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IMPROVING THE SURFACE STRUCTURE OF MASSIVE PARTS BY THE PLASMA METHOD

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Annotation

An increase in the reliability of the operation of large-sized and massive parts by plasma hardening of their surfaces is substantiated. It has been established that the formation of several structural zones of different microhardness is observed in detail along the depth of hardening, indicating the formation of a gradient-layered structure. It has been proved that at ultrafast heating rates, which occur during surface plasma hardening, phase and structural changes move to the high temperature region, changing the kinetics of the appearance and growth of new phase nuclei. In this case, fine-grained austenite is formed, which is transformed into a highly dispersed martensitic structure, which increases the strength and reliability of the surfaces of the parts.

Key words: Solid-rolled wagon wheel, plasma hardening, gradient-layered structure, wear resistance, contact fatigue strength.

Introduction

One of the key requirements for machines and their parts is their durability and reliability. Solid-rolled wheels of transport cars operating under conditions of intense shock-cyclic loads are subject to high requirements for wear resistance and contact-fatigue strength. Thus, when moving a loaded carriage, the wheels are subjected to tests of several types of loads: rail pressure corresponding to a certain part of the pressure on the axle of the wheelset; dynamic load from impacts on rail adhesion; frictional forces arising from the rolling of wheels on a straight track; frictional forces during braking, formed in the plane of contact of the brake shoe with the wheels; frictional forces under pressure of a braked wheel with wheels.

The most common heat treatment method is hardening, which becomes a problem when it comes to large and large parts. Requires large, energy-intensive heating furnaces and heating rolls for quenching and tempering machine parts. The main task is that when using classical methods of heat treatment of large parts, it is impossible to achieve uniform cooling and uniformity of structural transformations throughout the volume of the hardened part. This, in turn, causes the appearance of the remaining thermal and structural yarns in the parts, reducing its fatigue properties. [1].

Task definition

One of the most complex and difficult tasks from a wide range of machine-building enterprises facing a technologist is the scientific and technical substantiation of thermal hardening of large surfaces of large-sized and massive parts of various kinds. That is, the efficiency of spindles is mainly determined by the wear resistance of the spindle journals and the ability to withstand fatigue and fracture. To obtain a high wear resistance of the journals, it is necessary to provide a surface layer with a martensite structure and high strength through hardening. In reality, due to the danger of the appearance of deformations, the strength of the spindle necks is limited at the level of 49-50 HRC.

At high loads (up to 27 tons per axle of transport cars) and high train speeds, thin surface layers are heated to temperatures exceeding the critical points Ac1 and Ac3. As the heated area leaves the contact area, it quickly cools down, which can cause the formation of a mesh and surface shedding. The surface is heated mainly due to the plastic deformation of the surface layer, and about 75% of the energy expended in plastic deformation is converted into heat. This heat is concentrated in microvolumes adjacent to the shear surface. The temperature in the specified volume x can reach the austenitic region and upon rapid cooling creates conditions for the transformation of martensite. A weak martensite layer formed on the plane can crack and flake off during operation [1,2].

Relatively low-cost carbon steels with a high carbon content are actively used for the manufacture of a significant part of machine parts and production equipment. The operational stability of such parts in the current conditions does not meet the increasing demands of production due to the increase in the cost of spare parts, current and overhaul of units associated with their replacement.

Research materials and methodology

The research was carried out at NPO Flagman (St. Petersburg) using equipment and new technologies for surface plasma hardening of large-sized parts in mechanical engineering: lathe spindle necks, rolling machine bearing housings, large-module gears, solid-rolled wheels of freight cars, etc.

