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METHODS FOR INCREASING WEAR RESISTANCE AND CONTACT ENDURANCE OF GEARS

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ABSTRACT

The paper presents the results of experimental studies on the wear resistance and contact fatigue strength of samples made of various steels after strengthening by heat treatment and ion nitriding in hydrogen-containing and hydrogen-free environments under rolling-sliding friction conditions. The importance of the influence of the property gradient of the resulting compositions on performance characteristics is noted. Methods for improving the contact fatigue strength and wear resistance of gear wheels are proposed. The results of experimental studies of the wear resistance and contact endurance of specimens of various steels after hardening by heat treatment and ion nitriding in hydrogen and hydrogen-free environments under rolling friction with sliding are presented. The importance of the influence of the property gradient of the resulting composites on performance characteristics is noted. Methods for improving the contact endurance and wear resistance of gears are proposed.

1. Introduction

Gears are widely used in engineering. Their durability and reliability often determine the reliability and longevity of the machines as a whole. Experience with gear operation shows that the vast majority of failures occur due to contact surface degradation in closed gears and tooth breakage due to bending in open gears. Currently, there are many ways to improve the wear resistance and longevity of gears, but the problem remains unresolved and remains relevant.

During operation, the surface layers of gears are destroyed as a result of the cyclic action of contact stresses, the value of which reaches 3570 MPa [1], and wear out due to slippage of the contacting surfaces of the gear and wheel. Maximum bending stresses occur when the entire load is supported by one pair of teeth, and the point of its application is in the position furthest from the tooth root. In this case, the maximum bending stresses are concentrated at the root of the tooth, and a stress concentration occurs in the fillet zone. For spur gears of gearboxes, maximum bending stresses reach 850 MPa [2], and for case-hardened heavily loaded gears – up to 2500 MPa [1].

In gear pairs, joint rolling occurs only at the pole. Since the directions of movement of the contact lines of the pinion and wheel are opposite, slippage occurs between them. The slip velocity is

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equal to the difference in rolling speeds of the pinion and wheel and increases with increasing gear ratio. Slippage of the contacting tooth surfaces causes friction in the contact zone and material wear.

The stress-strain state of the tooth material is greatly influenced by the rate of load application. Studies [3, 4] have shown that contact between two teeth occurs within 10-3 -10-4 s. Calculations show that even in low-speed gear transmissions, the load is applied to the contact by an impact [3]. The combined action of normal and shear stresses in a thin surface layer of the material creates a volumetric stress state, which promotes the occurrence of plastic deformation. High contact stresses and plastic deformation cause instantaneous temperatures at the points of actual contact, reaching 700-800°C, which rapidly decrease over the course of the cycle [3].

Thus, the surface of the contacting teeth experiences cyclic thermal effects. As a result of the force and temperature effects in microvolumes, rapid diffusion of elements to the contact surface occurs. Thus, an analysis of the operating conditions of gears shows that the service life of gears depends largely on a detailed study of the engagement conditions, the nature of the stress-strain state of various zones of the gears, and the correct selection of materials and methods for strengthening these zones, in accordance with the magnitude and nature of the stress state. Solving this problem with a single technology is difficult. A combination of several hardening technologies is required for the working surface and core of the gear, ensuring optimal properties both on the surface and in depth in each zone, in accordance with the magnitude and nature of the load. Such technologies may include: thermal and thermochemical treatment of the material; application of coatings with predetermined properties to the surface, in accordance with the stress state in the surface layers of the gears.

Currently, carburizing and nitrocarburizing of low-carbon steels, followed by heat treatment, are widely used to strengthen gears. These processes significantly increase wear resistance and durability. However, these technologies are carried out in environments containing large amounts of hydrogen, which adversely affects the strength of the steel.

According to modern concepts [6-9], hydrogen can exist in steel for long periods of time in the form of ions and molecules. A small amount of hydrogen in steel does not cause noticeable changes in its properties. Increasing the hydrogen concentration in steel above a certain limit, dependent on the steel's quality, alters its physical and mechanical properties and can cause defects affecting its strength. Hydrogen in steel alters its mechanical properties under short-term and long-term static loading, as well as under repeated alternating and impact loading [6-9].

A promising technology for strengthening the surface of materials is ion nitriding in hydrogen-free saturating environments (mixtures of nitrogen with argon) [10], the use of which eliminates the harmful effects of hydrogen on metal.

