the surface layer of the nitrided sample (6870 MPa on the surface and 4100...420).

Study of the structure and properties of the surface layers of 50HFA steel subjected to nitriding followed by laser treatment. In a number of works [5, 6, 7, 8] it was shown that laser surface treatment of carbon, low-alloy and alloy steels leads to an increase in surface strength and hardness according to due to the formation of structures of the hardening type. This section presents the results of research into the structure and properties of the surface layers of nitrided samples subjected to laser treatment with a concentrated flow of energy — a pulsed laser beam. As previous studies have shown, laser processing leads to the formation of a complex microrelief with depressions, depressions, and microcracks on the working surface of 50HFA steel. This is caused by local melting of the volume of metal and its accelerated solidification. By the method of successive sanding of the working surface of zones with such a relief, micro-grindings for metallographic analysis were made. Metallographic studies have established that the areas of steel exposed to the influence of laser processing have a white color under the microscope, in contrast to the surrounding volumes of the base metal with a ferrite-carbide structure. Separate inclusions of the same white color with micropores of different sizes are observed in these areas (Figs. 3.). The formation of such white inclusions is associated with local melting of metal volumes and its accelerated solidification. The microhardness of the central zone of the light area (Fig. 3b) is quite high and is H50 = 9277 MPa. Studies of the nature of the distribution of microhardness in the zone of laser exposure were carried out according to the scheme shown in Fig. 3 Injections with a diamond pyramid were carried out along a conventional line passing through the middle of the elliptical spot of laser exposure at equal intervals so as to cover all crater zones and zones adjacent to the areas of laser exposure.

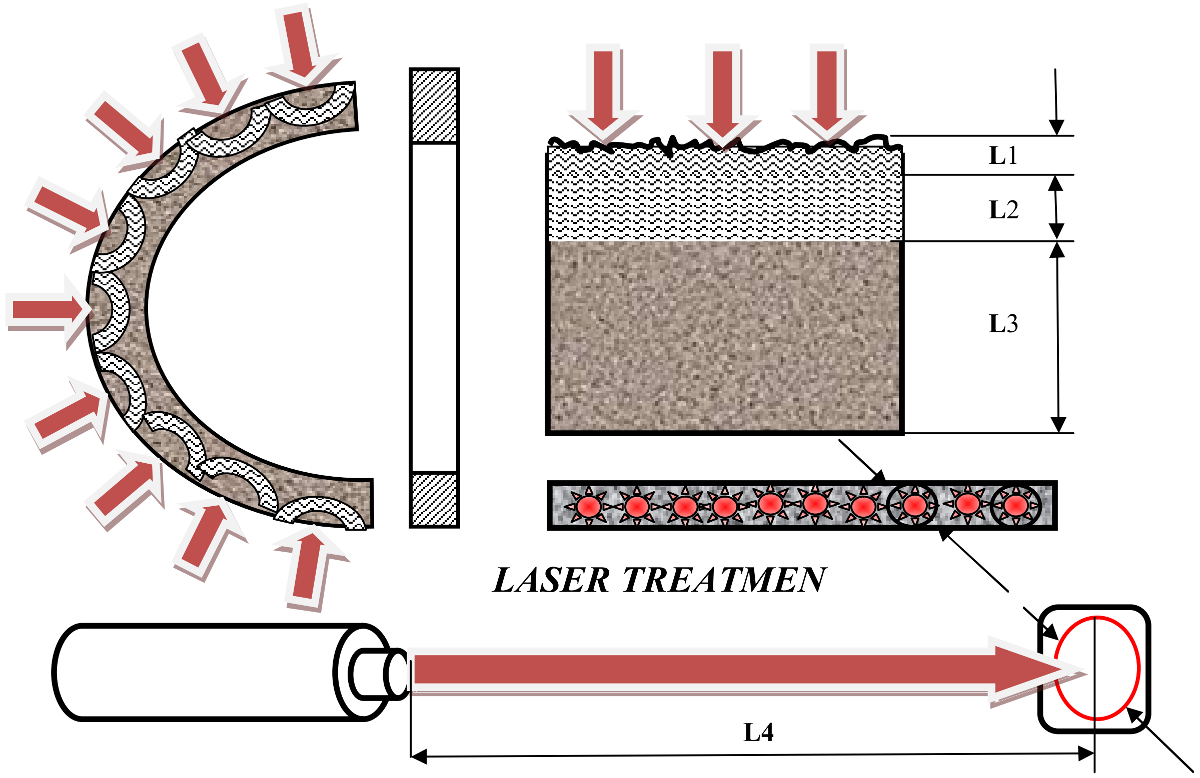

Fig. 2. Scheme of laser processing of a piston ring of an internal combustion engine: L1= 10-15 µm zone of laser influence, L2=60-70 µm — subsurface nitrided layer, L3=70-150 µm — zone of the main material, L4=700 mm — focal distance to the target at LO