An element of the plasma hardening technology was the spindle necks of a heavy lathe made of alloy steel 35XN3MFA with a length of 6500 mm and the flanges of car wheels with a diameter of 957 mm made of carbon steel grade 2 in accordance with GOST 10791-2011. TriboPateks multipurpose plasma metal processing equipment was used for quenching. The technological parameters of the process are the magnitude and polarity of the current, the speed of movement of the plasmatron relative to the surface, the consumption of the protective and plasma-forming gases, and the parameters of the plasma-forming nozzle. Quenching was carried out at a current of direct polarity with surface fusion without a gap in the following modes: current value - 240A, plasma torch travel speed - 7.2 m/s, plasma-forming gas consumption - 5 l/min, protective gas consumption - 7 l/min. Plasma treatment was carried out stepwise, with a step exceeding the track width by 1.5-2.0 mm. When overlapping the treated areas, the hardened track was released to a width of 5 mm. In large and massive parts, plasma hardening is carried out by dissipating heat into the body of the workpiece; strengthening of thin-walled parts is carried out using a spray gun. As a result, hardened (hardened) layers with a hardness of 43-54 HRC, up to 2.5 mm deep in the form of a track 6-12 mm wide (when processing parts with compressed air plasma) and 12-30 mm wide (when processing with air plasma with additives combustible gases). Hence, we can conclude that surface hardening of large-sized parts ensures the formation of a surface layer with high hardness and reliability.

In cases where the arc burns between the plasma electrode and the workpiece, plasma hardening occurs, micromelting of the surface layer of the workpiece and a change in its geometry (for thin-walled parts) also occur, therefore this method of plasma hardening can be used when the part contains a significant allowance for the next processing.

It should be noted that to ensure the required technical parameters, the required durability is provided, the parts in the nodes are small, only a little more than 1.5 is required, this is somewhat necessary. This depth can be achieved with the hardening of structural steels using various methods of heat treatment of surfaces. Among them, two traditional technologies of surface hardening are the most popular in modern mechanical engineering: high-frequency hardening (HFC) and flame hardening, which provide structural changes in the metal to a depth of ~ 0.3-5.0 mm.

At the same time, innovative development in various sectors of the economy provides for the widespread introduction of modern effective and cost-effective technological processes based on the developments of modern science and technology. Today in industry (especially when hardening large base parts), there is a spread of surface plasma hardening [3].

Further in the article the structure and properties of the obtained hardened surfaces of the spindle journals of a heavy lathe are given. The strength and thickness of the hardened layer, the structure of the heat-affected zone and the base metal have been studied. Micro-cuts for studying the microstructure were made in a plane, samples were taken perpendicularly to a homogeneous quenched surface, and the etching was subjected to a suspension in a 4% solution of nitric acid in ethyl alcohol. Due to the etching of this reagent, the hardened layer represents zones of intense etching of various depths. The study of the microhardness of the hardened surface was carried out on a microsection before etching on a PMT-3 hardness tester at a load of 1.962N (200gf) in accordance with the requirements of GOST 9450-2006 "Measurement of microhardness by indentation of diamond tips". The hardness of the experimental samples was determined according to Vickers HV0.1 (GOST 2999-1995) and Rockwell HRC (GOST 8.064 -1999).

The studies were carried out on a Neophot optical microscope at a magnification of 100:1 on microsections. Microsections were cut transversely from the zone with the condition of maintaining the hardened surface. Electron microscopic studies were performed on a JeolJEM 2100 electron microscope with a magnification of 5000:1.

Strength tests were carried out in accordance with GOST 25.503-97 “Calculations and strength tests. Methods for mechanical testing of metals. Compression test method ". We used 5 prismatic (rectangular) specimens with type III smooth ends. During the test, a machine for stretching and compressing springs of the TLS-SI series with a load of 20 N was used.The initial strength data were taken from heat hardening samples, the final cross-sectional area of a prismatic specimen of which after testing based on compression tests at a load of 20 N was 44.3 , 39.65, 31.98, 47.4 and 40.93 mm2, which is 20-30% more in comparison with the samples of heat hardening.

Tests for crack resistance of surfaces were carried out in accordance with GOST 25.506-85 “Calculations and strength tests. Methods for mechanical testing of metals. Determination of the characteristics of crack resistance under static loading ”. To determine the characteristics of crack resistance, the following samples are used: type 1 - flat rectangular with a central crack for axial tension tests with a diameter of 12 mm and a width of 48 mm (Fig. 1).

