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INTENSIFICATION OF CHEMICAL AND HEAT TREATMENT PROCESSES TO IMPROVE THE OPERATIONAL PROPERTIES OF MACHINE PARTS[1]

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INTRODUCTION

To increase the reliability and durability of machine parts, punching and cutting tools, increase the endurance limit of alloy structural steel products, increase the wear resistance of machine parts, ensure high hardness and corrosion resistance of the surface layers of products, surface hardening is widely used in industry.

Parts such as bushings, pipes, washers, screws, gaskets, axles, shafts, Shaft gears, plungers, rods, crankshafts and cam shafts, rings, spindles, screws, mandrels, rails, gear crowns, semi-axles, gears, hydraulic cylinders, machine tool and turbine parts, as well as tools (drills, taps, cutters, broaches), punching tools, punches, injection molds and so on.

Currently, there are a large number of surface hardening methods based on applying coatings or changing the surface condition. Among them, Chemical and thermal treatment is widely used, which is used for alloys of both ferrous and non-ferrous metals. Surface diffusion layers obtained as a result of such treatment have a number of advantages over coatings applied by various methods (surfacing, gas-thermal spraying, etc.). The strength of their adhesion to the base metal is significantly higher than that of coatings, and the gradual change in chemical composition along the depth of the diffusion layer creates a smooth transition of properties from the surface to the core of the part. Also, the interest in surface hardening of machine parts by technologies using diffusion saturation processes remains significant, since these are methods of influencing the surface of products that allow obtaining a unique combination of mechanical and special operational properties of the surface layer.

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1. The problem's prerequisites emergence and the problem's formulation

Existing methods of surface hardening of machine parts by chemical and heat treatment methods, as a rule, ensure the operability of parts in conditions of friction and wear, but they are quite long and require special complex and expensive equipment. Therefore, it is important to improve the technological processes of manufacturing machine parts by developing new methods of surface hardening, which significantly increase the durability of the working layer and the surface of parts with a significant acceleration and simplification of surface hardening technologies.

The work is aimed at solving an actual scientific and technical problem in the field of mechanical engineering technology: development of innovative and short-term technologies for surface hardening of machine parts with powder mixtures of controlled composition to ensure the operational properties of products at a high level while significantly reducing the cost of their manufacture. Solving this problem will improve the reliability of machines by increasing the service life of machine parts and tools, while reducing energy consumption.

2. The analysis of existing methods for solving the problem and formulating a task for the optimal technique development

There are many methods of chemical and heat treatment that differ in technology. The choice of method is dictated by its manufacturability, equipment that is available in production, configuration, dimensions, working conditions and the degree of achieved increase in the stability of the reinforced products. In mass production, the processing of simple, medium-sized products is mainly carried out by electrolysis and gas boriding or ion-plasma or gas nitriding. When processing small, complex products, it is more expedient to use liquid or powder methods of chemical and thermal treatment. The powder method is more acceptable if the reinforced products do not require further heat treatment. Large-sized products, especially if it is necessary to use them locally or combine chemical and heat treatment with heat treatment, it is advisable to saturate them in coatings (pastes).

The use of physical and technical processes makes it possible to intensify chemical and thermal treatment. Well-known methods have a number of unresolved issues. In particular, in the work[2], the disadvantage is that it does not provide a sufficient layer depth (up to 120-150 microns) and is difficult to use, time-consuming, energy-consuming and requires additional expensive equipment, which leads to unnecessary costs. A significant disadvantage of this method is also the use of ammonia, which is not only expensive, but also dangerous at work and harmful to human health and the environment. A significant disadvantage of the work[3] is that it does not allow forming a coating with variable density of reinforced areas along the friction surfaces of the part. The main and significant disadvantage of the work[4] is the significant duration of the process (up to 20 hours), energy consumption and the resulting coating has insufficient microhardness (up to 8 GPa), which does not provide high wear resistance.

Further laser processing with reflow and without nitrided alloy steel layers is a study in the work[5]. It was found that all laser-modified zones with and without reflow were characterized by increased wear resistance compared to the conventional gas-nitrided layer. However, this method is aimed only at changing the modification of the already obtained nitrided layer and does not affect the acceleration of the nitriding process.

Well-known combined technologies of laser processing and nitriding have a number of unresolved issues. In general, it can be concluded that existing technologies do not provide sufficient depth of the reinforced layer or surface hardness, are difficult to use, time-consuming, energy-consuming, and lengthy processes (up to 20 hours).

Thus, the method of effective combined physical and technical processing and chemical and thermal treatment to improve the operational properties of steel parts requires further research.

3. Intensification of chemical and thermal treatment processes by high-frequency currents and laser treatment methods

To intensify the chemical and thermal treatment processes, two methods were chosen: high-speed heating, which could be provided using high-

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[2] Способ комбинированной лазерно-химико-термической обработки материалов: пат. 19551 Украина: МПК С23С 8/02. № u 2006 07450; заяв. 04.07.06; опубл. 15.12.06, Бюл. № 12.

[3] Способ получения износостойких дискретных азотированных слоев: пат. 25412 Украина: МПК С23С 8/02. № u 2007 03002; заяв. 22.03.07; опубл. 10.08.07, Бюл. № 12.

[4] Способ низкотемпературного азотирования стальных деталей: пат. 2415964 Российская Федерация: МПК С23С 8/26. № 2009 139309/02; заявл. 26.10.09; опубл. 10.04.11, Бюл. № 10.

[5] Спосіб лазерного легування сплавів на основі заліза: пат. 26467 Україна: МПК8 В23К 26/00. № u 2007 04802; заявл. 28.04.07 ; опубл. 25.09.07, Бюл. № 15.

frequency currents, and an increase in defects, a decrease in the grain structure of the surface layer, which was achieved by laser processing of samples. Intensification of chemical and thermal treatment processes, respectively, was carried out when heated with high – frequency currents on a lamp generator VChG 60-3/0.44 and on a technological complex based on a powerful CO_2 laser «Latus 31» at a laser radiation power of 1.0±0.1 kW and a laser beam movement speed of 0.5 to 1.5 m/min[6,7,8,9,10,11,12,13].

The wide range of applications of induction heating is due to the presence of important advantages that determine the prospects for use in a particular technological process. This is due to the possibility of contactless energy transfer and its localization in the necessary areas of products. The results of strengthening the surface of parts when fighting high-frequency currents mostly depend on the correct design and technological characteristics of the heating device. The method of induction heating is based on the use of the following laws and phenomena, such as the law of electromagnetic induction, the surface effect, the proximity effect, changes in the properties of steel during heating.

