EDDY-CURRENT TESTING OF LASER HARDENED CEMENT CHROMONICKEL STEEL FOR DRILLING BITS

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Introduction

Carburized chromonickel steels are widely used in the production of drilling tools, pinions, shafts, sleeves, power studs, bolts, clutches, worm shafts, and other parts operating under conditions of strong contact and impact loads, friction, abrasive media, and temperatures below 0°C; therefore, the requirements of high surface hardness, strength, plasticity, and core ductility are imposed on these steels. The development of nondestructive methods for controlling the quality of carburized layers is an important practical problem. The question of using electromagnetic methods for testing the structure, chemical composition, and properties of carburized steels continues to attract the attention of researchers [1-4].

Modern high-energy techniques for strengthening surfaces, such as laser and electron-beam processing, ensure significant improvement of tribological, mechanical, and other important operational characteristics [5]. The possibility of using electromagnetic methods to test the depth, hardness, and wear resistance of the surface layers of carbon and alloyed steels hardened under laser irradiation was established. However, little attention was given to specific features of testing of laser-hardened carburized steels (with a variable carbon content in the surface layer). This study is devoted to features of eddy-current (EC) testing of carburized chromonickel steel 20KhN3A subjected to processing with continuous CO_2-laser radiation.

Laser-hardened articles can be exposed to significant heating during grinding, welding, and under operational conditions (e.g., frictional heating). To increase the hardness and resistance to different types of wear, after laser and bulk hardening, carburized steels are treated with cold. Therefore, in this study, we consider the influence of tempering at temperatures lower than 400°C on the hardness, wear resistance, and EC characteristics of a laser-irradiated carburized layer of steel 20KhN3A additionally cooled by liquid nitrogen.

Laser hardening and laser hardening combined with cooling efficiently increase the resistance to abrasive and contact–fatigue wear of bearings of rock-roller bits [5]. This study is devoted to the possibilities of the EC method for controlling the quality of laser hardening of bit leg journals. Because the roller paths of drill bits are intricate curvilinear surfaces, in this study, we consider an EC probe with a protruding rodlike core.

Industrially produced steel 20KhN3A was studied. In addition to Fe, it contained (wt. %) 0.20 C, 0.68 Cr, 2.90 Ni, 0.14 Mo, 0.28 Si, 0.44 Mn, and 0.01 P. Specimens with dimensions of 7×7×20 mm were subjected to carburization in a solid carburizer at 950°C for 12 h, cooling in air from 890°C, hardening in oil from 790°C (holding for 1.5 h), tempering at 180°C for 2 h, laser irradiation, cooling in liquid nitrogen at T= -196°C, and tempering at T= 100-400°C (holding for 2 h). The depth of the carburized layer was 1.1-1.3 mm, and the maximum carbon concentration in the layer was 0.95 wt %. Before laser irradiation, the specimens were ground to remove the decarburized layer and were etched in an aqueous solution of ammonia persulfate to increase the absorption coefficient of laser radiation. The working surfaces of the specimens (7×7 mm) were processed in a helium jet with radiation of a continuous-wave CO_2-laser forming a rectangular spot of 7×0.7 mm in a single pass in a mode of surface melting. To increase the heat removal rate, during irradiation, the specimens were partially immersed into water. The radiation power was 2.3 kW, the beam-displacement speed was 30 m/h, and the energy density was 40 J/mm^2. The depth of the melted zone was 0.10-0.15 mm, and total depth of the hardened zone was 0.8-0.9 mm. Roller paths of the legs of rock-drilling bits 190.5 mm in diameter produced from carburized steel 20KhN3A were also subjected to laser hardening without melting.

Changes in the abrasive wear resistance along the depth of the carburized layer of specimens were determined from multiple tests, which resulted in a sequential removal (wear) of the surface layer. The structure of the carburized layer was studied by the metallographic and electron-microscopic methods. The phase composition was determined by X-ray diffraction analysis in FeK_{α} radiation. The carbon content in the retained austenite and martensite in laser-hardened carburized steel 20KhN3A was determined using the techniques considered in [5].

The electromagnetic parameters were measured with a laboratory prototype of an EC instrument using differentially connected attachable transformer transducers with pot cores having flat end surfaces (with a testing locality 5-6 mm in diameter) [6] and protruding rod ferrite cores (with a locality 3-4 mm in diameter) (Fig. 1). The locality of the employed transducers allowed measurements at the end surfaces of specimens (7×7 mm) without any influence of the edge effect. Measurements were performed at a frequency f = 72 kHz, at which the calculated penetration depth of an electromagnetic field into the material is about 0.17 mm. In this case, the changes in the electromagnetic characteristics depending on the depth of the zone of laser influence were determined during layer-by-layer grinding down of the carburized layers of specimens. The curvilinear surfaces of the roller paths of journals of drill-bit legs were studied with a transducer with a protruding core at frequencies f = 72 and 2.4 kHz (in the latter case, the penetration depth of the electromagnetic field is about 0.85 mm).