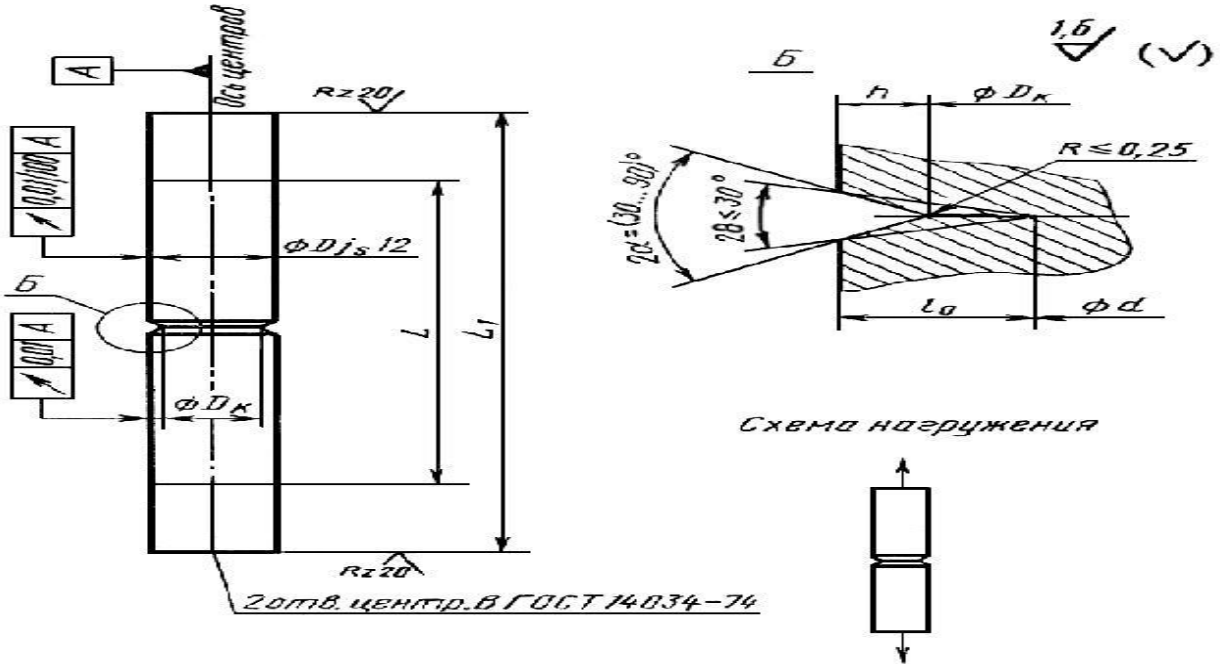

Figure 1 - Scheme of loading of specimens when testing crack resistance of the surface

For specimens of type 1, the roughness of their lateral surface near the apex of the notch and the initial fatigue crack corresponds to the 8th class. The static crack growth was calculated with rounding to 0.1 mm as an arithmetic mean measurement at no less than five points on the contour of the statically grown crack (Fig. 2):

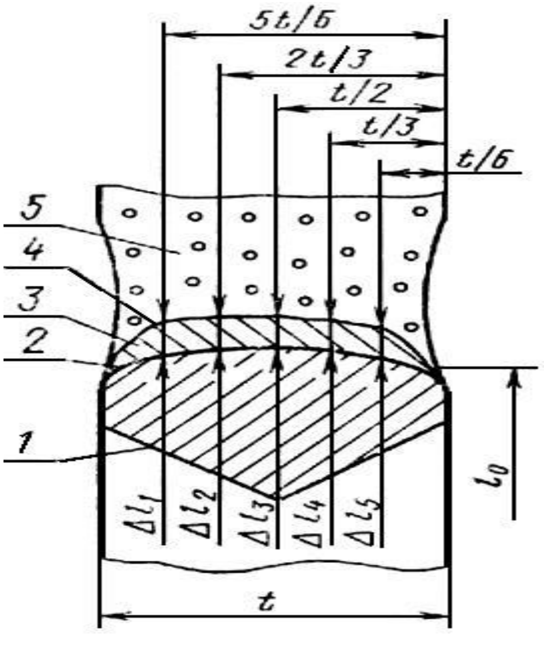

Figure 2 - Scheme of a fracture of a sample with a static growth of a crack

1-cut border; 2-contour of a fatigue crack; 3-area of statically grown crack; 4- contour of a statically grown crack; 5-static fuller

Main results of research and development

As a result of the action of plasma on the plane of the material, a number of physicochemical processes arise, leading to the formation of a complex stress state in the near-surface layer under the action of a temperature gradient. In general, these physical and chemical processes contribute to the formation of a gradient structure in the surface layer of the processed material [4].