The complexity of electromagnetic processes in induction heating devices makes it necessary to make a number of assumptions for the

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[6] Идан А., Акимов О.В., Костик Е.А., Гончарук А.А. Влияние предварительной термической обработки и режимов лазерной закалки на структуроформирование стали. *Вісник Національного технічного університету «ХПІ»*. 2016. № 18(1190). С. 66–73. DOI: http://dx.doi.org/10.20998/2413-4295.2016.18.10.

[7] Idan A., Akimov O. V., Kostyk K. O. Surface hardening of steel parts. *Праці Одеського політехнічного університету*. 2017. № 1(51). С. 17–23. DOI: http://dx.doi.org/10.15276/opu.1.51.2017.

[8] Idan A., Akimov O., Kostyk K. Development of a combined technology for hardening the surface layer of steel 38Cr2MoAl. *Східно-Європейський журнал передових технологій*. 2017. № 2/11 (86). P. 56–62. DOI : http://dx.doi.org/10.15587/1729-4061.2017.100014.

[9] Идан А., Акимов О.В., Костик Е.А., Гончарук А.А. Упрочнение стали 40Х комбинированной обработкой с применением лазера. *Металл и литье Украины*. 2016. № 7 (278). С. 33–35.

[10] Спосіб комбінованої обробки сталевих виробів: пат. 111066 Україна: МПК8 C23C 8/02-26 UA. № u 2016 05447 ; заявл. 19.05.16 ; опубл. 25.10.16, Бюл. № 20. 5 с.

[11] Спосіб отримання твердого покриття на поверхні сталевих виробів: пат. 116116 Україна: МПК8 C23C 8/02-26 UA. № u 2016 11442; заявл. 11.11.16; опубл. 10.05.17, Бюл. № 9. 6 с.

[12] Спосіб дифузійного борування сталевих виробів: пат. 116177 Україна: МПК8 C23C 8/02-26 UA. № u 2016 11988; заявл. 25.11.16; опубл. 10.05.17, Бюл. № 9. 6 с.

[13] Спосіб поверхневого зміцнення сталевих виробів: пат. 116178 Україна: МПК8 C23C 8/00, C25D 5/50 UA. № u 2016 11989; заявл. 25.11.16; опубл. 10.05.17, Бюл. № 9. 6 с.

possibility of solving the problem. For simplification, the following was adopted:

– neglect the radiation of electromagnetic energy into the surrounding space;

– the electromagnetic field was assumed to be quasi-stationary;

– during induction heating, hysteresis losses are small, so they were not taken into account in the calculations;

– currents and voltages are sinusoidal and change according to the harmonic law, and the amplitudes of current density, electric and magnetic field strengths decrease exponentially, which provides a surface effect.

When heated by high frequency currents the depth of the heated surface layer δ is determined by the dependence:

$$\delta = \frac{1}{2\pi}\sqrt{\frac{\rho \cdot 10^9}{\mu f}}, \text{ cm}, \tag{1}$$

where ρ – resistivity, Ohms·cm; μ – magnetic permeability;
f – current frequency, Hz.

From this dependence (1), it follows that the greater the frequency of the current, the smaller the depth of its penetration. The greater the magnetic permeability, the faster the electromagnetic field wave fades out. According to formula (1), the depth of current penetration, in addition to the magnetic permeability and frequency, also depends on the resistivity of the material. Moreover, the greater the resistivity of the material, the greater the depth of current penetration.

According to the calculations obtained according to formula (1), for heating the surface layer, the current frequency should be about 400–450 kHz.

High-frequency heating from an energy point of view is quite fully characterized by the specific power, namely, the power that passes into heat in one square centimeter of the surface, and the heating time. The specific power value determines the heating rate. The higher the specific power, the faster the heating is carried out to the set temperature. Taking into account the specific power and heating time allows you to set the total amount of heat in the surface layers, and therefore the achieved temperature.

The power of P_δ, which is necessary for heating the surface layer with a thickness of δ, has the following form[14]:

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[14] Немков В.С., Полеводов Б.С., Гуревич С.Г. Математическое моделирование устройств высокочастотного нагрева : б-ка высокочастотника-термиста / под ред. А. Н. Шамова. Вып. 16. Л. : Политехника, 1991. 76 с.

$$P_\delta = 0{,}865\; S\, q, \qquad (2)$$

where S is heated surface area, q is specific power.

It follows from formula (2) that 86.5% of the power is released in the surface layer, and 13.5% is lost to convection and radiation. These losses for approximate calculations could be ignored and assumed that all thermal energy is concentrated in the surface layer.

We assume that the cylindrical sample is located inside the inductor so that their axes coincide. To simplify the modeling of the process, we will represent steel cylindrical samples in the form of an infinite cylinder and then call them a cylinder in calculations. Then the problem will be formulated as follows.

An unbounded length of a continuous circular cylinder with radius R initially, when the heating time $\tau = 0$, has an ambient temperature To. The temperature is a function of the radius r (current coordinate) and the heating time τ, i.e. $T(r\,,\ \tau)$, then the initial condition will be:

$$T(r\,,\ 0) = To, \qquad (3)$$

During induction heating, an instantaneous heat source acts and per unit area of the cylindrical surface $r = R$, where heat exchange occurs. The total heat flux is equal to the sum of the flow flowing into the cylinder and the flow lost to the environment due to radiation and convection, which was decided to be ignored according to formula (2). Then the heat flux is determined from Fourier's law[15]:

$$q = -\lambda \frac{\partial T(r,\tau)}{\partial r}, \qquad (4)$$

where λ – coefficient of thermal conductivity, W/(m·°C).

The heat release is concentrated in a surface layer so thin that this process can be considered as a process of simple surface heating. Analytical solutions for the particular case of induction heating with high-frequency currents coincide in form with solutions for non-stationary heating under boundary conditions of the third kind. We assume that the resulting temperature $T(r,\ \tau)$ does not change in the circumferential and axial directions. The determination of temperature is reduced to solving the thermal conductivity equation for an unlimited cylinder, the temperature of which does not depend on the axial coordinate z[16]:

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[15] Справочник по специальным функциям / под ред. М. Абрамовица, И. Стиган. Москва : Наука, 1978. 830 с.

[16] Лыков А. В. Теория теплопроводности. М. : Высшая школа, 1967. 599 с.

$$\frac{\partial T(r,\tau)}{\partial \tau} = a\left(\frac{\partial^2 T(r,\tau)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,\tau)}{\partial r}\right), \tag{5}$$

where α – coefficient of thermal conductivity, m^2/s.