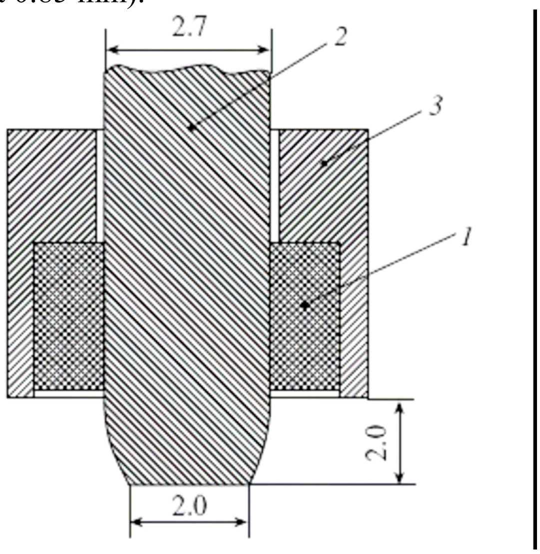

Fig. 1. Schematic diagram of the attachable EC transformer-type transducer with a protruding rod ferrite core: (1) windings of the transducer, (2) rod ferrite core, and (3) pot core.

Results

Specimens of steel 20KhN3A subjected to carburization and standard heat treatment (hardening from 790°C in oil and tempering at 180°C) before laser irradiation contained up to 25 vol. % of retained austenite in the carburized layer. In this case, the microhardness preserved values at a level of 7.5-8.0 GPa to a depth of approximately 0.7 mm and then smoothly decreased to 4.7-5.1 GPa [1, 5].

The layer formed as a result of laser processing consists of three main zones: melting I, hardening without melting II, and tempering III (Fig. 2a). The melted layer and the region of the hardened zone without melting adjacent to it are characterized by the maximum amounts of retained austenite (up to 40 vol %) and, correspondingly, by a relatively low level of microhardness (7.3-8.5 GPa) (Fig. 3a, curves 1). This is due to the presence of increased carbon concentrations in the above-mentioned areas (Fig. 3b) and a significant overheating of the metal above the temperature Acm (A_{C3}). The considered surface zones are characterized by nonuniform etchability and an appreciable spread of the microhardness values (see Fig. 2a and Fig. 3a, curve 1), which are caused by their significant chemical and structural inhomogeneities. A certain decrease in the amount of retained austenite (Fig. 3a, curve 1) observed near the melted surfaces of specimens is associated with the partial decarburization of steel after laser processing. In this case, blasting the laser-heated zone with helium did not ensure complete protection against carbon burning out.

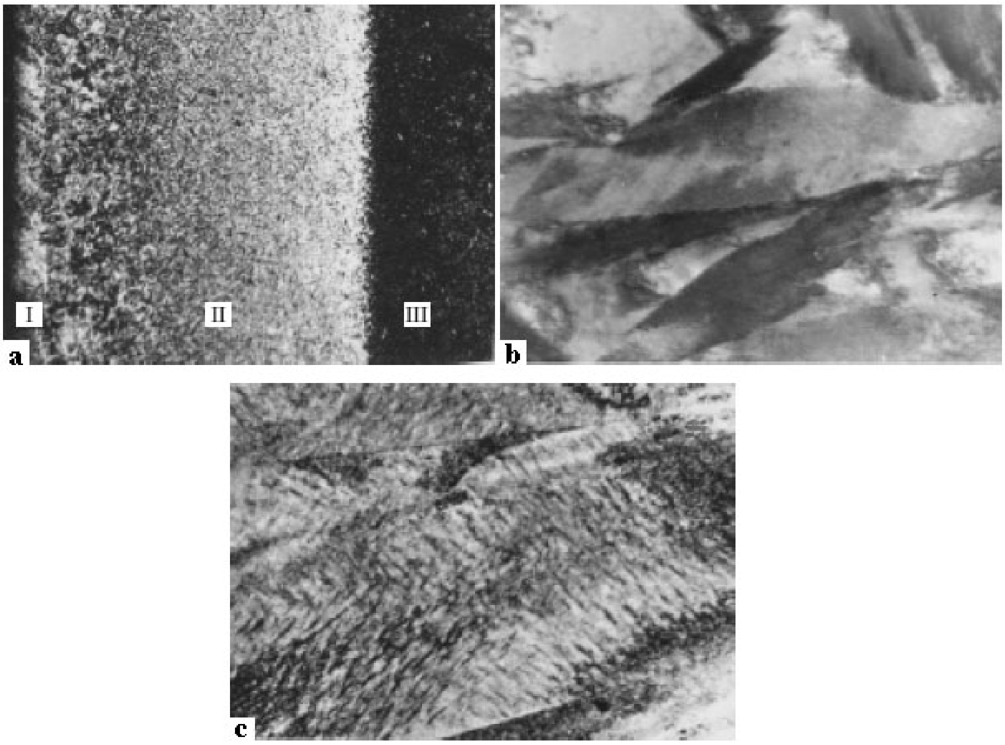

Fig. 2. Structure of a carburized layer of steel 20KhN3A subjected to laser irradiation with surface melting:
(a) general view of laser-irradiated zones (melting I, hardening without melting II, and laser tempering III, ×60;
(b) martensitic–austenitic structure of the laser-hardened zone, ×22000;
(c) low-tempered martensite (hardening from 790°C in oil and tempering at 180°C for 2 h, ×42000; (a) optical microscopy; and (b, c) transmission electron microscopy, light-field images