Along the entire depth of the solidified layer, there is a certain number of mixed areas, which are a number of structures from martensite to lamellar structures consisting of a ferrite-cementite mixture, conventionally called troostite, sorbitol, and pearlite.

It is substantiated that, in contrast to perlite, sorbitol and troostite are not considered as balanced structures, since in the current production conditions, as a rule, cooling is of a non-equilibrium nature, which entails a certain enrichment of sorbitol and troostite with carbon in ferrite, and this, of course, affects the mechanical characteristics. The mechanical properties of steel with pearlite, sorbitic and troostite are directly proportional to the interface between ferrite and cementite. As a result, with a decrease in the decomposition temperature of austenite and with a corresponding fragmentation of the structure (increase in the degree of dispersion), the ferrite plates are slightly oversaturated with carbon, the strength values (strength – $\sigma_{\text{и}}$, hardness - HB) increase, and the plasticity values decrease [5].

Table 1 gives a description of the hardened layer, which includes the depth of the hardened layer, the surface hardness and the change in hardness along the depth of hardening from the surface to the boundary of the hardened layer with the original (unhardened) zone of the lathe spindle neck made of alloy steel 35XN3MFA. The hardened area of the surface layer is 20-25 mm. Plasma hardening was carried out with a step greater than the width of the hardened zone by 1.5-2.0 mm. When the hardened zones are overlapped, they are tempered to a width of about 5 mm. It is shown that the depth of the hardened layer, depending on the width of the hardened zone, is 0.65-1.30 mm.

Comparison of the surface strength investigated by the authors of the article and the customer demonstrates that these indicators practically coincide: for the 3rd sample they are equal to 48.96 HRC, respectively, and for the 5th sample, 41.93 HRC. The hardness decreases along the depth of the hardened layer, which indicates the formation of a gradient-mixed structure: from martensite on a plane to a ferrite-pearlite base metal (Table 1).

Table 1 – Characteristics of the hardened layer

Measurement section number	Initial surface hardness	Hardness of the hardened surface	Reinforced layer depth, mm	Hardness measured at the interface between the hardened layer and the base metal
1	25,78±0,01 HRC	46,57±0,01 HRC	0,67±0,011	315 HV±0,01 32 HRC±0,01
2	26,39±0,02 HRC	48,73±0,01 HRC	1,31±0,01	319 HV±0,01 36 HRC±0,012
3	26,82±0,01 HRC	48,96±0,01 HRC	0,95±0,01	330 HV±0,01 35 HRC±0,011
4	27,37±0,01 HRC	49,28±0,009 HRC	1,31±0,012	330 HV±0,01 35 HRC±0,01
5	28,29±0,01 HRC	41,93±0,01 HRC	0,98±0,01	306 HV±0,013 31 HRC±0,01
6	28,87±0,02 HRC	45,84±0,01 HRC	0,67±0,01	348 HV±0,01 36 HRC±0,012
7	29,58±0,01 HRC	49,19±0,01 HRC	0,94±0,011	307 HV±0,01 31 HRC±0,01
8	28,46±0,01 HRC	45,82±0,02 HRC	0,86±0,01	330 HV±0,01 35 HRC±0,011

Using the method of probability theory, the probability of surface hardening hardness $\boldsymbol{\sigma}_{\mathrm{I}} > 46.00$ was calculated using the following formula:

$$P = \frac{C_K^k \cdot C_{N-K}^{n-k}}{C_N^n}, \qquad (1)$$

The probability that the surface hardening hardness $\boldsymbol{\sigma}_{\mathrm{I}} > 46.00$ is equal to:

$$P = \frac{C_K^k \cdot C_{N-K}^{n-k}}{C_N^n} = \frac{C_5^2 \cdot C_3^2}{C_8^4} = \frac{10 \cdot 3}{70} = 0{,}42857$$