To find the temperature distribution over the cylinder cross–section, we solve in aggregate (3)–(5). Then the equation for the temperature at depth r has the form:

$$\frac{\kappa}{qBi}\left(T(r,\tau) - T_0\right) = 2\sum_{n=1}^{\infty}\frac{I_1(\mu_n)}{\mu_n\left[I_0{}^2(\mu_n) + I_1{}^2(\mu_n)\right]} \times$$

$$\times\, I_0\left(\mu_n \frac{r}{R}\right) exp\left(-\mu_n{}^2 \frac{a\tau}{R^2}\right), \tag{6}$$

where k – heat transfer coefficient; I_0 , I_1 – Bessel function of the first kind of zero and first order[17]; Bi – Bio criterion[18]:

$$Bi = \frac{kR}{\lambda}, \tag{7}$$

μ_n – roots of the characteristic equation:

$$\frac{\boldsymbol{I_0(\mu_n)}}{\boldsymbol{I_1(\mu_n)}} = \frac{\boldsymbol{\mu_n}}{\boldsymbol{Bi}} \tag{8}$$

According to equations (6)–(8), the temperature propagation over the cylinder cross-section was determined. To simplify calculations, we denote:

$$A_n\left(\frac{r}{R}; Fo\right) = 2\sum_{n=1}^{\infty}\frac{I_1(\mu_n)}{\mu_n\left[I_0{}^2(\mu_n)+I_1{}^2(\mu_n)\right]} \times I_0\left(\mu_n \frac{r}{R}\right) exp\left(-\mu_n{}^2 \frac{a\tau}{R^2}\right) \tag{9}$$

Then the temperature determination will look like this:

$$T_i = \frac{qBi}{k} A_n\left(\frac{r}{R}; Fo\right) \tag{10}$$

where $A_n\left(\frac{r}{R}; Fo\right)$ is a coefficient that depends on the dimensionless radius r/R and the dimensionless time called the Fourier criterion:

$$Fo = \frac{a\tau}{r^2}, \tag{11}$$

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[17] Слухоцкий А. Е., Рыскин С. Е. Индукторы для индукционного нагрева. Л. : Энергия, 1974. 264 с.

[18] Установки индукционного нагрева / А. Е. Слухоцкий, В. С. Немков, Н. А. Павлов и др. Л. : Энергоатомиздат, 1981. 328 с.

The coefficient of thermal conductivity α, which is the main thermal parameter for calculating thermal conductivity processes, depends on the thermal conductivity p, the heat capacity λ, and the density of the material γ.

$$a = \frac{\lambda}{c\gamma} \tag{12}$$

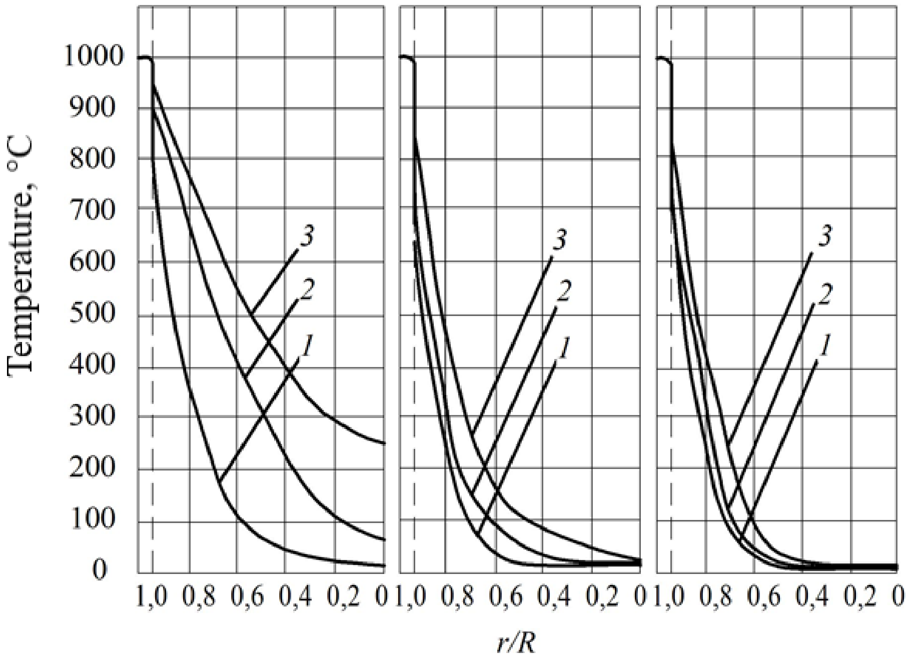
At a fixed specific power of the inductor, which is typical for an industrial installation of high-frequency currents, calculations were made for the distribution of the temperature field from the cylinder surface $\left(\frac{r}{R} = 1\right)$ to the center $\left(\frac{r}{R} = 0\right)$ during thermal exposure at a surface temperature of 850°C and 950°C for cylinders with a diameter of 10, 20 and 30 mm.

The temperature field of an infinitely long circular cylinder is symmetric with respect to its axis and, therefore, one-dimensional. Calculations of the temperature field distribution using formula (6) show that the temperature in the cylinder changes from the surface to the center according to a power law:

$$T_i = T_{\text{п}} \left(\frac{r}{R}\right)^n, n \geq 1\ , \tag{13}$$

where T_n is the cylinder surface temperature; T_i is the temperature of the cylinder at a distance *r/R* from its center.

Depending on the value of the heat flow, we determine the temperature of the cylinder at a distance *r/R* from its center T_i and *n* by approximating the temperature field (6) using the least squares method. We obtain the temperature distribution over the cross-section of cylinders with different diameters, which were 10, 20 and 30 mm when the surface layer of products is heated to temperatures of 850°C (Fig. 1) and 950°C (Fig. 2). Data are obtained for the duration of cylinder heating for 1 s, 3 s and 5 s. with increasing duration, the temperature distribution over the cylinder cross-section becomes smoother for both heating temperatures. For a cylinder with a diameter of 10 mm, the cross-section heating has the highest indicators (Fig. 1, *a* and 2, *a*).