5. Statement of the problem

To study the effect of ion nitriding on the strength characteristics and residual stresses in steels, and to determine the effect of coating and base hardness on the contact endurance of samples during rolling with slippage.

6. Research results and their discussion

In order to identify the effect of hydrogen on metal during ion nitriding, experimental studies were conducted on the physical, mechanical and operational characteristics of nitrided samples of various steels in hydrogen-containing and hydrogen-free saturated environments under tension, bending and cyclic contact loading.

Tensile strength and ductility were studied using flat specimens of St.3, 40X, 65G, and 12X18N10T steels manufactured according to GOST 9651-73 and subjected to ion nitriding under various process conditions. The specimens were 75 mm long and had a working cross-section of 3 x 3 mm. The studies were conducted using an IMASH 20-78 test facility. The following characteristics were examined during the experiments: tensile strengthσV, yield strengthσT, proportionality limitσPC, relative elongation δ, relative contraction ψ, specific fracture work A, and factual studies of the destruction process were also carried out. In the course of the research, the cross-sectional dimensions of the specimens were measured before and after the tests, the tensile diagram was recorded and the destruction process was videotaped. All experiments were carried out at room temperature at a moving clamp speed of 0.1 mm/min and repeated 3 times. Table 1 shows the results of studies of the strength and ductility characteristics of steels St.3, 40X, 65G and 12X18N10T during tensile testing. Specimens from these steels were subjected to ion nitriding in a hydrogen-containing environment (75 vol.% N2 + 25 vol.% H2) and a hydrogen-free environment (75 vol.% N2 + 25 vol.% Ar) according to the following regime: nitriding temperature T = 580 °C; medium pressure p = 240 Pa, nitriding duration τ = 4 hours.

Table 1. Physical and mechanical characteristics of samples from various steels during tensile tests before and after ion nitriding (nitriding mode: T=580°C, p=240 Pa, τ=4 hours)

№	Steel Grade	Ion Nitriding Medium	Ultimate Strength σ_b, MPa	Yield Strength σ_t, MPa	Relative Elongation δ, %	Relative Reduction ψ, %	Specific Deformation Work A, MJ/m³
1	St.3	not nitrided	500	247	30.0	60.0	105.0
		75 vol.% N_2 + 25 vol.% Ar	557	295	10.0	25.0	51.0
		75 vol.% N_2 + 25 vol.% H_2	474	338	6.0	18.0	25.0
2	40X	not nitrided	560	380	10.0	30.0	41.1
		75 vol.% N_2 + 25 vol.% Ar	623	551	5.65	21.4	28.9
		75 vol.% N_2 + 25 vol.% H_2	605	566	3.12	6.87	15.2
3	65G	not nitrided	700	320	9.0	25.0	59.8
		75 vol.% N_2 + 25 vol.% Ar	744	587	3.83	14.9	29.4
		75 vol.% N_2 + 25 vol.% H_2	661	544	2.67	10.8	16.5
4	12X18H10T	not nitrided	520	280	40.5	55.2	182.3
		75 vol.% N_2 + 25 vol.% Ar	551	321	37.5	49.4	170.2
		75 vol.% N_2 + 25 vol.% H_2	546	318	36.1	45.2	156.7

Studies have shown that ion nitriding significantly affects the strength and ductility properties of steels, increasing strength and decreasing ductility. During ion nitriding in a hydrogen-free environment, the tensile strength of the steel samples studied increased by 4-11%, while their ductility decreased by 1.1-3 times. Ion nitriding has a greater effect on less alloyed steels. For example, while for 12Kh18N10T steel, the tensile strength of the samples increased by 4%, and the relative elongation and contraction of area decreased by approximately 10%. For St.3 steel, the tensile strength of the samples increased by 11%, while the ductility characteristics δ and ψ decreased by more than 3 times.