As the distance from the melted zone increases, the microhardness in the hardened zone increases to 9.0-9.5 GPa (Fig. 3a, curve 1) and the structure becomes more homogeneous (Fig. 2a, zone II). The content of retained austenite in this region smoothly decreases with the layer depth in accordance with a decrease in both the carbon concentration in the carburized layer (Figs. 3a, 3b) and the laser-heating level. Below the hardened zone, laser-tempering zone III is located, which is characterized by increased etchability (Fig. 2a, zone III) and a relatively low (3.5-4.5 GPa) microhardness level (Fig. 3a, zone III). An electron-microscopic image of the martensitic-austenitic structure of the laser-hardened zone of carburized steel 20KhN3A shows (Fig. 2b) that the martensitic phase has the form of untempered twin lenticular martensite. The absence in martensitic crystals of ε-carbide precipitations, which are typical of the martensite structure tempered at 180°C (Fig. 2c), indicates that self-tempering during laser hardening is suppressed.

Tests for abrasive wear resistance have shown that the laser-hardened zone throughout its entire depth is characterized by a decreased wear rate (Fig. 3c, curves 1) regardless of the presence of melting and, correspondingly, of the change in the amount of retained austenite (from 15 to 40 vol. %) and microhardeness (from 9.5 to 7.3 GPa) in the hardened layer (Fig. 3a, curves 1). In wear tests with flint and corundum, laser hardening reduces the wear rate (increases the wear resistance) of a carburized layer by 45-65% and 20-25%, respectively, in comparison to the standard heat treatment (hardening from 790°C in oil and tempering at 180°C-Fig. 3c, curves 3). The melted layer has a high wear resistance equal to that of a layer obtained upon laser irradiation without surface melting [5]. In the zone of laser tempering, the wear rate of the carburized layer abruptly increases

(Fig. 3c, curves 1) and becomes higher than the wear rate of hardened and low-tempered steel (Fig. 3c, curves 3).