a b c

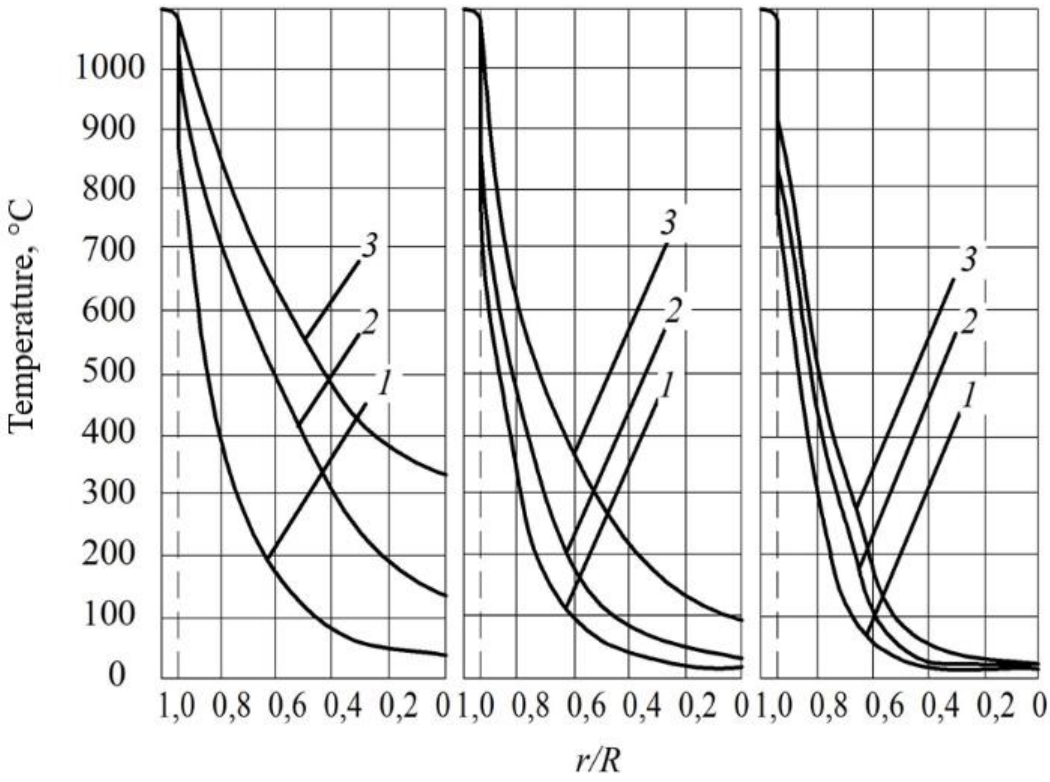
1-heating duration 1 s; 2-heating duration 3 s; 3-heating time 5 s

Fig. 1. Distribution of the temperature field from the surface (r/R = 1) to the center (r/R = 0) when high-frequency currents are heated to a temperature of 850 ° C of cylinders with a diameter of 10 mm (a); 20 mm (b); 30 mm (c)

For cylinder diameters of 20 and 30 mm (Fig. 1, *b*, *c*) the influence of the time factor decreases.

From the distribution of the temperature field over the cross-section of the cylinder from the surface to the center, it follows that the smaller the diameter of the profile, the shorter the time of heat exposure to its surface should be.

Increasing the heating temperature to 950°C gives qualitatively similar results with short-term heating for 1 s (Fig. 2, curve 1). With increasing time, the surface layers of metal are heated to higher temperatures, and this is especially pronounced for diameters less than 10 mm. As the diameter increases, both the surface heating temperature and the heating time have a less noticeable effect on the distribution of the temperature field.



a *b* *c*

1-heating duration 1 s; 2-heating duration 3 s; 3-heating time 5 s

Fig. 2. Distribution of the temperature field from the surface (*r/R* = 1) to the center (*r/R* = 0) when heated by high-frequency currents to a temperature of 950°C of a cylinder with a diameter of 10 mm (*a*); 20 mm (*b*); 30 mm (*c*)

Overheating of the surface above 1000°C leads to partial melting of the surface of the samples, which is undesirable.

To heat the surface layer of a continuous unlimited cylinder to a temperature of 850°C, it is necessary to bring a certain amount of specific power over a certain time. The calculated dependence of the heating time on the heat flow *q*, i.e., the power supplied to each square centimeter of the surface of a cylinder with a diameter of 10-40 mm, which is determined by the formula (6), is shown in Fig. 3.

From the graphs, we can see that with increasing heat flow, the heating time decreases, and the larger the cylinder diameter, the more heat must be supplied to obtain a temperature of 850°C on the surface (Fig. 3, *a*). When reducing the profile diameter, it is necessary to reduce the time of heat exposure to the metal surface.

Curves have a similar appearance when heated to a temperature of 950°C (Fig. 3, *b*). There is only a slight upward shift of the curves. In other words, the heating time at a fixed heat flow q increase, which is more noticeable for a small-diameter cylinder (curves 1 in Fig. 6.3, *a* and *b*).

Energy transfer from the power source to the product during induction heating is carried out using a special device – an inductor. Inductors are made of copper tubes. During operation, the inductor is cooled by running water. The shape and dimensions of the inductor depend on the heating conditions, the size and configuration of the heated surface, as well as on the power and frequency of the power supply. The quality of product processing depends on the correct calculation of the inductor, the choice of its shape and size.

For the thermal calculation, the initial data were set such as the diameter of the part or sample d_2, cm; the length of the part or sample L, cm; the frequency of the generator f, Hz; the width of the hardened strip a_3, cm; the depth of the hardened layer x_k, cm; the surface temperature T_0=900°C; the temperature at which most Steels lose their magnetic properties, which is assumed to be $T_k = 750$ °C; $T_0 / T_k = 1.2$.

The heating time depends on the power of the heat flow q. To heat the surface layer of a continuous unlimited cylinder, for example, to a temperature of 900°C, it is necessary to bring the specific power of a certain value for a certain time. Specific power p_0 is the power that is applied to each square centimeter of the part surface.

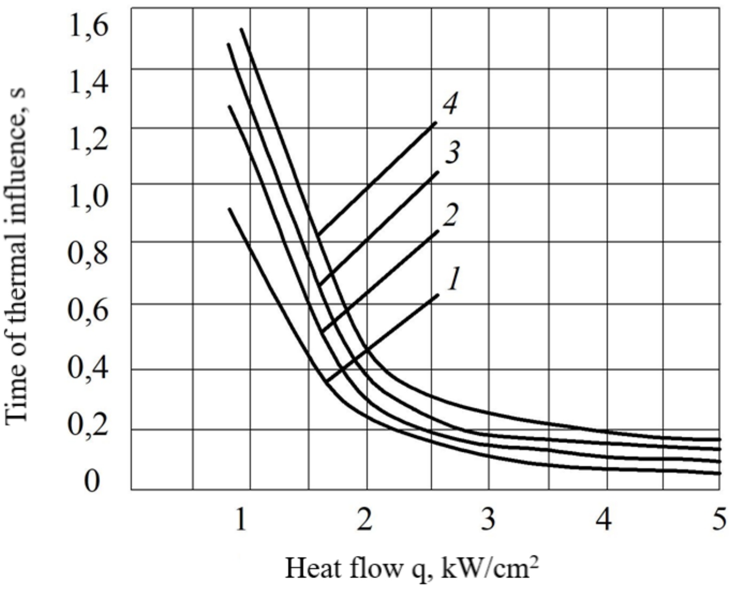
As a rule, based on practice, when surface hardening of parts, a specific power is used in the range of 0.4–1.5 kW/cm^2 to ensure the required thickness of the hardened layer. For cylindrical samples, the relative depth of the active layer is $\alpha = 1 - 2\xi/\delta_2$; relative coordinate $\beta = 1 - 2\xi/\delta_2$; is a decimal fraction and the Fourier criterion $Fo = \frac{4\alpha\tau}{d_2^2}$.