A comparison of strength and ductility characteristics after ion nitriding in hydrogen-containing and hydrogen-free environments (Table 1) shows that the presence of hydrogen in the saturating medium significantly reduces these characteristics of low-alloy structural steels. Thus, the tensile strength of St.3 and 65G steel specimens after ion nitriding in a hydrogen-containing environment decreased by 17.7% and 12.5%, respectively, compared to their value after ion nitriding in a hydrogen-free environment. The results were even lower than those of non-nitrided steels. The hydrogen-containing environment has an even greater impact on the reduction of steel ductility during ion nitriding. Thus, for steels St.3, 40Kh and 65G, nitrided in a hydrogen-containing environment, the relative elongation δ decreased by 40, 45 and 31%, respectively, and the relative contraction ψ by 28, 68 and 27.5% compared to their values during nitriding in a hydrogen-free environment (Table 1). This is due to the harmful effect of hydrogen on steel, associated with hydrogen embrittlement and hydrogen corrosion of the metal, which confirms the theoretical concepts put forward in [6-9].

The detrimental effect of hydrogen on the plastic properties of steels is clearly demonstrated by the specific work of deformation, which is the area of the tensile stress-strain diagram in the σ, δ coordinate system. Calculations have shown that the specific work of deformation of steels St.3, 40Kh, 65G, and 12Kh18N10T, nitrided in a hydrogen-containing environment, is 2.1; 1.9; 1.8, and 1.05 times lower, respectively, compared to its values during nitriding in a hydrogen-free environment (Table 1). From the presented data, it is evident that with an increase in the degree of alloying of the steel, the detrimental effect of hydrogen on its mechanical properties decreases.

High-cycle bending fatigue tests were conducted on smooth cylindrical specimens with a diameter of 5 mm using an IMA-5 bending machine under pure bending with rotation (frequency of 50 Hz), in a 3% NaCl solution and in air. The specimens were made of Steel 45, some of which were subjected to ion nitriding in hydrogen-containing (60 vol. % N2 + 40 vol. % H2) and hydrogen-free (60 vol. % N2 + 40 vol. % Ar) environments with other process parameters remaining constant (T = 540 °C, p = 80 Pa, τ = 240 min).

The results of these studies (Figure 1) show that the fatigue limit of the samples subjected to ion nitriding in a hydrogen-free environment increased by 1.75 times (from 210 to 370 MPa) when tested in air, and by 3.6 times (from 30 to 110 MPa) when tested in a 3% NaCl solution, compared to its values for non-nitrided samples.

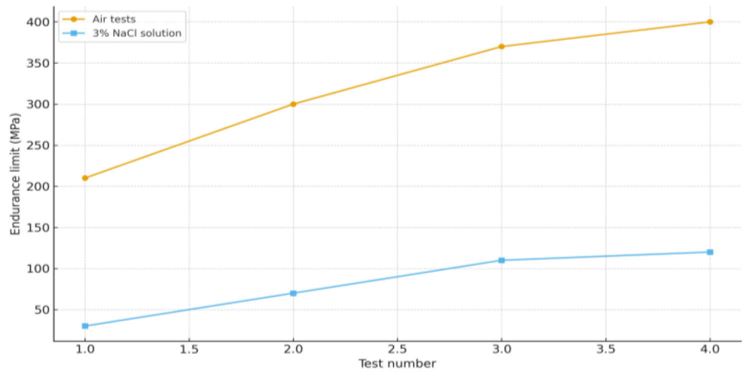

Fig. 1 Fatigue curves of steel 45 under bending tests

The fatigue limit of samples nitrided in a hydrogen-containing environment (curve 3) when tested in a 3% NaCl solution is 25% lower compared to samples nitrided under a similar regime in a hydrogen-free environment. The reason for such a decrease in the fatigue limit of steel is the harmful effect of hydrogen, which causes: decohesion of the crystal lattice of the metal; interaction of hydrogen atoms in the metal with dislocations; pressure of molecular hydrogen in microcavities of steel; chemical interaction of hydrogen with alloy components and the release of hydrogen-containing phases [6].

A significant increase in high-cycle fatigue of samples after ion nitriding is due to the formation of nitride phases on the metal surface and the development of residual compressive stresses in the nitrided layers. Compressive stresses during ion nitriding reach 800 MPa and can be varied within a wide range by adjusting the process parameters of the diffusion saturation process (Figure 1b). The maximum effect of residual compressive stresses is achieved at their optimal value.

