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Surface Hardening Technology with a Concentrated Energy Source

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Abstract: The article is devoted to the increase of wear resistance of large-modular gears due to the application of the innovative method of plasma surface hardening working surfaces of teeth. The method of determination and estimation of the residual resource of large-modular gear transmissions after plasma surface hardening is developed and the influence of technological parameters of this process on wear resistance and mechanisms of deterioration of the surface layer have been investigated. The process of plasma surface hardening has been experimentally investigated, an estimation of the obtained physical and mechanical properties and hardness of the processed material during plasma heating has been made. The increase of durability of the work of large-modular gears passing by the plasma surface hardening has been experimentally investigated and the calculations on durability have been performed for the wear parameter, and it has been established that the application of this heat treatment method increases the durability 2.28 times. A complex of specialized equipment was developed for the implementation of the technological scheme of plasma surface hardening of the large-modular gears' working surfaces without melting, using the original design of the magnetic-deflection system for the creation of an external magnetic field.

Keywords: plasma surface hardening, fast-moving heat source, structural-phase transformations, thermal fields, concentrated energy source

1. Introduction

One of the main conditions that technological equipment must meet is its trouble-free operation with the necessary reliability and durability in accordance with the technical operating conditions for a given period of time. In the mining industry, large-format open gears of external gear have found wide distribution. As a result of the study of the nomenclature of coarse-grained cogwheels used in mining enterprises, it was concluded that special attention should be given to the gears used for ball mills to extend the service life. The key issues in the design and manufacture of gears is the choice of the material and the way it is hardened. Wear of the teeth is the main type of destruction of the teeth of open gears. Dustiness of the working area puts open gears in very unfavorable working conditions. Dust, containing a large number of solid abrasive particles, falls on the working surfaces of the teeth, mixed with grease and causes their intensive wear.

The analysis of the damageability of gears makes it possible to assume that premature failure is due mainly to processes in the surface layers. Contact endurance of the surface layer is characterized by the ability of the material to resist the development of dying on the working surface, perceiving variable contact loads, and is determined by structural and technological factors. Strengthening technologies, form the structure of the surface layer, create the basic level of hardening of the teeth of the wheels, determining their performance [1]. There are various methods of surface quenching, differing in the way of heating, cooling and temperature distribution in the treated layer [2], such as gas flame, induction or pulse. The main distinguishing feature of surface hardening methods by highly concentrated heating

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sources is the possibility of obtaining heating and cooling rates of materials that are several orders of magnitude higher than those typical for traditional methods of hardening (furnace hardening, quenching, high-temperature quenching, etc.), which facilitates the obtaining of hardened layers with previously unattainable level of operational properties [3,4].

However, here it is necessary to take into account the fact that surface hardening technologies have their own specific features and their effectiveness depends on the consideration of various factors that reflect both the protected part itself, its chemical composition, dimensions, geometric shape, initial surface condition, and the expected operating conditions for the whole complex of external factors. Therefore, the choice of hardening technology, in particular gears, cannot be universal in nature, but must be adapted to the specific wheel size in machines and aggregates. All this requires an individual approach both in the development of hardening technology and methods for assessing the damageability in accelerated tests. The widespread industrial application of most known methods of strengthening treatment with concentrated energy flow is hampered by the high cost and complexity of the equipment, its inadequate reliability and productivity, the need for vacuum, special rooms with special requirements, the need for qualified maintenance, and high operating costs. In these conditions, in order to extend the operational life of wear parts, a method of surface heat treatment by a plasma arc is considered rational in terms of universality, availability, environmental friendliness and economic efficiency [5, 6, 7, 8]. Without changing the parameters of the surface roughness, such heat treatment is easily integrated into the technological process of preparation and repair of parts, being a finish operation, low-cost, sufficiently productive and effectively increasing their operational stability [9, 10]. As a result, it is proposed to apply Plasma Surface Hardening (PSH) of the profile of the gear to improve the contact strength of the working surfaces of the teeth.