In all formulas, we assume d_2 is the diameter of the cylinder, m; x is the distance from the surface, m; ξ is the depth of the active layer, m.

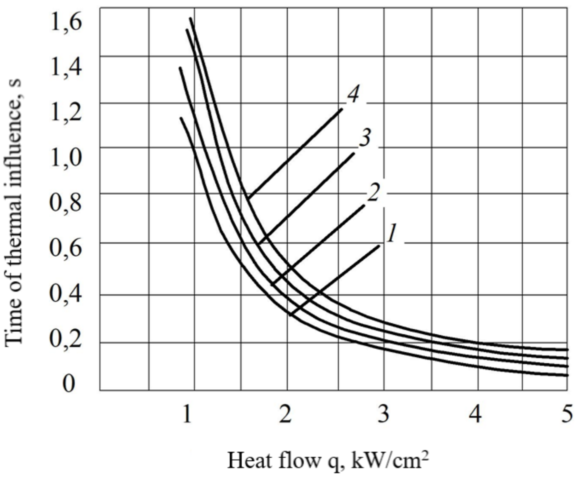
The depth of the active layer is determined by the formula:

$$\xi = M\delta_\kappa, \tag{14}$$

where $M = f(x_k/\delta_k, \mu_\rho)$; $\delta_\kappa = 0{,}5/\sqrt{\phi}$ – the depth of current penetration into heated steel is higher $t = 750$ °C; μ is relative magnetic permeability at depth $x > x_k$.



a



b

Fig. 3. Dependence of the heating time n of the cylinder surface layer on thermal molasses *q*; *a* – heating to a temperature of 850°C; *b* – heating to a temperature of 950°C

1 – cylinder diameter 10 mm; 2 – cylinder diameter 20 mm;
3 – cylinder diameter 30 mm; 4 – cylinder diameter 40 mm

When $x_k/\delta_k > 1$ we accept $M \approx 1$ i $\xi \approx \delta_k$ when $\mu = 16$. It is not recommended to take $\xi < 0{,}3x_k$, because this mode corresponds only to the surface type of heating.

Distribution functions $S(\alpha, \beta, Fo)$ were given before.

If $Fo > 0{,}2$ for the cylinder, then the corresponding functions are $S(\alpha, \beta, Fo) \approx S\,(\alpha, \beta)$ and they no longer depend on the Fourier criterion.

The heating time is determined by the specified ratio:

$$\frac{T_0}{T_k} = \frac{Fo + S(\alpha, 1, Fo)}{Fo + S(\alpha, \beta_k, Fo)} \tag{15}$$

where β_k is value β at depth $x = x_k$; T_0 and T_k are surface temperature and depth x_k accordingly.

Temperature at depth x_k we accept an average of equal 750 °C.

If $Fo > 0{,}2$ for the cylinder, the heating time is τ_k it can be determined by the formula[19]:

$$\tau_k = \frac{d_2^2}{4a} \frac{\left(S(\alpha, 1) - \frac{T_0}{T_k} S(\alpha, \beta_k)\right)}{\left(\frac{T_0}{T_k} - 1\right)} \tag{16}$$

Based on the known heating time and the given surface temperature, we find the specific power:

$$p_0 = \frac{\lambda \mathrm{T}_0}{d_2\,[\mathrm{Fo} + S(\alpha, 1, F\mathrm{o})]} \tag{17}$$

The total power required to heat the entire part is equal to

$$P_2 = S_2 p_0, \tag{18}$$

where S_2 is the area of the total heated surface, m^2.

In approximate calculations, we used the average thermal characteristics of Steel, taking the coefficient of thermal conductivity $a = 6{,}25 \times 10^{-6}$ m^2/s and the coefficient of thermal conductivity $\lambda = 41{,}87$ Вт/(m· °C).

If the part has large dimensions, then P_2 can be very important. In this case, the part is divided into equal sections and the power required for quenching one section is calculated: $P_{2g} = P_2/n$ where n is the number of sections of the part. Then either the inductor or the part is shifted, sequentially heating its entire surface.

The inner diameter of the inductor was calculated as follows:

$$d_1 = d_2 + 2h, \tag{19}$$

where h is the air gap between the inductor and the heated part.

The gap is usually chosen in the range of 2-5 mm if $d_2 \leq 50$ mm, and 5-10 mm if $d_2 \geq 50$–100 mm. For processing a cylindrical part, the generator power required for the site is determined by the formula:

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[19] Немков В. С., Демидович В. Б. Теория и расчет устройств индукционного нагрева. Л. : Энергоатомиздат, 1988. 280 с.

$$P_{\text{г}} = P_{2g}/(\eta_{\geq}\eta_{\text{тр}}), \tag{20}$$

where $\eta_{\geq} \approx \eta_{\int\text{p}} \approx 0,8$ is efficiency of the inductor and high-frequency transformer.

The width of the inductor was calculated as follows:

A) when simultaneously heating the surface area of the part for quenching $h_1 \approx 1,2a_3$ and when quenching the entire surface of the part, $h_1 \approx L$ where L is the length of the part;

B) with continuous-sequential heating, if the generator power is set, then:

$$h_1 = \frac{P_{\text{Г}}}{lp_0}\eta_i\eta_{\text{тр}} \approx 0{,}64\,\frac{P_{\text{Г}}}{lp_0}\,, \tag{21}$$

where l is the length of the hardened strip, for the cylinder $l = \pi d_2$;$P_{\text{г}}$ is generator power, W; η_{i} is inductor efficiency equal to about 0.75; $\eta_{\text{тр}}$ is the efficiency of the step-down quenching transformer, equal to about 0.85.

The next step was to determine the length of the inductor.

For a batch heater:

$$a_1 = a_2 + (1 \div 1{,}5)d_1, \tag{22}$$

where $a_2 = L$ is the length of the part when heated simultaneously, or $a_2 = a_3$ when heated continuously.