The study of contact fatigue of steels under rolling friction with sliding was carried out on a special rolling friction setup [12], which was mounted on the basis of a drilling machine with a vertical spindle. Balls or cylindrical rollers with a slip coefficient of 0.4 and 17.7%, respectively, rolled along a circular track of flat samples. The loads on the rolling elements were 50, 100, 160, 250 N (maximum pressure p0 2075; 2615; 3057; 3180 MPa, respectively), the spindle speed was 900 min–1. Samples of various steels were studied after ion nitriding in hydrogen and hydrogen-free environments with different heat treatments and chromium and titanium nitride coatings.

The results of comparative studies of wear resistance and contact endurance of samples are shown in Tables 2 and 3 and in Figure 2.

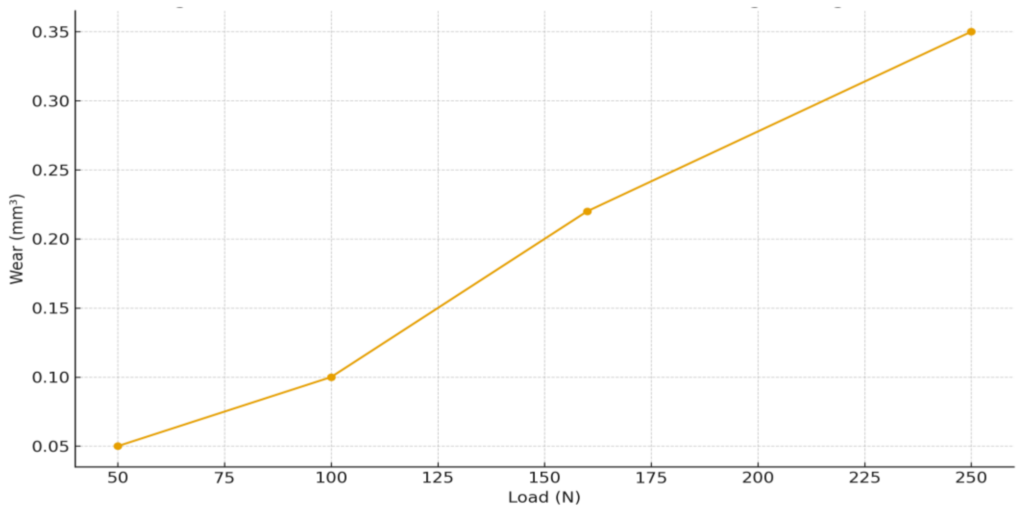

Fig. 2. Dependence of pitting fatigue life on wear intensity

Figure 2 – Dependence of 20Kh13 steel wear under rolling friction with sliding on the number of cycles under various ball loads: N=50, 100, 160, and 250N. At a friction coefficient of 0.4, these wear cycles reach the surface. Many researchers believe that tangential forces at the contact surface cause tensile stresses, which contribute to the formation of microcracks. Residual compressive stresses in the surface layer reduce tensile stress and contribute to increased crack resistance of the material.

Table 2. Physical, mechanical and tribological characteristics of samples after ion nitriding and heat treatment and their durability during rolling friction tests in I-20 lubricant, ball load 150N (p0=3180 MPa)

No	Steel grade	Heat treatment / technology / coating	Surface microhardness, MPa	Base microhardness, MPa	Rolling track microhardness after testing, MPa	Coating thickness, μm	Wear intensity, $I \cdot 10^{-11}$	Pitting fatigue life, $N \cdot 10^6$ cycles
1	20X13	without heat treatment	2550	2370	3460	0	620	0,58
2	20X13	ion nitriding in 60% Ar + 40% N_2 atmosphere	7380	2370	3650	260	570	0,88
3	45	without heat treatment	3200	2450	3290	0	600	0,6
4	45	ion nitriding in 60% Ar + 40% N_2 atmosphere	7440	2450	4100	280	452	0,98
5	45	quenching	5100	4110	5230	0	21,2	9,1
6	45	quenching + ion nitriding in 60% Ar + 40% N_2 atmosphere	7460	4110	7200	290	16,1	12,9
7	45	ion nitriding in 60% Ar + 40% H_2 atmosphere	8420	2450	4050	290	440	0,75
8	45	quenching + ion nitriding in 60% Ar + 40% H_2 atmosphere	8560	4110	8210	300	15,4	11,2
9	20X13	ion nitriding in 60% Ar + 40% H_2 atm.	7640	2370	3670	280	580	0,7

The figure 2 shows that plastic deformation accounts for the majority of the total wear, increasing sharply with increasing ball load. Ball slippage wear is insignificant due to the low slip coefficient (0.4%). When cylindrical rollers were used as rolling elements, the slip coefficient was 17.7%, and wear from sliding friction, before pitting, was predominant compared to plastic deformation of the surface layer. The contact fatigue life of the samples was 25-30% lower. This is explained by the fact that point contact of the material with the balls results in a more favorable volumetric stress-strain state compared to the linear contact of cylindrical rollers.