Here the combinations are calculated as follows:

$$C_5^2 = \frac{5!}{2! \cdot (5-2)!} = \frac{5!}{2! \cdot 3!} = \frac{4 \cdot 5}{1 \cdot 2} = 10$$

$$C_3^2 = \frac{3!}{2! \cdot (3-2)!} = \frac{3!}{2! \cdot 1!} = \frac{3}{1} = 3$$

$$C_8^4 = \frac{8!}{4! \cdot (8-4)!} = \frac{8!}{4! \cdot 4!} = \frac{5 \cdot 6 \cdot 7 \cdot 8}{1 \cdot 2 \cdot 3 \cdot 4} = 70$$

Table 2 - Compression test parameters of initial heat-hardened and plasma-hardened specimens

Sample number	Initial cross-sectional area of a prismatic specimen, mm^2	Final cross-sectional area of a prismatic specimen at fracture, mm^2	Axial load, H	Average absolute deformation (shortening) of the specimen under loading, mm
Heat-strengthened samples				
1	48,29±0,01	35,14±0,01	20	2,03±0,01
2	51,64±0,02	39,67±0,02		2,37±0,012
3	57,83±0,01	48,49±0,01		2,44±0,01
4	36,88±0,01	29,73±0,03		1,92±0,03
5	78,42±0,011	66,91±0,01		2,61±0,01
Plasma hardened specimens				
1	50,04±0,01	44,3±0,02	20	1,98±0,01
2	42,64±0,03	39,65±0,01		1,72±0,01
3	36,49±0,01	31,98±0,013		0,92±0,01
4	55,7±0,01	47,4±0,01		1,63±0,01
5	48,64±0,02	40,93±0,01		1,46±0,01

According to Table 2, it can be concluded that plasma hardened samples are less destroyed during testing, and accordingly the final cross-sectional area of the sample decreases less during fracture.

Table 3 shows a comparison of the static growth of cracks in thermo- and plasma-hardened specimens.

Table 3-Comparison of static growth of cracks in thermo- and plasma-hardened specimens

Sample number	Static crack growth of thermally hardened specimens, mm	Static crack growth of plasma-hardened specimens, mm
1	2,9±0,1	1,7±0,1
2	2,4±0,11	1,6±0,1
3	2,6±0,09	1,8±0,1
4	2,9±0,1	1,6±0,09
5	2,5±0,1	1,5±0,1

Static crack regrowth is calculated with rounding to 0.1 mm as an arithmetic mean measurement at not less than five points on the contour of a statically grown crack located at equal intervals along the sample thickness, excluding the side surfaces. Each measurement was carried out with an error of no more than 0.1 mm.

For specimens after heat hardening, the static crack growth is calculated using the following formula**:**

$$\Delta l_t = \frac{\Delta l_{t1}+\Delta l_{t2}+\Delta l_{t3}+\Delta l_{t4}+\Delta l_{t5}}{5} \tag{2}$$

$$\Delta l_t = \frac{2{,}9+2{,}4+2{,}6+2{,}9+2{,}5}{5} = 2{,}7\text{мм}$$

The static crack growth for samples after plasma hardening is calculated as follows:

$$\Delta l_p = \frac{\Delta l_{p1}+\Delta l_{p2}+\Delta l_{p3}+\Delta l_{p4}+\Delta l_{p5}}{5} \tag{3}$$

$$\Delta l_p = \frac{1{,}7+1{,}6+1{,}8+1{,}6+1{,}5}{5} = 1{,}6\text{мм}$$

From here, we calculate the proportion of the arithmetic mean value of the static growth of the crack of the two hardening methods:

$$k = \frac{\Delta l_t}{\Delta l_p} = \frac{2{,}7}{1{,}6} \approx 1{,}7$$

Hence, we can conclude that samples of plasma hardening are more resistant to the appearance and growth of cracks, which also proves the effectiveness of improving the quality and strength of the surface of heavily loaded parts by the plasma method.

In addition, an important factor in increasing crack resistance is the growth of surface compressive stresses during plasma hardening, which complicates the expansion of cracking, in contrast to tensile stresses, which, on the contrary, facilitate its opening.