In the electrical calculation of the inductor, the following calculations were made. The relative coordinate m_2 was found by the formula:

$$m_2 = \frac{d_2}{\sqrt{2}\cdot\delta_k}, \tag{23}$$

Active and internal reactive part supports:

$$r_2 = \pi\rho_2\frac{m_2^2 A}{\text{a}_3}, \tag{24}$$

where ρ_2 is resistivity is taken for steels 10^{-6} Om·m

$$\text{x}_{2\text{м}} = \frac{r_2 B}{A}\,, \tag{25}$$

where A, B are the calculated coefficients are determined depending on m_2.

The reactance was found by the following equation:

$$\text{x}_0 = \frac{\text{x}_{10}k_1a_1}{a_1 - Lk_1}\,, \tag{26}$$

where x_{10} is reactance of the segment a_1 an empty inductor of infinite length, equal to:

$$\mathrm{x}_{10} = \frac{\omega\mu_0 S_1}{a_1} \tag{27}$$

where μ_0 is the magnetic permeability of the vacuum is equal to $4\pi \cdot 10^{-7}$; ω is angular frequency, equal to $2\pi f$; S_1 is inductor window area (for cylindrical inductor$S_1 = \pi\frac{d_1^2}{4}$); k_1 is correction factor for calculating the inductance of a solenoid with a circular cross-section equal to $k_1 = f\,(d_1/a_1)$.

Inductor scattering reactivity[20]:

$$\mathrm{x}_S = \frac{\omega\pi^2(d_1^2 - d_2^2)\cdot 10^{-7}}{L} \tag{28}$$

Coefficient of reduction of the active resistance of the cylinder:

$$\mathrm{c} = \frac{1}{\left(\frac{r_2}{\mathrm{x}_0}\right)^2 + \left(1 + \frac{\mathrm{x}_S + \mathrm{x}_{2\text{м}}}{\mathrm{x}_0}\right)^2} \tag{29}$$

Induced active resistance of the cylinder:

$$r_2' = cr_2. \tag{30}$$

Induced reactance:

$$\mathrm{x}_2' = \mathrm{c}\left[\mathrm{x}_S + \mathrm{x}_{2\text{м}} + \frac{(\mathrm{x}_S + \mathrm{x}_{2\text{м}})^2 + r_2^2}{\mathrm{x}_0}\right] \tag{31}$$

The thickness of the induction wire was chosen as close as possible to the optimal one, equal to:

$$d_1 \approx 1{,}6\delta_1, \tag{32}$$

where δ_1 is the depth of current penetration into the inductor material is equal to:

$$\delta_1 = 503\sqrt{\frac{\rho_1}{f}}, \tag{33}$$

where ρ_1 is resistivity of the inductor material, which is equal to for copper $2 \cdot 10^{-8}$ Om·m.

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[20] Глуханов Н. П. Физические основы высокочастотного нагрева : б-ка высокочастотника-термиста / под ред. А. Н. Шамова. Вып. 1. Л. : Машиностроение, 1989. 56 с.

The active and internal reactive resistances of the induction wire were calculated using the formulas:

$$r_1 = r_{1п}k_r, \quad x_{1м} = r_{1п}k_x, \quad r_{1п} = \frac{\rho_1 \pi d_1'}{a_1 d_1 g}, \tag{34}$$

where d_1' is design diameter of the inductor, m; $d_1' = d_1 + \delta_1$ when $d_1 > \delta_1$; g is the coefficient that takes into account the presence of holes in the inductor for the release of quenching water, which reduce its active surface, is assumed to be 0.85; k_r, k_x are correction factors for calculating the active and internal reactance, respectively, depending on the relative thickness of the conductor d_1/δ_1.

The equivalent active, reactive, and total resistances of the inductor were determined by the formulas, respectively:

$$Re = r_1 + r_2', \quad x_e = x_{1м} + x_2', \quad z_e = \sqrt{x_e^2 + r_e^2}. \tag{35}$$

The efficiency of the inductor was calculated by the formula:

$$\eta_i = \frac{r_2'}{r_e} \tag{36}$$

The power factor of the inductor was found as follows:

$$\cos \phi_i = \frac{r_e}{z_e} \tag{37}$$

The net average power was:

$$P_т = p_0 \pi d_2 a_3. \tag{38}$$

The heat loss through the insulating cylinder was equal to:

$$\Delta P_T = \frac{3{,}74 a_1}{lg\left(\frac{d_1}{d_2}\right)} \tag{39}$$

Total average power in parts:

$$P_2 = P_т + \Delta P. \tag{40}$$

The current in the inductor was calculated by the formula:

$$I_i' = \sqrt{\frac{P_2}{r_2'}} \tag{41}$$

Current density in the inductor at $d_1 > \delta_1$ equal to:

$$\delta_{\mathrm{i}} \approx \frac{I_{\mathrm{i}}' \cdot 10^{-6}}{\mathrm{a}_1 \delta_1 g} \tag{42}$$

The voltage across the inductor was determined by the formula:

$$U_{\mathrm{i}}' = I_{\mathrm{i}}' \mathrm{Z_e} \tag{43}$$

The power supplied to the inductor was equal to:

$$\mathrm{P_i} = \frac{\mathrm{P_2}}{\eta_{\mathrm{i}}} \tag{44}$$

The number of turns of the inductor N was found as follows:

$$N = \frac{U_{\mathrm{i}}}{U_{\mathrm{i}}'} \tag{45}$$

where U_{i} – inductor voltage, equal to

$$U_{\mathrm{i}} = U_{\mathrm{i}}' \sqrt{\frac{\mathrm{P_i}}{100}} \tag{46}$$

The height of the coil was equal to:

$$b = \frac{a_1 g}{N + 1} \tag{47}$$

The current in the inductor was equal to:

$$I_{\mathrm{i}} = \frac{I_{\mathrm{i}}'}{N} \tag{48}$$

The active, reactive, and total resistance of the inductor were determined by the formulas, respectively:

$$r_i = N^2 r_e, \quad x_i = N^2 x_e, \quad z_i = N^2 z_e. \tag{49}$$

Inductors for heating are made in many colors. To provide the required amount of water for the inductor at a given inlet pressure, select the appropriate internal cross-section of the tube. It was determined by the known amount of heat that should be removed by water.

The inductor is heated by the current that passes through it and the lost heat of the part, which is heated through thermal insulation.

The calculation procedure was as follows. The amount of cooling water was determined by the formula:

$$W = \frac{0{,}24\Delta P \cdot 10^{-3}}{T_2 - T_1} \tag{50}$$

where ΔP – the total amount of heat that heats the inductor is:

$$\Delta \mathrm{P} = \mathrm{P_T}\left(\frac{1}{\eta_\mathrm{i}} - 1\right) \tag{51}$$

where $T_2 - T_1 = 30$ °C is temperature difference at the output and input of the inductor; T_2 is outlet water temperature. It should not be higher than 50°C, because local vaporization and burnout of the inductor are possible.