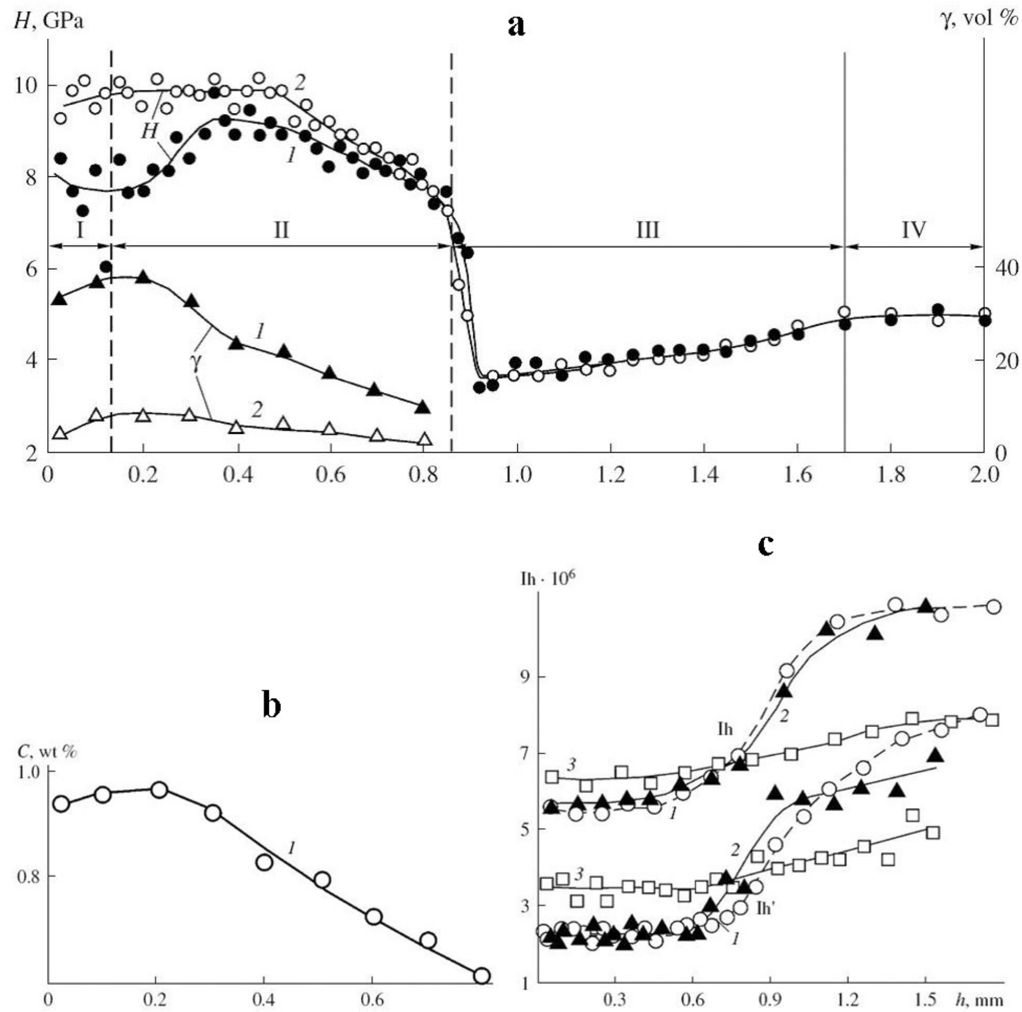

Fig. 3. Changes in the (a) microhardness H and amount of retained austenite γ, (b) carbon content in martensite C, and (c) abrasive wear rate in tests with corundum Ih and flint Ih' along the depth of the carburized layer h on steel 20XH3A specimens (1) laser hardening; (2) laser hardening followed by treatment with cold at –196°C; and (3) hardening from 790°C in oil, tempering at 180°C for 2 h. Zones: (I) melting, (II) laser hardening, (III) laser tempering, and (IV) initial structure.

From curve 1 (Fig. 4a), it follows that, as the distance along the depth of the laser-hardened carburized layer of steel 20KhN3A increases, the value of the informative signal of an EC transducer with a flat end surface constantly decreases. After treatment with cold a sharp decrease in readings α after treatment with cold is observed (Fig. 4a, curve 2). Figure 4b shows that, when an EC transducer with a protruding core is used, a qualitatively similar character of changes in its readings is generally observed along the depth of the surface layer of carburized steel hardened with laser radiation and then treated with cold, as compared to a transducer with a flat core (Fig. 4a). Only the initial segments of the curves in Figs. 4a and 4b are different: curves 1 and 2 in Fig. 4b (transducer with a protruding core) better correspond to a nonmonotonic change in the amount of retained austenite along the depth of the surface layer (Fig. 3a) caused by partial burning out of carbon on the laser-melted surface.

It follows from Fig. 5a (curves 2) that, for specimens subjected to laser hardening and subsequent cooling to -196°C and containing less than 10 vol. % of austenite in the strengthened layer, the hardness of martensitic structures continuously decreases and the abrasive-wear rate continuously increases under heating in the temperature range 100-400°C. For steel subjected to laser hardening and containing 20-40 vol. % of retained austenite, an increase in the wear rate begins at a tempering temperature of 150°C (Fig. 5a, curve 1). A further increase in the tempering temperature to 200°C causes a weaker increase in the wear rate (curve 1) than for steel additionally treated with cold (curve 2).

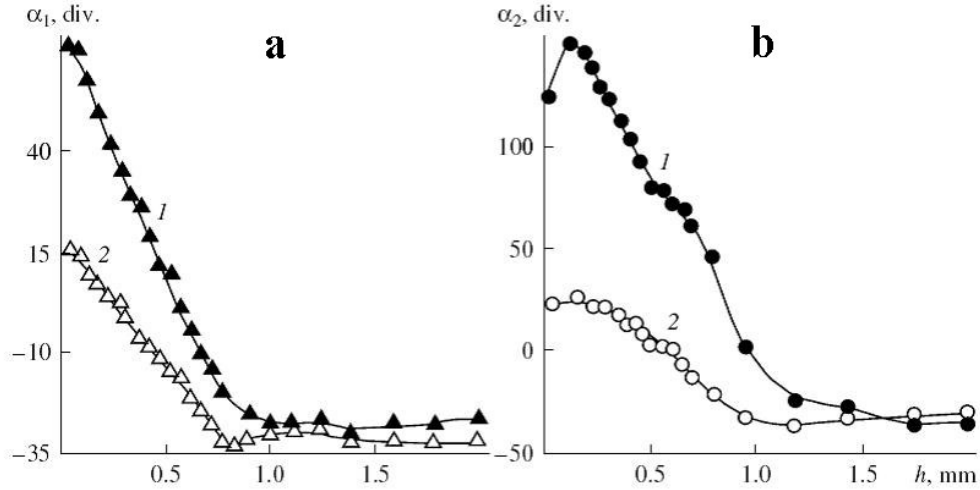

Fig. 4. Changes in the readings of the EC instrument at a frequency f = 72 kHz along the depth of a carburized layer h of steel 20XH3A using transducers with (a) a flat end surface α_1 and (b) a protruding rod ferrite core α_2: (1) laser hardening and (2) laser hardening followed by treatment with cold at -196°C.