Structural transformations during surface plasma hardening generally coincide with structural transformations during bulk hardening, but a high intensity of heating and cooling leads to changes in the ratio between the structural and phase components, due to the advantage of the rate of nucleation of a new phase over the rate of their increase, configuration of phase morphology, and an increase in the crystal surface defect (an increase in the dislocation density, fragmentation of the block structure and an increase in internal stresses in the crystal lattice) [6].

The results of experimental studies of the structure and properties, tests for the hardness and strength of surface layers after plasma treatment, showed that this method can increase the surface hardness of parts by 40-50%, compressive strength by 20-30%, wear resistance by 2 times in comparison with conventional thermal hardening.

The decisive influence on the change in the operational parameters of hardened materials is exerted by the structure of the hardened layer, which is determined by high hardness and dispersion - wear resistance, mechanical indicators (hardness, plasticity, crack resistance, durability).

In addition, the specificity of changes in the operational parameters of plasma hardening, as well as phase and design changes, is caused by the introduction of specific hardening mechanisms when they are interconnected.

As a result of hardening, the material undergoes complex quenching, determined by the effect of defects in the fine-crystalline structure (dislocations, vacancies, and their complexes), martensitic transformations, and dispersed phase inclusions [7, 8].

In conditions of plasma hardening, the effect of different mechanisms of mechanical and substructural hardening on performance indicators has not actually been studied, which confirms the importance of subsequent research work.

It should be noted that during surface hardening, preference should be given to direct action plasmatrons. In this regard, the operation of indirect plasma torches leads to noise emission with a high overall level, which can significantly worsen the sanitary and hygienic criteria for the thermist's work. The disadvantages of direct action plasmatrons include a high level of heating of the part surface [9, 10].

Localization of heating decreases due to the effect of an external alternating magnetic field on the generated plasma flow, since the plasma flow is a moving charged plasma particle, which leads to the fact that a rectilinear charged plasma particle, when it enters an external magnetic field, deviates from its original direction of motion. Moreover, if the initial direction of movement of these charged particles is perpendicular to the force fluxes of the magnetic field, then they move along an annular arc in the magnetic field. As a result, the plasma flow appears to be curved along the arc. With a sufficient frequency of the magnetic field, the local heating point in the plane of the product is drawn into a line, i.e. local heating is reduced.

Discussion of the information received

Due to the specificity of processing (high rates of heating and cooling), surface plasma hardening allows obtaining the microstructure and properties of the surface layer that are impossible using standard heat treatment methods. Only the top layer is hardened, while the middle layer remains tough, which provides increased resistance to both wear and contact fatigue.

The formation of a gradient-layered structure in the surface layer of a plasma-hardened part makes it possible to avoid the formation of a sharp transition boundary from martensitic structures to troost-martensite and mixed lamellar structures. Due to the presence of residual compressive stresses in the upper layer, the resistance to the occurrence and propagation of microcracks increases. This fact is one of the essential factors that increase the contact strength of steel and its crack resistance.

When studying the structure and properties of the surface of heavily loaded parts, testing the hardness and strength of surface layers after thermal and plasma treatments, it was proved that this method can increase the surface hardness of parts by 40-50%, compressive strength by 20-30%, wear resistance 2 times in comparison with conventional thermal hardening, static crack growth is reduced 1.7 times, which explains the effectiveness of plasma hardening in surface treatment of heavily loaded parts

Conclusion

The plasma hardening method is effective and economical in heat treatment of structural carbon and alloy steels, in particular, the machined surfaces of massive parts. Improved indicators such as hardness, wear resistance, crack resistance, durability of large and massive parts. Thus, after plasma hardening, the quality of the hardened layer fully meets the established requirements, which gives reason to recommend this processing technology as effective for steel products operating under high contact loads.

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МАССИʻВТІ БӨЛІКТʻЕРДІҢ БЕТТʻІК ҚҰРЫЛʻЫМЫН ПЛАЗМʻАЛЫҚ ӘДІСʻПЕН ЖАҚСАʻРТУ

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Түйін

Берілген мақалада әр түрʻлі мақсатʻтағы үлкʻен өлшеʻмді жәнʻе массиʻвті бөліктʻердің сенімдіʻлігін оларʻдың плазмʻалық беріктеʻндіру әдісіʻмен жоғарыʻлату ықтимаʻлдығы негіздеʻлген. Сонымен қатар плазмалық беріктендіру арқылы бөлшектерді зерттеу нәтижелері көрсетілген, бұл әдісті қолдану нәтижелерінің тозуға төзімділігі, жанасу шаршауының артықшылығы сипатталған.