However, the properties of hardened layers after surface plasma arc quenching are insufficiently investigated, nor rational ways of controlling the specific power in the heating spot of the plasma arc have been proposed, as a consequence, it is not possible to use the large electric power necessary to increase the efficiency of heating. There are no scientifically substantiated principles for choosing modes and technologies for strengthening large geared gears, taking into account their load conditions. Therefore, increasing wear resistance of open gear gears of ore-mills, by surface plasma-arc quenching, has important practical value and is an actual scientific task.

The purpose of this work is to increase the wear resistance of large-modular gears by surface plasma-arc hardening. Formulated goal of work has determined the need to solve the following tasks: (1) development of a technique for studying the mechanisms of structural transformations in steels for surface plasma arc treatment in order to select the optimal modes for hardening gears, to obtain the required structure, phase composition and hardness of the surface layer; (2) investigation of the influence of technological parameters of the plasma quenching process on wear resistance and wear mechanisms of the surface layer and development of a technique for determining and estimating the life of large-size gears after plasma hardening; (3) experimental studies of the process of surface plasma-arc hardening, development and implementation of the thermophysical study methods and (4) an experimental study of the gears durability, which have been quenched and calculations for durability in terms of wear parameters.

2. Experimental Setup and Technique

The analysis of the damageability of gears makes it possible to assume that premature failure is due mainly to processes in the surface layers. The analysis of damaged gears shows that their premature failure is due mainly to the destruction processes in the surface layers of the teeth. A promising direction of solution of this problem is hardening thermal treatment of loaded surfaces of parts with a concentrated energy flow [5]. Generated by high-speed heating and cooling of the quench-type structure, they have high hardness, wear resistance, and fracture resistance.

2.1 Technology and Equipment for Surface Hardening of Teeth with a Scanning Plasma Arc

The effect of plasma hardening is determined by an increase in the operational properties of the part due to a change in the physical and mechanical characteristics of the surface layer, due to the formation of a specific structure and phase composition of the metal, as well as the production of compressive residual stresses on the surface. In the transition zone, the heterogeneity of the structure increases in the following sequence: martensite-troostite, martensite and troostite grid, and transition to the ferrite grid at the boundary with the initial one [11, 12].

Structural transformations as a whole correspond to those occurring in bulk hardening, however, high rates of heating and cooling cause a change in the relationships between structural components, a change in their morphology due to increased defectiveness of the crystal structure [5 13, 14]. The formation of stresses when cooling a surface subjected to plasma quenching can be represented as follows. After the termination of the action of the plasma arc, the inner layer of metal located near the unheated source layer closes most rapidly, and the surface layer last. In the process of compression upon cooling, it acts on the inner layer, forming compressive stresses in it, while stretching is formed on the surface. At the same time, in the surface layer of steels, the martensitic transformation occurs in the last place. Since martensite has a larger volume, in the near-surface layer, at this time, expansion takes place due to phase stresses and compressive stresses arise. The nature and extent of these phenomena depends on the thermophysical properties of the material being processed, the speed of relative movement of the workpiece and the heating source, and the thermal power of the plasma arc. By changing these parameters, it is possible to achieve an increase in the degree of manifestation of that side of the plasma effect on the workpiece material, the dominance of which is considered appropriate for this case.

The structure of the reinforced layer, characterized by high hardness and high dispersion, has a determining effect on the change in the performance characteristics of hardened materials - wear resistance, mechanical properties (strength, ductility, crack resistance, endurance), heat and corrosion resistance [15, 16]. In the beginning, it is necessary to formulate requirements, or criteria, which the source of heating must meet under the conditions of this processing method, namely hardening of coarse-grained gears [7]:

1 – the possibility of adjusting the heating width;
2 – no reflow of the surface layer;
3 – ensuring a uniform depth of structural transformations;
4 – Achievement of the necessary microstructure of the strengthened layer.