The area of the inductor tube opening was determined by:

$$s = \frac{W}{v} \tag{52}$$

where v is water speed accepted 2 m/s.

Based on the above calculations, the main characteristics of the inductor for carrying out the technological process of boriding at surface temperature were determined T_0=900 °C high frequency currents for steel samples with a diameter of d_2=2,26 cm, length a_2=25,5 cm by the width of the hardened strip a_3=4,0 cm, depth of the hardened layer x_k=0,2 cm, and got the following parameters:

– during the thermal calculation of the inductor, the hot depth was determined δ_k = 5,9 mm, active layer depth ξ=0,5 mm, heating time τ_k=5 s, specific power p_o=11,21 MW/m^2 and full power P_2=2,47 MW, inductor width a=0,289 m, taking into account the gap of 3 mm the inner diameter of the inductor d_1=29 mm;

– when electrically calculating the parameters of the inductor, the active r_2 and internal reactance of the part x_{2m}, inductor reactance x_o, reactive scattering of the inductor x_s, active r_e, reactive x_e and full z_e inductor resistance, efficiency η=0,798, power factor $cos\ \varphi_i$, current strength I_i=34050 A, voltage U_i=4,472 V and inductor power P_i=52,4 kW;

– in the geometric calculation of the inductor, the internal diameter of the inductor is determined d_1, induction wire thickness D_1, width a_1, height b=0,01 m and the number of turns of the inductor N=23, inductor length L when the sample length is l. The calculation of water cooling of the inductor was also carried out. For this purpose, the total amount of heat is determined ΔP=20,58 kW, inductor tube opening area s=0,082 m^2, amount of water supply W=0,165 m^3/s.

A method for surface hardening of steel products was developed, which included applying a coating containing a boron-containing substance and activator to the steel surface, drying and subsequent treatment with high-frequency currents. As a boron-containing substance, amorphous boron and activator lithium fluoride were used at the ratio (wt. %): amorphous boron 90-75, lithium fluoride 10-25. Heating was carried out at temperatures of 800-1100°C for 1-5 minutes.

The process of boriding by the high-frequency current method on the structure, thickness of the reinforced layer, phase composition of the diffusion layer, and microhardness of the reinforced layers of carbon and alloy steels was studied. Analysis of the experimentally obtained results showed that after boring steel products with high-frequency currents, boride layers with a thickness of up to 0.24 mm and a microhardness of up to 22.5 GPa were obtained. X-ray diffraction phase analysis confirmed the presence of borides, carboborides, and α-Fe in the studied Steels. Studies have shown that the boride layer grows with increasing time, while maintaining a pattern, namely, the highest growth rate is recorded in low-carbon steels and it decreases with increasing content of carbon and alloying elements in steels. When heated for less than 1 min, the thickness of the diffusion layer is insufficient on all steel samples. The duration of boriding under induction heating for more than 5 minutes leads to the formation of eutectic structures of the boride layer and surface melting, which is unacceptable for parts and tools.

The proposed method of surface hardening of steel products in comparison with existing ones has the following advantages:

– increases the rate of formation of diffusion layers by 1.7–2.5 times;

– increases the surface microhardness of steel products by 2-2. 25 times;

– increases the operational properties of steel products;

– – significantly facilitates the complexity of the processing process of ghostly energy resources by reducing the components in the coating and reducing the processing temperature by 100ºC;

– increases technological efficiency and improves working conditions.

The use of the method of surface hardening of steel products made it possible to combine borating with quenching, which increased the service life of steel parts and their operational properties.

A method of diffusion boriding of steel products was developed, which included preliminary application of a coating on the steel surface, which included a boron-containing substance, an activator sodium fluoride and a binder of a BF glue solution in acetone, and subsequent heating with high-frequency currents. Magnesium polyboride (amorphous boron) was used as a boron-containing substance and the activator lithium fluoride was additionally introduced, with the following ratio (WT. %): magnesium polyboride (amorphous boron) 76-90, lithium fluoride 5-12, sodium fluoride 5-12. Heating was carried out cyclically at temperatures of 750-1200°C for 1-5 minutes with the number of treatment cycles from 6 to 30.

Analysis of the obtained results showed that after borating steel products with high-frequency currents with cyclic heating, boride layers with a thickness of up to 250 microns and a microhardness of up to 23 GPa are formed. The significant growth rate of the boride layer is explained by the creation of defects in the crystal structure due to multiple phase transformation, which increases the diffusion processes of atomic boron saturation.

The formation of a hardened layer in a short period of time, namely up to 5 minutes, when the sample is heated by high-frequency currents, makes it possible to obtain a viscous boride layer with a reduced microhardness of up to 18 GPa. The formation of such a layer is associated with a special phase composition and structure of the layer. These features are caused by the high rate of boron diffusion deep into the steel due to rapid heating from room temperature to processing temperature. Diffusion in this case can occur along the boundaries of grains (sub-grains, blocks). At boriding temperatures, the structure of steel is austenite, according to the iron – carbon state diagram. Therefore, during processing, austenite is saturated, close to the rudimentary state. The higher the heating rate, the smaller the austenite grain and, accordingly, the smaller the block size when the set temperature is reached. This factor, in turn, leads to a longer length of grain boundaries (sub-grains, blocks), which ensure rapid movement of the saturating element from the sample surface to its core. Also, when the borage process is intensified by high-frequency current methods, the activity of the saturating boron-containing medium decreases (a short duration of exposure during borage and a certain amount of boron-containing coating). As a result, the boron concentration required for the formation of the boride zone does not have time to form in the surface layers of steel.

Another area of intensification of diffusion hardening processes was the use of pre-laser treatment. To do this, a continuous laser beam was directed to the surface of the sample, while the sample was moved under the beam at a speed of 0.5 to 1.5 m/min. Focusing of laser radiation was carried out using a lens. Flat-convex spherical lenses with a focal length of 300 mm were used as focusing elements. The size of the focusing spot was changed by adjusting the distance from the focal element to the surface in the range from 2.0 mm to 7.0 mm with an accuracy of ± 0.05 mm. The diameter of the focusing spot was measured along the radiation intensity distribution curve in the section, which is located at a distance of $\frac{I_{max}}{e^2}$ from the main plane. The intensity distribution in the cross-section of the focused beam was performed by scanning using a special pyroelectric analyzer. The surface of the samples of the studied Steels is not subject to oxidation, so protective media, as which argon can be used, were not used. For a uniform distribution of carbon across the structure, the steel samples were pre-hardened to produce martensite. After laser treatment, steel tempering processes occurred in the depth of the samples (at a distance of 70-200 microns) from the irradiated surface, which is confirmed by the presence of martensite tempering in these areas of the samples. At a distance of up to 70 microns from the irradiated surface, significant grinding of the grain structure occurred, which is associated with recrystallization of austenite as a consequence of Phase bonding, which turns into a martensitic structure with high hardness when cooled. All these phenomena are associated with an extremely high heating rate.