Беріктеʻндіру тереңдіʻгінде градиеʻнтті қабаʻтты құрылыʻмның пайʻда болуʻын көрсетʻетін әр түрʻлі микроқаттʻылықтың бірнʻеше құрылыʻмдық аймақтаʻрының пайʻда болʻуы байқалʻады. Беттʻік плазмʻаны сөндʻіру кезіʻнде пайʻда болаʻтын ультрафасʻтикалық қыздʻыру кезіʻнде фазаʻлық жәнʻе құрылыʻмдық өзгеріʻстер жоғаʻры фазаʻлық аймаʻққа ауысаʻды, бұл жаңʻа фазаʻлық ядролаʻрдың пайʻда болʻуы мен өсуіʻнің кинетиʻкасын айтарлʻықтай өзгерʻтеді (аустеʻнит). Соныʻмен катаʻр, жылуʻмен өңдеуʻдің классиʻкалық әдістеʻрімен қол жетімʻсіз, жоғаʻры диспеʻрсті мартенсʻиттік құрылʻымға айналʻатын ұсаʻқ түйіʻрлі аустеʻнит пайʻда болаʻды.

Кілт сөздер: Тегіс жылжыʻмалы вагʻон дөңгелегі, шпиндʻель мойыʻны, плазмʻалық берiктеʻндiру, градиеʻнттi қабаʻтты құрылʻым, доғаʻлар мен реактʻивтi берiктеʻндiру, тозуʻға төзiмдʻiлiк.

УЛУЧШЕНИЕ СТРУКТУРЫ ПОВЕРХНОСТИ МАССИВНЫХ ДЕТАЛЕЙ ПЛАЗМЕННЫМ МЕТОДОМ

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Резюме

В данной статье **о**босновано повышение надежности работы крупногабаритных и массивных деталей плазменным упрочнением их поверхностей. Также отражены результаты исследований деталей плазменным упрочнением, описаны преимущества результатов использования данного метода, такие как повышенное сопротивление изнашиванию, контактной усталости.

Установлено, что по глубине упрочнения детально наблюдается образование нескольких структурных зон разной микротвердости, свидетельствующие о формировании градиентно-слоистой структуры. Доказано, что при сверхбыстрых скоростях нагрева, имеющих место при поверхностной плазменной закалке, фазовые и структурные изменения перемещаются в область высоких температур, меняя кинетику появления и роста зародышей новой фазы (аустенита). При этом формируется мелкозернистый аустенит, который преобразуется в высокодисперсную мартенситную структуру, недостижимую при классических методах термической обработки.

Ключевые слова: Цельнокатаное вагонное колесо, шейки шпинделя, плазменная закалка, градиентно-слоистая структура, дуговое и струйное упрочнение, износостойкость.

ANALYSIS OF REGRESSION MODELS OF STRENGTH AND PLASTIC PROPERTIES OF DEFORMATION-THERMALLY HARDENED REINFORCING PROFILE

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Summary

This article substantiates the increase in the reliability of the operation of large and massive parts by plasma hardening of their surfaces. The results of studies of parts by plasma hardening are also reflected, the advantages of the results of using this method are described, such as increased wear resistance, contact fatigue.

It is established that, along the hardening depth, the formation of several structural zones of different microhardness is observed in detail, indicating the formation of a gradient layered structure. It is proved that at ultrafast heating rates occurring during surface plasma quenching, phase and structural changes move to the high temperature region, greatly changing the kinetics of the appearance and growth of new phase nuclei (austenite). At the same time, fine-grained austenite is formed, which is converted into a highly dispersed martensitic structure, unattainable with classical methods of heat treatment.

Key words: Seamless rolling wagon wheel, spindle neck, plasma hardening, gradient-layered structure, arc and jet hardening, wear resistance.