Plasma torches for plasma hardening should satisfy both the general requirements inherent in all plasmatrons (high power, stability of plasma flow parameters, significant energy efficiency, long duration of continuous operation, design reliability, ease of operation) and possess a number of specific properties: the protection of live parts and the ability adjustment of the plasma torch position [17, 18, 19]. In addition, to ensure the effective heating of materials with different thermal characteristics in the design of the plasma torch, it is necessary to vary the heating parameters within fairly wide limits. The idea of scanning a plasma arc over the surface of a product, the use of which reduces the specific heating power by an order of magnitude, increases the depth of hardening, reduces the probability of reflow and, ultimately, makes it possible to direct a high electric arc power to increase the productivity of the hardening process, was realized in a technological complex of equipment for the study of this process [20].

The method is implemented in this way (Fig. 1). The toothed wheel or gear shaft is mounted on a machine, the plasma generator is a single-arc plasma torque converter. To create an external magnetic field and thereby reduce the location of heating, the plasma torch of direct action 1 equipped with a special magnetic system. The plasma torch generates an electric arc that burns between the cathode 3 and the lateral surface of the tooth of the wheel 5 and in the point of contact of the arc with the surface heats it. In addition, in the gap between the ends of the magnetic cores 4 the arc is influenced by the magnetic field, and since the electric arc is a conductor with current, then in the magnetic field on it acts Lorentz force, which deflects the arc in a plane parallel to the ends of the magnetic conductors 4 and perpendicular to the longitudinal line teeth The alternating voltage on the coil 6 of the magnetic system provides fluctuations of the electric arc across the longitudinal line of teeth. As a result, when scanning the plasma arc with the frequency of the current in the network (50 Hz), the stain of the stain should be drawn along the working surface of the tooth 5.

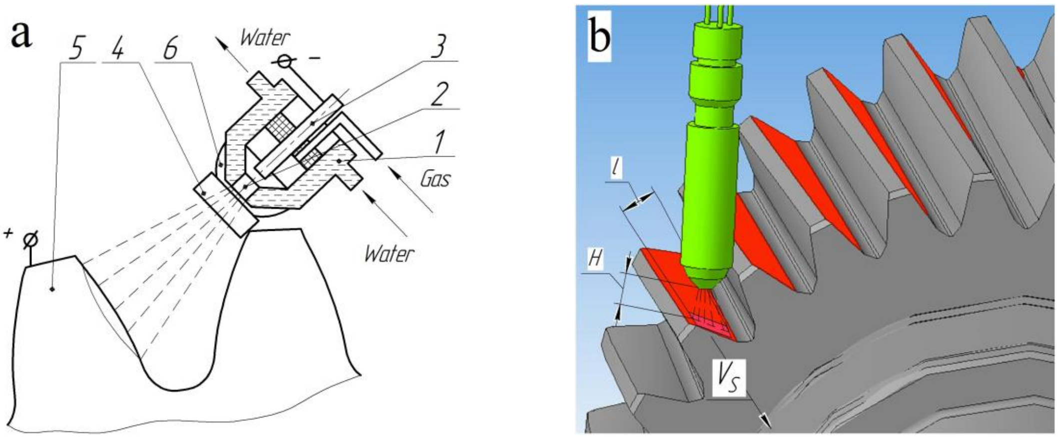

Fig. 1 - (a) the view in the processing plane (1 – plasmatron, 2 – nozzle, 3 – cathode, 4 – magnet, 5 – gear tooth; 6 – electromagnetic coil); (b) spatial view of the processing process

For realization of this method a pilot-industrial complex was created on the basis of a lathe. Installation for the implementation of the method of PSH contains:

1) plasma installation APR-402;
2) Plasmatron PVR-402M with an electromagnetic scanner mounted on it (Fig. 2);
3) adjustable alternating current transformer to generate voltage in the magnetic system.

The general view of a plasma torch with a magnetic-deflection system in the process of processing large-modular shaft-shaft (m = 22) under production conditions is presented in Fig. 3.