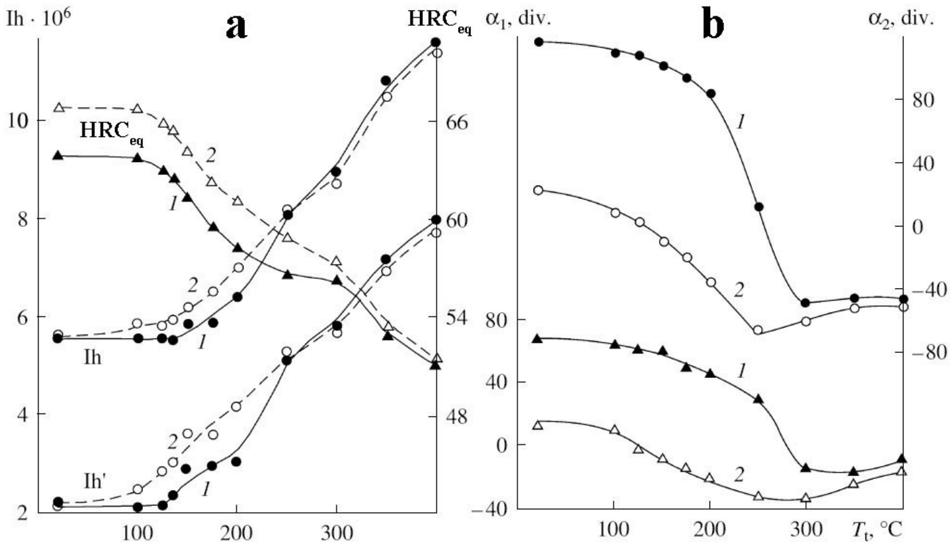

Fig. 5. (a) Influence of the tempering temperature T_t on the hardness HRC_{eq} and the average abrasive-wear rate in tests with corundum Ih and Flint Ih ' of a surface layer 0.5 mm thick and (b) readings of the EC instrument at frequency f = 72 kHz in tests of steel 20XH3A with a transducer with a flat end surface α_1 and a transducer with a protruding rod ferrite core α_2: (1) laser hardening and (2) laser hardening followed by treatment with cold at -196°C.

The results of measurements presented in Fig. 5b show that, when the tempering temperature increases to 300°C for hardened steel (curves 1) and to 250°C for steel subjected to cooling (curves 2), the readings of the EC instrument decrease in measurements with transducers of both types. Hence, the EC method allows evaluation of decreases in the wear resistance and hardness of carburized steel 20KhN3A subjected to laser hardening and subsequent cooling. In this case, after the treatment with cold decreasing the amount of retained austenite in the carburized layer, the sensitivity of the EC method to changes in the mechanical characteristics during tempering decreases (Fig. 5b).

The disclosed regularities were used to select the regimes of laser strengthening of the roller paths of a bearing unit of rock-drill bits with a diameter of 190.5 mm manufactured from carburized steel 20KhN3A (Fig. 6a). Under the operational conditions of drill bits, the working capacity of a bearing unit is largely determined by the resistance of the carburized surface to contact-fatigue and abrasive wear. Laser processing of the roller paths of drill-bit legs, which had been subjected to standard thermochemical treatment (carburization, double hardening in oil, and tempering at 180°C) and grinding, was performed without surface melting, because melting leads to the formation of an increased amount of retained austenite and, correspondingly, to a lower hardness and a reduced supporting ability of the surface. When the technological scheme of laser processing was chosen, it was necessary to avoid the presence on roller paths of weakened zones of laser tempering, which are formed when laser tracks mutually overlap and each subsequent pass of a laser beam partially weakens the zone hardened in the previous pass. In addition, tensile stresses substantially reducing the fatigue strength of metalware appear at the boundaries of the laser-hardened zones. The presence of weakened areas and zones with tensile stresses is especially undesirable in the central parts of ball roller paths, which are characterized by a point force contact with rolling bodies (balls).