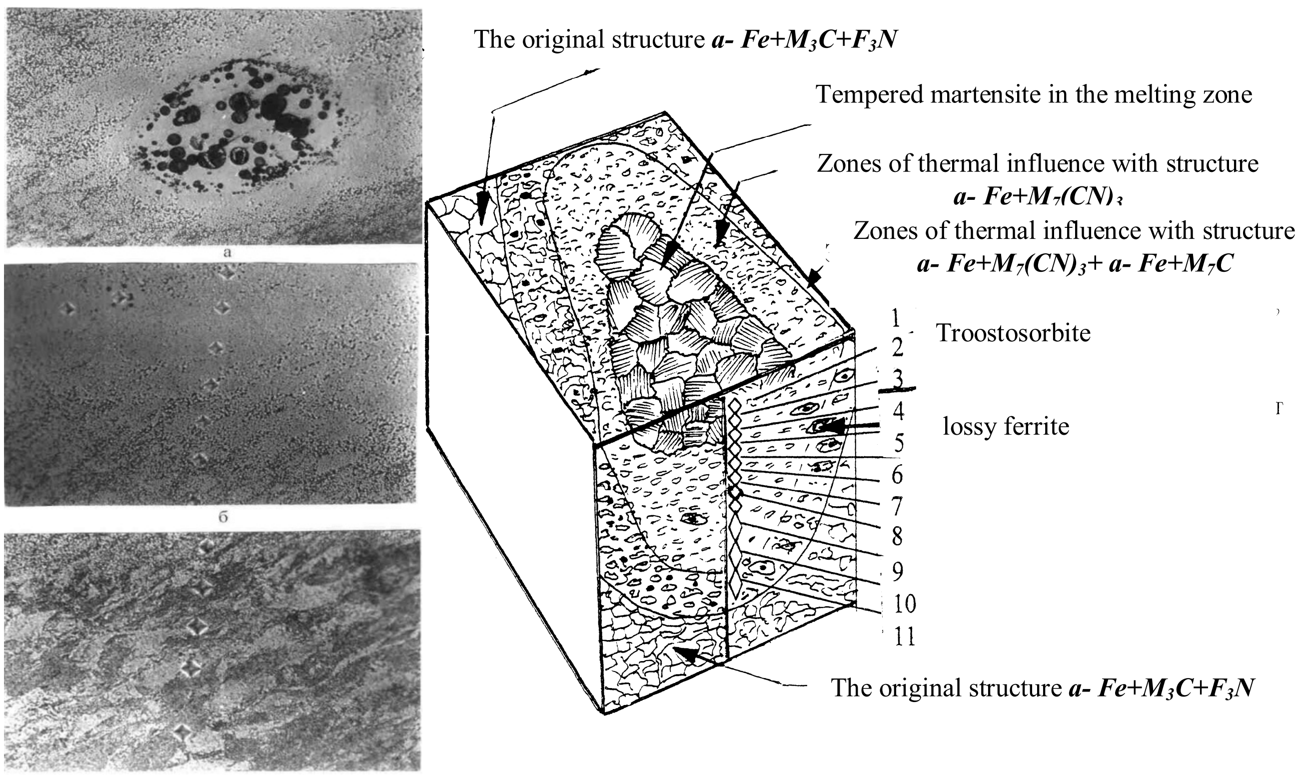

Fig. 3. Schematic representation of the melted zone of thermal influence on the surface and in the end part (in cross-section) of a sample made of 50HFA steel tempered at 550°C and the route of microhardness measurements along the end of the sample

In addition, two injections were made into the porous inclusion lying slightly away from the main line of measurements of the microhardness of the investigated surface. The results of microhardness measurements performed according to the scheme of Fig. 3 are given in Fig. 4. When analyzing the measurement results (Fig. 3), it can be seen that injection points 1, 2, 3, 14, 15 shown in the diagram correspond to areas of the surface that are outside the zone of intense laser exposure and have microhardness 1.5 ... 2.0 times lower than the central zone of the crater. Points 4, 5, 6, 7, 10, 11, 12, 13 are located in the area adjacent to the crater, their microhardness is H50 = 6992 ... 8738 MPa, that is, it is quite high. The reason for this is the formation of a special ferrite-carbide structure in this zone, the genesis of which will be described below.

The generalization of these results made it possible to schematically visualize the structure of structural zones formed in samples of 50HFA steel during laser treatment and subsequent relaxation (Fig. 3). At high temperature in the region of existence and carbide decomposes, which contributes to the formation of high-hardness carbonitride and nitrogenous ferrite.