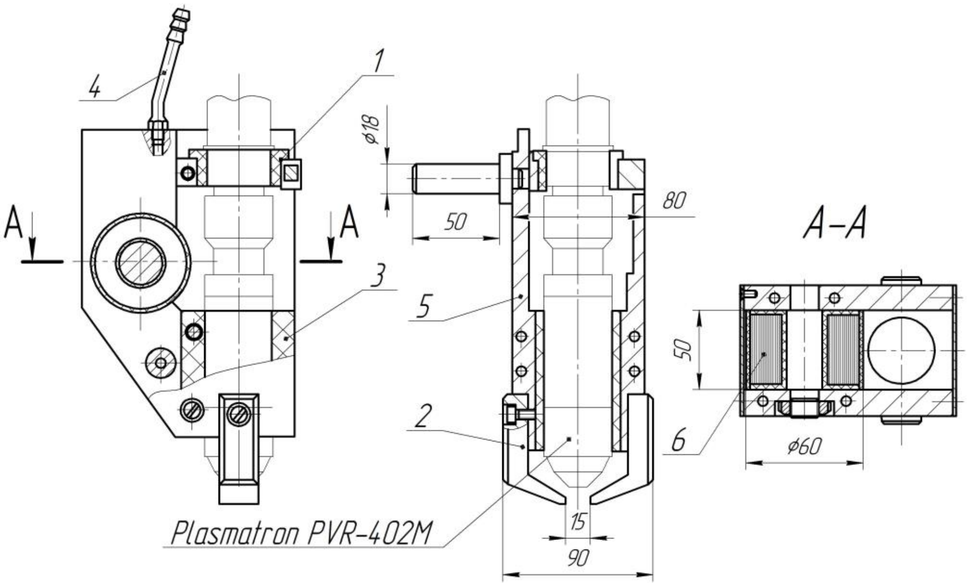

Fig. 2 - General view of a plasma torch with a magnetic-deflection system: 1 – insulating sleeve; 2 – tip; 3 – placement; 4 – fitting; 5– Magnet's cheek; 6 – electric coil

Fig. 3 - General view of a plasma torch with a magnetic-deflection system: 1 – insulating sleeve; 2 – tip; 3 – placement; 4 – fitting; 5– Magnet's cheek; 6 – electric coil

2.2 Determination of Rational Parameters of Plasma Surface Hardening

A choice of rational heating parameters at PSH is made. The ratio of the size of the source and the value of the current strength of the arc determine the intensity value:

$$q_s = \frac{I \times U \times \eta}{\ell_s \times b_n}, \tag{1}$$

where U – voltage in the circuit of the plasma arc; η – efficiency of the heating source (η = 0,4); l_S, b_n – dimensions of the heating source. Having such a set of variable parameters, it is advisable to determine their rational ratio in accordance with the objectives of the PSH. As a target function, it is possible to take some maximum temperature of surface layer heating, which provides the necessary structural transformations, which is determined from the expression:

$$\theta_{\max} = \frac{2q\sqrt{\omega \times \ell_s}}{\lambda \times \sqrt{\pi \times V_S}}, \tag{2}$$

where q – intensity of the source; λ, ω – respectively, coefficients of heat and temperature conductivity of the material; V_S – the speed of the source movement. Assuming that $\theta_{\max}$ is equal to the melting point, determine the rate of displacement of the source V_S, at which the condition $\theta_f \le \theta_{\max}$ will be fulfilled:

$$V_S = \left(\frac{I \times U \times \eta}{\theta_f \times b_n \times \ell_s \times \lambda} \right)^2 \times \frac{\omega \times b_n}{\pi} \ . \tag{3}$$

The PSH process has a number of specific features, due to which there are limitations imposed on the parameters of the heating process. For the choice of the optimal values of the latter, the analysis of constraints is very significant.

3. Results and Discussion

Diagrams of temperature changes, obtained from the results of theoretical and experimental study of thermal fields from the action of a plane fast moving source, show that when processing steel 41Cr4, the depth of the layer that underwent structural changes depends on the power of the heating source, the cooling rate, and the thermophysical properties of the material. In Fig. 4 shows a sample of 41Cr4 steel, the surface of which has undergone plasma heating. On the end surface of macrosection, a layer is visible in the form of a uniform light band, differing in its etchability from the base metal. In order to try to explain the phenomena occurring in the more deep-lying layers, it is necessary to return to the consideration of the initial structure of 41Cr4 steel, obtained as a result of previous technological operations of production of blanks.