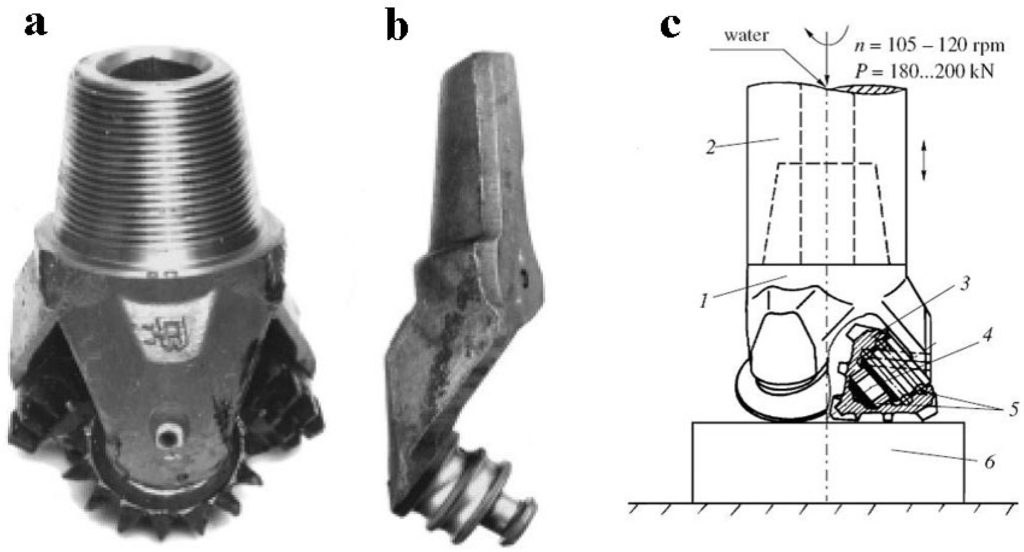

Fig. 6. General view of (a) a drill bit, (b) a drill-bit leg after laser processing of roller paths, and (c) scheme of loading in studies of contact–fatigue strength of the bit bearing under the conditions of bench tests on a metal bottom: (1) drill bit, (2) shaft, (3) roller cone, (4) leg journal (bearing), (5) rolling bodies (balls and rolls), and (6) steel slab (steel 40).

Therefore, drill-bit legs were processed with an LT1-2M CO_2-laser (in a helium jet, at a laser power of 2 kW and a laser-spot speed of 25 m/h) using a rectangular spot, which allowed obtaining a hardened zone with a depth of 0.7-0.9 mm in a single beam pass over almost the entire width (10-11 mm) of a roller and two ball paths of a drill-bit leg journal (Figs. 6b, 6c). The strengthened layer formed as a result of laser hardening had a homogeneous martensitic-austenitic structure throughout its full depth and was characterized by a content of retained austenite of 25-35 vol. % and a constantly high (8.6-9.8 GPa) microhardness level.

The resistance of a carburized layer to contact-fatigue damage during rolling friction was studied under conditions of factory bench tests of drill bits on a metal bottom (the load applied to a bit P = 180-200 kN, the bit rotational speed n = 105-120 rpm, and water cooling, see Fig. 6c). The bench tests have shown that the working capacity of the laser-hardened drill bits is 55% higher than the working capacity of production type bits.

An EC instrument equipped with the designed attachable transducer with a protruding core (Fig. 1) was used to measure the electromagnetic characteristics of segments of roll and ball races with the optimal and a decreased (underheated) depth of the laser-hardened zone, with the laser-tempered zone (considerable underheating), and with the melted zone (overheating). The use of two frequencies for exciting an electromagnetic field (f = 72 and 2.4 kHz) allowed us to analyze surface layers of different thicknesses (approx. 0.17 and 0.85 mm, respectively).

The data presented in the table show that the levels of the readings α of the EC instrument obtained in measurements at both frequencies for the optimal laser hardening without melting (a strengthened-layer depth of 0.7-0.9 mm) differ from the levels from other (undesirable) considered zones formed in nonstandard laser-processing regimes and from the carburized layer after standard heat treatment (hardening in oil followed by low-temperature tempering at 180°C). In this case, the absolute values of α for the optimal laser-processing conditions (regime 1) exceed the readings of the EC instrument for the cases of laser underheating (regimes 2 and 3) and standard bulk heat treatment (regime 5) but are lower than the values for laser processing with surface melting (regime 4), which leads to an increased content of retained austenite.

Table. Eddy-current characteristics of the roller paths of drill-bit leg journals produced from carburized steel 20KhN3A obtained in measurements at different frequencies f

Regime no	Heat treatment	Readings α (divisions) of the EC instrument			
		Roll race		Ball races	
		f = 72 kHz	f = 2.4 kHz	f = 72 kHz	f = 2.4 kHz
1	Laser hardening without melting with an optimal depth h approx. 0.7-0.9 mm (optimal laser processing)	110-128	60-74	76-92	40-50
2	Laser hardening without melting with a reduced depth h approx. 0.2-0.3 mm (underheating)	95-105	32-44	65-74	10-20
3	Laser tempering in the absence of a laser-hardened zone (considerable underheating)	28-40	14-22	22-34	5-13
4	Laser processing with surface melting (overheating)	150-163	78-90	118-130	52-61
5	Double hardening in oil, tempering at 180°C for 2 h (standard heat treatment)	63-74	42-52	44-56	20-30

Discussion

Let us consider the structure, phase composition, microhardness, and abrasive wear resistance of the laser-irradiated zone. It can be seen, that laser melting of the surface of carburized steel 20KhN3A does not guarantee noticeable surface strengthening compared to the standard heat treatment because of the formation of an increased amount of retained austenite and partial surface decarburization. As is shown in [5], when the carbon concentration in the carburized layer of the steel increases to 1.2 wt %, laser processing accompanied by melting may lead to an increase in the concentration of retained austenite to 90 vol %, thus determining a decrease in the microhardness to 2.5 GPa. In the zone of laser hardening without surface melting, the hardness of the carburized layer is higher than the hardness of the initially hardened state and then tempered at 180°C by 1.0-2.0 GPa. The microhardness of laser-hardening-induced martensite exceeds 10 GPa. This is indicated by the results of studying the carburized layer after laser hardening and subsequent treatment with deep cold (Fig. 3a, curves 2). The comparison of curves 1 and 2 in Fig. 3a shows that cooling to -

196°C causes a considerable decrease in the content of austenite in laser-hardened steel (to 5-10 vol %) and a substantial increase in the microhardness to a maximum level of about 10.0 GPa.