Research by many authors [1-5] shows that maximum stresses under contact loads and bending occur in the surface layers, leading to microcracks and failure of both the surface and the structure as a whole due to the development and propagation of microcracks from the surface into the core. Therefore, to improve the wear resistance and durability of structural components, and gears in particular, both the surface and the core should be strengthened, but with different physical and mechanical properties—large ones on the surface and smaller ones in the core. In other words, the surface layer structure should have a gradient structure corresponding to the stress-strain state occurring in the component.

Model studies of the stress-strain state of a plate with multilayer coatings under a contact distributed load on the contact area with normal forces changing according to a parabolic law have shown [11] that an increase in the strength and durability of the coating-base composition can be achieved by:

- application of hardening coatings with a high modulus of elasticity and a smooth gradient of change in properties in depth from the surface to the base (diffusion coatings);

- reducing the gradient of properties by depth, due to an increase in the coating thickness and an increase in the rigidity of the base;

- application of thin low-modulus films to the coating surface, providing an increase in the contact area and anti-friction properties.

These recommendations are clearly confirmed by the results of experimental studies (Table 3), in particular: application of a strengthening high-modulus coating of titanium and chromium nitride to a hard base; production of diffuse nitrided layers with a smooth gradient of change in hardness across the thickness; application of oxidizing films to nitrided layers; obtaining an optimal ratio of the hardness of the coating and the base during nitrohardening significantly increase the wear resistance and contact endurance of materials during rolling with slippage.

Table 3. Physical, mechanical and tribological characteristics and durability of samples after ion nitriding, heat treatment and other coatings during rolling friction tests in I-20 lubricant, ball load 150N (p0=3180 MPa)

No	Steel grade	Heat treatment / technology/ coating	Surface Micro-hardness, MPa	Base micro-hardness, MPa	Rolling track micro-hardness after testing, MPa	Coating thickness, μm	Wear intensity, $I \cdot 10^{-11}$	Pitting fatigue life, $N \cdot 10^6$ cycles
1	ШХ15	without heat treatment	3840	3340	3340	0	594	0,7
2	ШХ15	without heat treatment + ion nitriding	9180	2680	5400	300	312	1,08
3	ШХ15	without heat treatment + oxidation	6140	2680	5420	300	210	1,25
4	ШХ15	quenching	7210	7210	7130	0	8	25,1
5	ШХ15	quenching + ion nitriding	9180	4970	7160	300	8,4	24,2
6	ШХ15	quenching + ion nitriding	7660	5800	7300	290	7,5	26,4
7	ШХ15	quenching + ion nitriding	7860	5900	6350	120	13	22,8

8	ШХ15	quenching + TiN (CIB method)	10400	5120	5200	5	15	22
9	ШХ15	without heat treatment + TiN (CIB method)	14000	2680	3350	5	564	0,75
10	ШХ15	quenching + galvanic Cr coating	12000	7210	7140	5	7,6	28,4
11	ШХ15	quenching + galvanic Cr coating	12000	7210	7300	10	7	30,1
12	ШХ15	nitroquenching mode 1	8700	7200	7630	330	3,6	40,8
13	ШХ15	nitroquenching mode 2	7700	7420	7420	350	3,2	48,8
14	ШХ15	nitroquenching mode 3	7300	7200	7380	410	3,8	38,4
15	ШХ15	nitroquenching mode 4	8500	7410	7410	320	3,7	38,7

In the contact zone, under load, normal stresses arise with a maximum on the surface at the center of the contact area and shear stresses with a maximum at a certain depth. The presence of friction forces causes the maximum shear stress to shift from depth to depth.