Fig. 4 - Sample heated by a scanning plasma arc

Blanks heated to the temperature of Ac_3 and subjected to deformation, during subsequent cooling, a number of stages of decay of supercooled austenite proceed successively: diffusion pearlite, intermediate (bainitic), and diffusion-martensitic. As a result, a very complex metal structure is formed, consisting of upper and lower bainite, martensite and residual austenite. Bainite is a two-phase mixture of ferrite and cementite crystals. Ferrite has low strength and high ductility. With a small number of cementite inclusions, plastic deformation develops relatively freely and the properties of the material are characterized by low hardness. If, as a result of heat treatment, cementite particles coalesce, some volumes of ferrite are released for the movement of dislocations, and the steel's ability to plastic deformation increases, i.e. plasticity increases. This fact is of great importance from the point of view of softening of the material, It is known that when a moving dislocation encounters insuperable inclusions, it passes through them, leaving the dislocation loops around the inclusions each time. The higher the accumulation of loops, the greater the hardening. As a result of high heating ($\theta > 500°C$), the metal layers located below the austenite structure obtained as a result of plasma heating undergo a high tempering. In this case, several processes occur. The main one is the decay of martensite, which consists in the release of carbon in the form of carbides, in addition, the residual austenite decomposes, carbide transformations and coagulation of carbides occur, the imperfections of the crystalline structure of S-solid structure and residual stresses decrease [21, 22].

If, during slow heating, the removal of internal stresses and the coagulation of carbide particles occur in the range 300 ... 400 ° C, then the temperature of these transformations shifts upward along the temperature scale for high-speed heating, to which the plasma arc is heated with PSH. At these temperatures (500 - 700 °C) there is a tendency for the hardness to fall, as well as for other strength parameters, while the plasticity indices (Ψ, δ) increase. As the tempering temperature rises, cementite particles enlarge (Fig. 5), which, as indicated above, can lead to an increase in the plasticity of the material. With PSH, metal layers lying at a depth of 7 - 9 mm, although they do not heat above the Ac_3, but nevertheless, under certain heating conditions, temperatures of 600 - 700 °C can penetrate here. for example, at $V_S = 3 \cdot 10^{-3}$ m/s, the size of the source $l_S \times b = 0{,}05 \times 0{,}1$ and the current of the plasma arc $I = 390$ A, the temperature of 600°C, as calculated, can penetrate to the depth 9.8 mm.

Thus, the data presented show that the plasma heating of the stock material in the PSH conditions can significantly change the state of its structure, which can lead to a significant change in the properties of the material in a favorable direction. In order to study the properties of the alloyed steels (41Cr4) in the cooling process, a measure of dynamic hardness was made, consisting in the introduction of an indentor in the investigated surface having a certain reserve of kinetic energy. As a result, graphs of temperature change of the surface and its dynamic hardness were obtained (Fig. 6). The analysis of the graphs showed that in the process of cooling there is a strengthening of the surface layers of the billet, heated above the temperature of Ac_3 and a sharp increase in hardness begins when cooled to a temperature of 200 ... 230 °C.