It follows from the comparison of curves 1 and 2 (Fig. 3c) that additional treatment with cold at -196°C reducing the content of austenite in the laser-hardened structures has virtually no effect on the character of changes in the wear rate along the direction normal to the laser-hardened carburized layer. An increased level of abrasive wear resistance of the retained austenite corresponding to the wear resistance of high-carbon martensite, which appears directly during laser hardening and the subsequent treatment with cold, is determined by the transformation of austenite into finely dispersed (nanocrystalline) strain-induced martensite [5]. Strain-induced martensite, as well as cooling-induced martensite, is high-carbon untempered martensite characterized by high hardness and substantial ability to be strengthened by means of straining during wear resulting from the development of strain-induced dynamic aging in it. The level of microhardness at the surface of abrasive wear of laser-hardened steel appreciably exceeds the microhardness at the friction surface of hardened and low-tempered carburized steel 20KhN3A [5]. As a result, the structure produced in carburized steel under laser processing and consisting of untempered martensite and metastable retained austenite possesses a higher wear resistance compared to a structure predominantly consisting of tempered martensite (Fig. 3c, curves 1 and 3).

Let us consider EC characteristics of carburized steel subjected to laser hardening and additional treatment with cold. The change in α along the depth of the laser-hardened layer (Fig. 4a) is primarily determined by a decrease in the total level of the residual-austenite content as the distance from the surface of the irradiated specimen increases (Fig. 3a, curve 1). The readings α of the EC instrument are proportional to the generalized EC parameter β_m, which is determined by the values of the initial magnetic permeability and the electrical resistivity of the material ($\alpha \sim \beta_m \sim \sqrt{1/\mu_{r.in}\rho}$ under constant measurement conditions) [7]. It is obvious that a decrease in readings α is related to a prevailing increase in the initial permeability of steel in contrast to a decrease in its resistivity as the amount of retained austenite in the structure decreases.

This character of changes in α along the depth of the laser-hardened layer was qualitatively determined earlier for steel ShKh15, in which the content of retained austenite also decreased with the distance from the specimen surface into its depth and the corresponding attenuation of laser heating [8]. For carburized steel, as opposed to steel ShKh15, a characteristic feature is a variable carbon concentration observed in the surface layer. However, a change in the carbon content in untempered martensite in the range 0.3-0.9 wt % insignificantly affects the level of readings of an EC instrument because of a compensating influence of changes in the initial permeability and resistivity as functions of the carbon concentration in a solid solution. Therefore, the observed changes in the EC characteristics along the depth of the laser-hardened layer (Fig. 4a, curve 1) are evidently associated not with a decrease in the carbon concentration in the carburized layer but mainly with a decrease in the amount of retained austenite. This statement is confirmed by a sharp decrease in readings α after treatment with cold (Fig. 4a, curve 2).

A continuous decrease in the readings α observed in Fig. 4a is a consequence of grinding down of a thicker surface layer during preparation of the laser-melted steel surface for EC measurements with the flat-core transducer, whose locality is worse than that of the protruding-core transducer. Note that (see Fig. 4), in measurements with transducers of both types, the melted zone and the laserhardened zone, which was not melted (zones I and II, respectively, in Fig. 3a), differ greatly in the EC characteristics from the laser-tempered zones and the initial structure of steel 20KhN3A (zones II and IV, respectively, in Fig. 3a). These data point to the possibility of using the EC method to detect wear-resistant laser tracks on the surface of carburized chromonickel steel.

Let us consider influence of tempering on the hardness, abrasive wear resistance, and EC characteristics of carburized steel subjected to laser hardening and treatment with cold. The observed peculiarity of the influence of tempering on the hardness and abrasive wear resistance (Fig. 5a) can be due to a positive effect of metastable retained austenite, whose wear resistance is approximately equal to that of untempered martensite (Fig. 3c, curves 1 and 2), on the wear resistance of tempered steel. Tempering at T = 100-200°C does not change the wear resistance of the γ-phase because, in this range of tempering temperatures, austenite retains stability with respect to deformation-induced decomposition [5]. An appreciable stabilizing influence on the $\gamma \rightarrow \alpha$ transformation rate for carburized chromonickel steel subjected to abrasive action is observed only after tempering at 250°C. Martensite tempered at temperature above 100°C has a lower wear resistance than metastable retained austenite. Therefore, a structure containing an increased amount of retained austenite retains a relatively high wear resistance after tempering at T = 100-200°C, exceeding that for a martensite structure (Fig. 5a). At tempering temperatures above 200°C when retained austenite decomposes, the difference between the wear resistances of the compared structures (Fig. 5a, curves 1 and 2) disappears.

The observed nonmonotonic character of the dependence of readings α on the tempering temperature (with a minimum in values of α at 250-300°C, see Fig. 5b) is determined by the fact that the initial permeability of carburized steel first increases upon heating to 250-300°C and then drops as the tempering temperature increases further.