In the process of cooling from high temperatures, aging processes are carried out in the supersaturated ferrite of the + zone, which lead to its strengthening. During aging at T = 550 ^{o}C, despite the coagulation of cementite-type carbonitride and carbide microparticles that block dislocations during aging, the increase in hardness (microhardness) due to aging remains high at such an aging temperature [9—11].

Therefore, in the + zone, the effect of hardening from laser exposure is achieved due to significant supersaturation with nitrogen (ferrite) in the original structure, and in the released due to the strengthening contribution of cementite-type carbonitride and carbide phases, as well as due to the presence of finely dispersed, highly hard carbonitride particles.

Indeed, as follows from the course of the microhardness change curve along the route indicated in Fig. 3. Schematic representation of the melted zone of thermal influence on the surface and in the end part (in cross-section) of a sample made of 50HFA steel tempered at 550 °C and the route of microhardness measurements along the end of the sample.

Fig. 3 along the end of the sample subjected to laser exposure and subsequent relaxation at The maximum values of microhardness are observed directly in the thin subsurface layer 0.06...0.08 mm MPa thick, which has the structure of tempered martensite (Fig. 3).

The obtained data indicate a rather high microhardness and thermal stability of the structure and surface layer of samples made of 50HFA steel strengthened by laser exposure.

T = 550 ^{o}C, within the zone + surface layer with a thickness of 0.3...0.5 mm, where nitrogen supersaturation was the most pronounced, and the amount of carbonitride was the maximum, an increased level of MPa microhardness values was observed (Fig. 4).

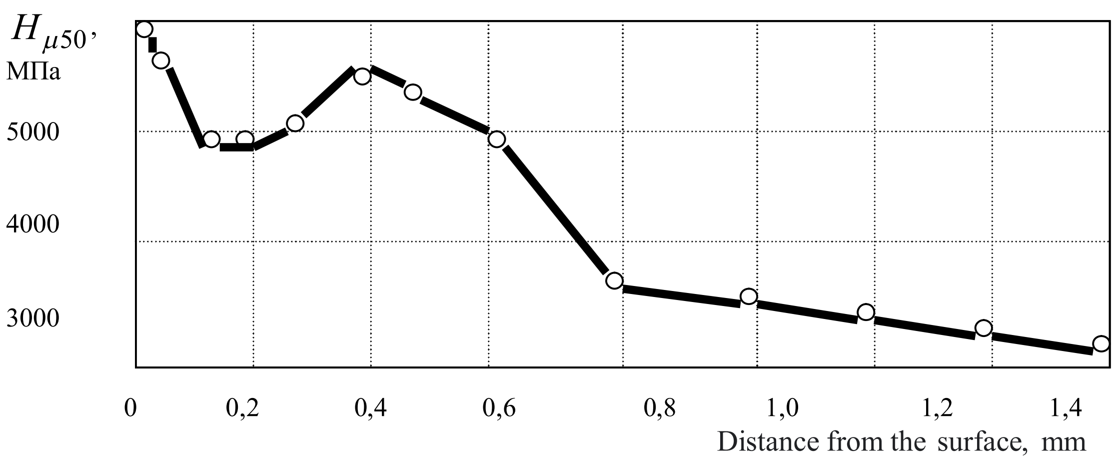

Fig. 4. Change in microhardness along the end of the sample subjected to laser exposure and subsequent tempering at 550°C along the route indicated

Conclusion

The structure of the surface layer of the model of piston ring samples subjected to nitriding and laser treatment was studied. It was established that nitriding leads to the formation of a diffusion layer with a thickness of 0.6 ... 0.8 mm with higher hardness indicators compared to coatings, which is due to the formation of highly solid continuous layers of nitrides and veins directed deep into the base metal in the subsurface layer.

It is shown that laser treatment with micromelting of the surface leads to the formation of areas with a high-hard phase that does not corrode in standard reagents — gardenite with MPa and areas (ferrite) with high-hard carbonitrides immediately adjacent to the hardened-type structures formed in the molten zone. It was established that the thermal stability of the structure formed in the surface layer of nitrided samples after laser treatment is quite high, and when resting at a temperature of T=550°C for up to 25 minutes, the value of microhardness in the surface layer up to 120 μm thick varies from 3000 MPa to 5000 MPa.

It is shown that the features of the phase transformations realized under laser exposure lead to the formation of a complex set of structures in the surface zone: gardenite in the melt volume, (ferrite) with highly hard carbonitride crystals in the zones directly adjacent to the melt volume, and with sections troostosorbite in the zones in contact with +.

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