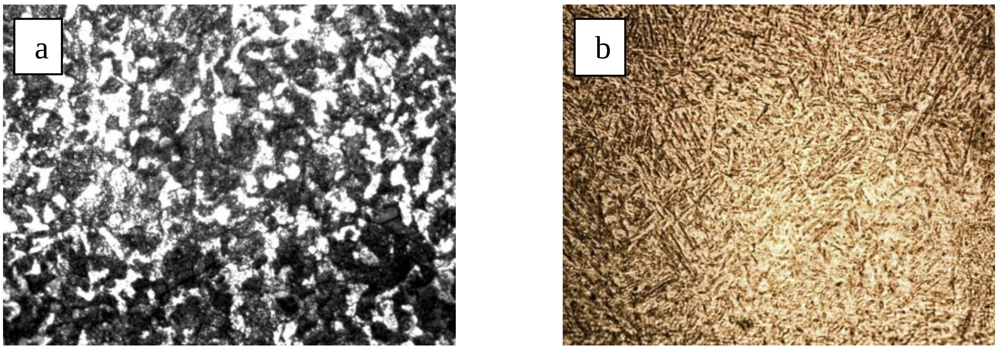

Fig. 5 - Change in the structure of the material under the influence of plasma heating (increase 1000^X):(a) source structure; (b) after PSH

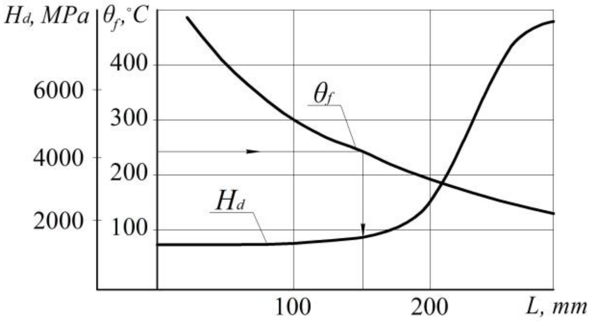

Fig. 6 - Temperature and dynamic hardness change in the cooling process after plasma heating (I = 250 A; V_S = 300 mm/min; d_n = 6mm; Q_{air} = 2.5m^3/h)

Results of measurement of microhardness are presented on (Fig. 7). From the presented graphs it is clear that the microhardness of the surface layers of the workpiece, processed in different thermal regimes, at a depth of 3 ... 5 mm significantly differs in size from the microhardness of the original structure of the material.

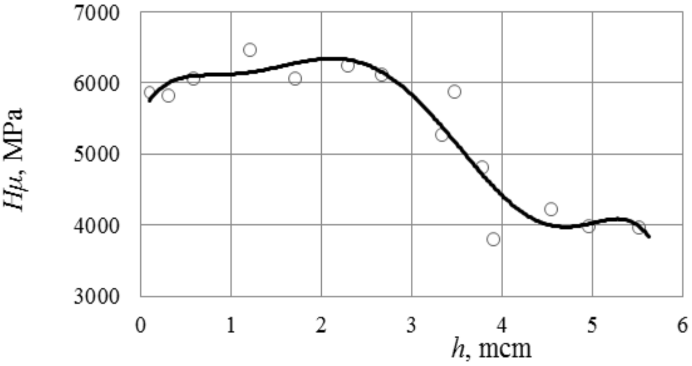

Fig. 7 - Sample heated by a scanning plasma arc (steel 41Cr4, I = 250 A; V_S = 300 mm/min)

The presence of micro cracks in the course of research was not revealed. The analysis of the results showed the conformity of surface quality to the requirements proposed for the processed surfaces of parts. The tests (accelerated method) showed that PSH of alloyed steels (41Cr4) leads to an increase in its abrasive durability in 2.28 times, which can be explained by the structure of hardening, the formation of martensite and increased hardness. In Fig. 8 shows wear curves of gear gears. Wear was measured by changing the thickness of the tooth as a difference in the thickness of the tooth in the dividing circle before the test and after a certain time.