Note that the transducer with the protruding ferrite core is more sensitive to structural alterations occurring in laser-irradiated carburized steel subjected to subsequent cooling and tempering (Fig. 5b, α_2) than the transducer with the flat end surface (Fig. 5b,α_1). This experimental result combined with the data obtained earlier using a transducer of the considered type for analyzing the laser-strengthened structural medium-carbon steel [6] indicates that it is promising to use a transducer with a protruding core for testing the structural state and physicomechanical properties of metal materials. This transducer has such important advantages as the high locality of analysis and design features extending the capabilities of the EC method for testing curvilinear and out-of-the-way surfaces, including areas directly subjected to wear.

Under the conditions of bench tests (see Fig. 6c), the laser-strengthened journal surface is destroyed in a way similar to the destruction of legs thermally treated according to the standard technology, i.e., via pitting wear of the carburized layer and chipping of collars. The analysis of the character of damage of the carburized layer in bench tests has shown [5] that the enhancement of the durability of drill bits resulting from laser strengthening is associated with an increase in the incubation period before the initiation of pitting wear, i.e., with an increase in the work of crack initiation.

An optimal regime of laser processing of drill-bit legs is irradiation without surface melting. Melting is an extremely undesirable effect because it not only increases the content of retained austenite in a carburized layer but also requires an additional operation, namely, grinding, which is frequently accompanied by surface burns. However, during laser processing in the regime without melting, there is a risk of obtaining an insufficiently deep hardened zone or even not obtaining it at all (in the latter case, a weakened zone of laser tempering is formed on the surface). The aforementioned deviations from the optimal laser-hardening conditions cannot be revealed visually. Therefore, we stated the problem of testing the quality of laser hardening of a drill bits bearing unit by a nondestructive method.

Let us consider EC testing of the quality of laser strengthening of drill-bit leg journals. The data presented in the table shows, that EC method with the use of an attachable transducer with a protruding core can be used to control the quality of laser strengthening of curvilinear races of drill-bit leg journals. An advanced analysis of the data from the table shows that the difference between the average α values for the optimal laser-processing conditions (regime 1) and the regime with a decreased strengthening depth (regime 2) is appreciably larger for the low operating frequency (f = 2.4 kHz) (the differences reach factors of 1.76 and 3.0 for roller and ball races, respectively) than for the high operating frequency (f = 72 kHz) (the differences reach factors of only 1.17-1.21). This is determined by the different thicknesses of the analyzed layers: at a frequency f = 72 kHz, the analyzed depth (approx. 0.17 mm) does not exceed even the underestimated (down to 0.2-0.3 mm) depth of the strengthened layer; at f = 2.4 kHz, in the case of the underestimated depth of the laser-strengthened layer, the zone of electromagnetic analysis (approx. 0.85 mm) covers the weakened zone of laser tempering (Fig. 3a, zone III) characterized by low values of the readings of the EC instrument (Fig. 4). For laser processing with surface melting (regime 4) compared to the optimal regime 1, more substantial differences in the values of α (by factors of 1.34-1.47) are observed for frequency f = 72 kHz than for 2.4 kHz (by 1.25) (see table). The absence of a hardened zone after laser heating (regime 3) causes an abrupt (by factors of 3.0-5.6) decrease in the readings α compared to regime 1 for both operating frequencies, because the electromagnetic characteristics of the laser-hardened and laser-tempered zones differ greatly (Fig. 4). No significant difference in the sensitivities of the EC method for different frequencies is observed when comparing the optimal laser hardening and standard heat treatment - the difference in the average values of α for regimes 1 and 5 is 1.4-1.8 for f = 72 and 2.4 kHz (see table). Hence, the low (f = 2.4 kHz) and high (72 kHz) frequencies should be preferred for revealing the reduced depth of hardening and the melted zone, respectively.

Conclusions

It is shown that the EC method can be used for detecting a wear-resistant layer formed at the surface of carburized chromonickel steel 20KhN3A as a result of laser hardening and subsequent treatment with cold and also for evaluating an abrupt reduction of the abrasive wear resistance observed after low-temperature tempering for steel strengthened with a laser and additionally treated with cold.

When an attachable transducer with a protruding ferrite core characterized by an increased locality was applied, we revealed the high sensitivity of the EC method to structural changes occurring in laser-hardened carburized steel subjected to treatment with cold and tempering to temperatures of 250–300°C. For roller paths of drill-bit leg journals manufactured from steel 20KhN3A, it is established that the EC method can be used to control the quality of laser hardening increasing the resistance of carburized layers to contact–fatigue and abrasive wear. The attachable transducer with a protruding rod ferrite core allows detection of segments with the optimal and decreased (underheated) depths of the laser-hardened zone, with the laser-tempered zone (considerable underheating and the absence of hardening), and with the melted zone (overheating under laser processing) on curvilinear surfaces of roll and ball races. It is desirable to perform EC testing of strengthened parts of drill bits using an electromagnetic-field frequency at which the depth of the analyzed layer approximately corresponds to the optimal thickness of the laser-hardened layer.

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