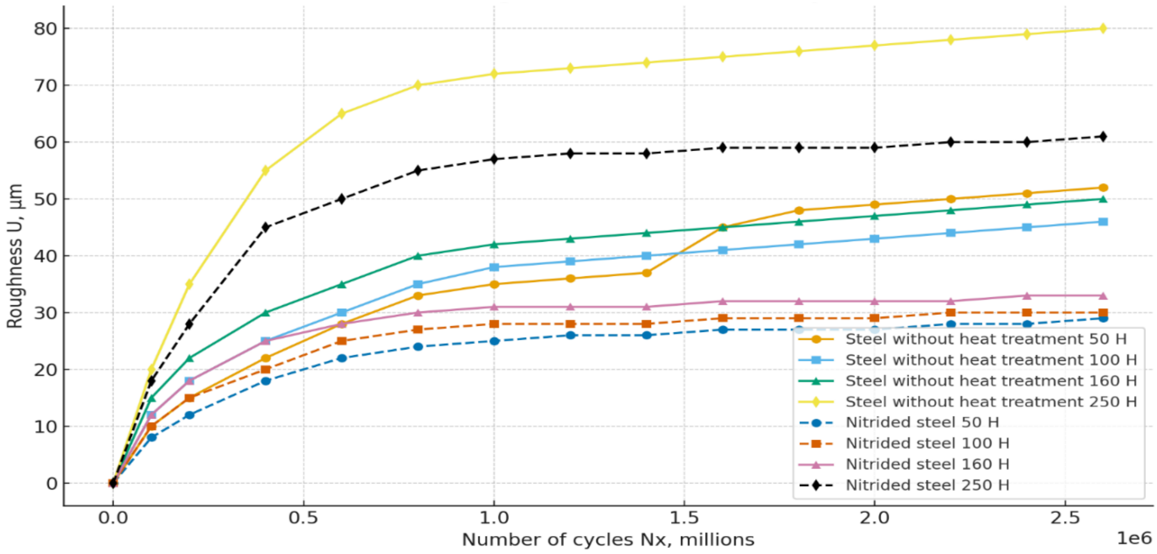

Fig. 3 Surface Roughness vs Number of Cicles

The graph 3 illustrates the dependence of the displacement amplitude (U) (µm) on the number of loading cycles (N \times 10^6) for steels with and without nitriding treatment under different applied loads (50, 100, 160, and 250 N). The solid curves correspond to steel without heat treatment, while the dashed ones represent nitrided steel (treated according to regime 1a). As the number of loading cycles increases, the displacement gradually grows for both materials, but the values for nitrided steel remain significantly lower throughout the entire range of cycles. This indicates a considerable increase in surface hardness and fatigue strength due to nitriding. For example, at the highest load of 250 N, the displacement of untreated steel reaches 70–80 µm, while the nitrided surface exhibits only 35–40 μm deformation, which means a reduction of about 40–50%. The curves show that, during the initial stage of loading (up to 0.4×10^6 cycles), the deformation grows rapidly due to the running-in process, after which the growth rate stabilizes. Nitrided steel demonstrates an earlier stabilization of the curve, indicating the formation of a stable surface layer resistant to plastic deformation and microcrack propagation. In contrast, the untreated steel continues to accumulate deformation, showing signs of progressive surface fatigue. The overall tendency confirms that surface nitriding significantly improves the resistance of steel to cyclic contact loading by forming hard nitride phases ($Fe_{2-3}N$, Fe_4N) that reduce wear and prevent structural damage. Therefore, nitriding can be considered an effective method for enhancing the operational durability and dimensional stability of mechanical components such as gears, shafts, and cutting tools subjected to long-term cyclic stresses.

7. Conclusion

Thus, an analysis of operating conditions and the stress-strain state of gear teeth revealed that different areas of the tooth surface experience varying stress levels and types. The most hazardous surface areas include the root, the gullet, and the mid-tooth surface region located at the engagement pole. Therefore, it is clear that these surface areas require different surface layer properties. This can be achieved by strengthening the tooth surface, particularly in hazardous areas, by applying hardening coatings with a gradient structure across the depth; by creating optimal residual compressive stresses in the surface layers; and by strengthening the tooth core. This requires heat treatment of the tooth material to increase the core hardness and the application of hardening coatings using thermochemical treatment in hydrogen-free environments, with the physical and mechanical properties and phase composition of the coatings controlled depending on the operating conditions and stress-strain state of the gears.

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