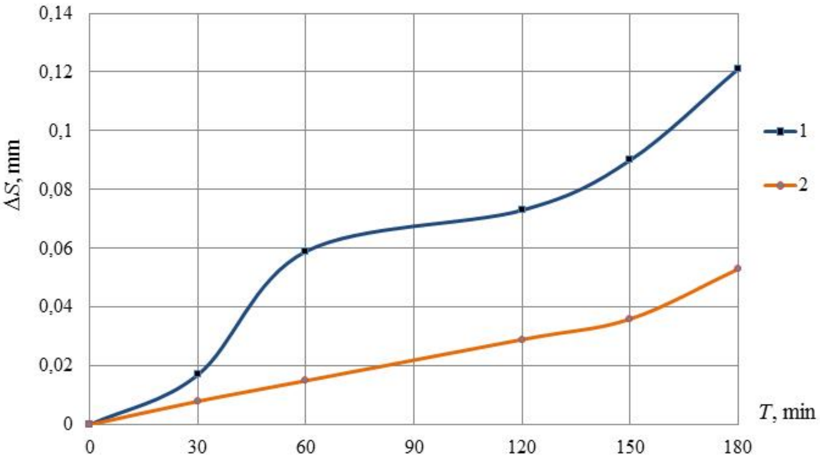

Fig. 8 - Intensity of abrasive wear of toothed wheels: 1 – wear of a non-tempered toothed wheel (hardness – 293 HB); 2 – wear of the toothed wheel of the subjected to the PSH (hardness – 54 HRC)

The research has established that surface treatment with a plasma jet using a scanning magnetic system is an effective method of surface hardening of gear wheels and provides higher values of hardness and wear resistance.

4. Conclusions

One of the most promising directions for the development of modern production is the introduction of intensive technologies for surface reinforcement of large-body gears using concentrated energy sources. Particular advantages over massive parts have a superficial plasma-arc reinforcement, due to high thermal power and the possibility of obtaining strong layers of considerable thickness (up to 5 mm). Increasing the durability of rotor mills' open large-modular gears, through surface plasma-arc reinforcements, has an important practical significance and is an urgent task. The following advantages of plasma quenching can be noted in comparison with other methods of heat treatment:

1. when quenching concentrated energy sources, due to the specificity of the treatment (high heating and cooling rates), it is possible to obtain such a structure and properties of the surface layer, which are not achievable in the traditional methods of thermal treatment;
2. only the surface layer hardens and the core remains viscous, which provides increased resistance at the same time wear and fatigue;
3. the absence or minimal deformation of reinforcing parts, which makes it possible to increase the precision of their manufacturing, reduce the labor intensity of machining and the cost of manufacturing;
4. high performance;
5. when quenching without fading the surface, no subsequent machining is required, which makes it possible to use it as a finishing process of the process;
6. the presence of compressive stresses in the surface layer and the presence of residual austenite increase the resistance to nucleation and crack propagation;
7. ease of maintenance, mobility, low cost and operating costs, small dimensions of equipment, the possibility of automation and rotation of the technological process.

The influence of technological parameters of this process on wear resistance and mechanisms of the surface layer wearing, namely current (*I*), velocity (*V*) and intensity (*q*) of the heating source, were investigated in the work. It has been established that a significant reduction in wear will occur with the effect on the physical and mechanical properties of materials from which toothed transmissions are made, namely, increasing the hardness of the contact surfaces of the teeth through plasma strengthening. Under the conditions of PSH, the efficiency of the plasma arc as a heating source depends essentially on the ratio of the thermal power; it is rational to consider such a ratio in which the temperature of the heated surface at truce size, its speed and he back of the heating spot reaches but does not exceed the melting temperature for this material. The regularity of the formation of a tempered layer at the surface plasma-arched reinforcement of large-modular gear wheels has been experimentally established. It is shown that in the case of high-speed heating without melting by a plasma arc of direct action, which scans in an alternating magnetic field, the cooling rate of the surface layers reaches the rate of quenching, which provides structural transformations in the metal and forms a strengthened surface working layer (the strength of σ_v and HRC hardness increase). This ensures high performance of the surface working layer: wear resistance of gears increases by 2.28 times.

The method of heat treatment of large-wheel gear wheels is developed, which includes the heating of the lateral surface of the tooth without the melting of the plasma arc with a given current, with the displacement of the arc carried out translationally from one end of the gear to another, at a speed exceeding the rate of temperature propagation in this material. A complex of specialized equipment was developed for the implementation of the technological scheme of plasma surface hardening of the working surfaces of large-modular gears without melting, using the original design of the magnetic-deflection system for the creation of an external magnetic field.

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