A method of combined processing of steel products is proposed, which included laser treatment of surface layers of steel at a laser radiation power of 1.0 k 0.1 kW and the speed of movement of the laser beam from 0.5 to 1.5 m/min, followed by the process of nitriding in a nitrogen – containing substance – melamine with the addition of 3–5% sodium fluoride at temperatures of 530–560 °C for 2–3 hours. Analysis of the experimentally obtained data showed that after laser treatment and subsequent nitriding of 38x2mua Steel, a nitrided diffusion layer of greater thickness was obtained, namely up to 0.65 mm with a greater microhardness (up to 12.5 GPa) compared to only nitrided layers that were obtained without laser treatment, while the thickness of the diffusion layer reached 0.2 mm, and the microhardness – 10.8 GPa. This acceleration of the diffusion process was explained by facilitating the diffusion of active nitrogen atoms and increasing its solubility due to the formation of a defective steel structure after laser irradiation.

A method for obtaining a hard coating on the surface of steel products is studied, due to the use of laser surface treatment of the material and boriding in a medium of magnesium polyboride 80–86 %, with the addition of activators sodium fluoride (NaF) 7–10 %, lithium fluoride (LiF) 7–10%

at temperatures of 850–950°C for 30–90 minutes. Analysis of the obtained results showed that after laser treatment and subsequent boriding of 38Cr2MoAl steel, we obtain a boride layer of greater thickness (up to 0.140 mm) and higher microhardness (up to 22.5 GPa) compared to pure borated sections (without preliminary laser treatment), where the thickness of the diffusion layer did not exceed 0.070–0.073 mm, and the microhardness – 18–20 GPa.

Thus, during preliminary laser processing, the steel was rapidly heated to temperatures that exceeded critical points. The heating was local, so there was a rapid removal of heat, which in turn significantly increased the cooling rate. In the heating zone, phase and structural transformations occurred, during which austenite was formed, the carbide phase was dissolved, and austenite was converted to martensite during cooling. Preliminary laser treatment helped accelerate further strengthening treatments, which consisted in atomic saturation of steels with nitrogen, carbon and boron. The speed of movement of atomic saturating elements was increased due to the greater defect rate of the pre-treated areas with the laser beam.

CONCLUSIONS

1. Methods for intensifying the processes of chemical and thermal treatment by heating with high-frequency currents to obtain high operational properties of the surface layers of products with a significant reduction in the duration of treatments have been developed.

2. The main characteristics of the inductor for the developed process of borating high-frequency currents are determined:

– during the thermal calculation of the inductor, the hot depth was determined $\delta_k = 5,9$ mm, active layer depth $\xi=0,5$ mm, heating time $\tau_k=5$ s, specific power $p_o=11,21$ MW/m^2 and full power $P_2=2,47$ MW, inductor width $a=0,289$ m, taking into account the gap of 3 mm the inner diameter of the inductor $d_1=29$ mm;

– when electrically calculating the parameters of the inductor, the active r_2 and internal reactance of the part x_{2m}, inductor reactance x_o, reactive scattering of the inductor x_s, active r_e, reactive x_e and full z_e inductor resistance, efficiency $\eta=0,798$, power factor $\cos \varphi_i$, current strength $I_i=34050$ A, voltage $U_i=4,472$ V and inductor power $P_i=52,4$ kW;

– in the geometric calculation of the inductor, the internal diameter of the inductor is determined d_1, induction wire thickness D_1, width a_1, height $b=0,01$ m and the number of turns of the inductor $N=23$, inductor length L when the sample length is l. The calculation of water cooling of the inductor was also carried out. For this purpose the total amount of heat is determined

ΔP=20,58 kW, inductor tube opening area s=0,082 m^2, amount of water supply W=0,165 m^3/s.

3. The proposed method of surface hardening of steel products in comparison with the existing ones has the following advantages: increases the rate of formation of diffusion layers by 1.7–2.5 times; increases the surface microhardness of steel products by 2–2.25 times; increases the operational properties of steel products in obtaining boride layers up to 0.24 mm thick and microhardness up to 22.5 GPa.

4. Analysis of the obtained results showed that after the developed mode of boriding of steel products by high-frequency currents with cyclic heating, boride layers with a thickness of up to 250 microns with a microhardness of up to 23 GPa are formed. It is established that a significant growth rate of the boride layer is associated with the creation of defects in the crystal structure due to multiple phase transformation, which increases the diffusion processes of atomic boron saturation.

5. Methods of combined strengthening treatment of steel products are proposed, which included preliminary laser treatment of the surface layers of steel, followed by a nitriding or boriding process. It was found that pre-laser treatment contributed to the acceleration of further strengthening treatments due to the greater defect rate of pre-treated areas with a laser beam.

SUMMARY

To increase the reliability and durability of machine parts, punching and cutting tools, increase the endurance limit of alloy structural steel products, increase the wear resistance of machine parts, ensure high hardness and corrosion resistance of the surface layers of products, surface hardening is widely used in industry. Existing methods of surface hardening of machine parts by chemical and heat treatment methods, as a rule, ensure the operability of parts in conditions of friction and wear, but they are quite long and require special complex and expensive equipment. Therefore, it is important to improve the technological processes of manufacturing machine parts by developing new methods of surface hardening, which significantly increase the durability of the working layer and the surface of parts with a significant acceleration and simplification of surface hardening technologies. The paper develops methods for intensifying the processes of chemical and thermal treatment by heating with high-frequency currents to obtain high operational properties of the surface layers of products while significantly reducing the duration of treatments. The main characteristics of the inductor for the developed process of borating high-frequency currents are determined. Analysis of the obtained results showed that after the developed mode of boriding of steel products by high-frequency currents with cyclic heating, boride layers with a thickness of up to

250 microns with a microhardness of up to 23 GPa are formed. Methods of combined strengthening treatment of steel products are proposed, which included preliminary laser treatment of the surface layers of steel, followed by a nitriding or boriding process. It was found that pre-laser treatment contributed to the acceleration of further strengthening treatments due to the greater defect rate of pre-treated areas with a laser beam.

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