Metal Science and Heat Treatment, Vol. 55, Nos. 3 – 4, July, 2013 (Russian Original Nos. 3 – 4, March – April, 2013)

TECHNICAL INFORMATION

UDC 620.179.14

CERTIFICATION OF HARDENED SURFACE LAYERS BY MAGNETIC AND ELECTROMAGNETIC METHODS

S. Yu. Mitropol'skaya[1, 2]

Translated from *Metallovedenie i Termicheskaya Obrabotka Metallov*, No. 3, pp. 42 – 48, March, 2013.

The possibilities of certification of hardened surface layers by measurement of coercive force, eddy current inspection and analysis of the field dependence of differential magnetic permeability $\mu_d(H)$ are considered. The advantages of analysis of the pattern of peaks on the $\mu_d(H)$ dependence for estimating the state of surface-hardened steels subjected to subsequent force loading are shown.

Key words: coercive force, eddy current method, field dependence of differential magnetic permeability, carburizing, laser hardening, plastic deformation.

INTRODUCTION

High operating properties can be provided in conventional structural steels with the help of methods of surface engineering. In the recent literature on materials science surface engineering is understood as a field of science and engineering that includes traditional and innovative processes of surface treatment of objects for creating a composite material with properties differing from those of the matrix material or of pure surface. The task of nondestructive inspection of modified surface layers has to be solved [2]. The magnetic properties of surface-hardened articles characterize two subsystems, i.e., a magneticallay soft core and a magnetically hard surface layer. The methods of magnetic and electromagnetic analysis used with allowance for the difference in the electrical and magnetic characteristics of the hardened layer and of the core of the article make it possible to diagnose the thickness and hardness of surface layers. In addition, in many cases they permit estimation of the wear resistance of the surface layer and of the level of the applied stresses, which becomes a base for predicting the operating capacity of the article. The aim of the present work was to show the possibilities of coercive force metering and eddy current methods and of analysis of the field dependence of differential magnetic permeability $\mu_d(H)$ for estimating the condition of steels after laser quenching, carburizing, gas powder facing, and surface deformation, in particular, with allowance for their subsequent temperature and force loading.

[1] Institute for Mechanical Engineering of the Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia (e-mail: mitr@imach.uran.ru).

[2] Ural Federal University in the Name of the First President of Russia B. N. Eltsyn, Ekaterinburg, Russia.

RESULTS AND DISCUSSION

Coercive Force Metering Control of Hardened Surface Layers

Fundamentals of the nondestructive method of inspection of surface-hardened steels with the help of attached electromagnets have been developed in Russia in the war years and in the first years after the war [3 – 5]. The essence of the method is magnetization of the tested article to different depths and obtainment of data on the magnetic properties at different distances from the surface.

To control the hardness the magnetic flux should permeate only the surface layer. To control the thickness of the hardened layer with the help of an attached Π-shape electromagnet a part of the core of the article is magnetized in addition to the surface layer. Growth in the thickness of the hardened layer is accompanied by increase in the demagnetization current of the coercive force meter I_{dc}, which is proportional to the coercive force H_c of the tested article. The higher the hardness of the layer the greater the coercive force. Successful application of the method involves preliminary determination of the correlation dependences of the outlet parameter of the device on the initial characteristics [6]. The more substantial is the difference between the coercive force of the hardened layer and the coercive force of the core, the more reliable is the result of the inspection.

It has been shown that the coercive force of a carburized layer and of the core can differ after quenching by more than a factor of 10 [7]. To control the quality of the carburization machine-building enterprises have long employed coercive force meters of type KIFM with attached electromagnets, the experience of the operation with which is generalized in [8, 9]. For simultaneous control of the thickness and hardness of quenched carburized layers on parts of drill bits from steels 17KhN2 and 20KhN3A, plunger blades from steel 20, and many other parts it is sufficient to use only one attached electromagnet. Ample statistical material gas been gathered in the production flow and used to plot two-parameter dependences of demagnetization current I_{dc}; the range of readings of the coercive force meter corresponding to the admissible values of the hardness and thickness of the layer on the article is determined. To determine the thickness and the hardness of the hardened layer individually, at least two attached electromagnets are used successively, which lowers the efficiency of the inspection.

It is known that the coercive force of a hardened layer obtained by HFC treatment is 2 – 4 times higher than the coercive force of the core [7]. To control the layers on articles hardened after heating by high-frequency currents, in particular on crankshafts from steels 45 and 40KhFA, it is necessary to use two attached electromagnets, one for controlling the hardness and the other for controlling the thickness of the layer [10].

It has been shown that the magnetic characteristics measured in particular cycles of magnetic hysteresis in weak magnetic fields are sometimes more sensitive to the thickness of the hardened layer than the characteristics determined for the major hysteresis loop [7]. This makes it possible to lower substantially the energy intensity of sensing devices.

The method of metering coercive force is suitable for certifying the surface layers reinforced by cold plastic deformation. The readings of a coercive force meter Ipc increase upon growth in the force of roll burnishing of bars from steel 10, axles from steel 35 and other articles with an initial ferrite-pearlite structure [11].

As a result of a hardening friction treatment of the surface of steel St3 by a hard-alloy indenter under the conditions of sliding friction the coercive force H_c over the major loop of magnetic hysteresis has been shown to grow by 30 – 70% with respect to the coercive force in the initial annealed state [12]. This effect is explainable by considerable refining of the structure of the surface layer with a thickness of 70 μm and marked growth in the dislocation density in the layer accompanied by elevation of the surface microhardness from 1.68 to 4.25 GPa. The coercive force h_c measured in weak

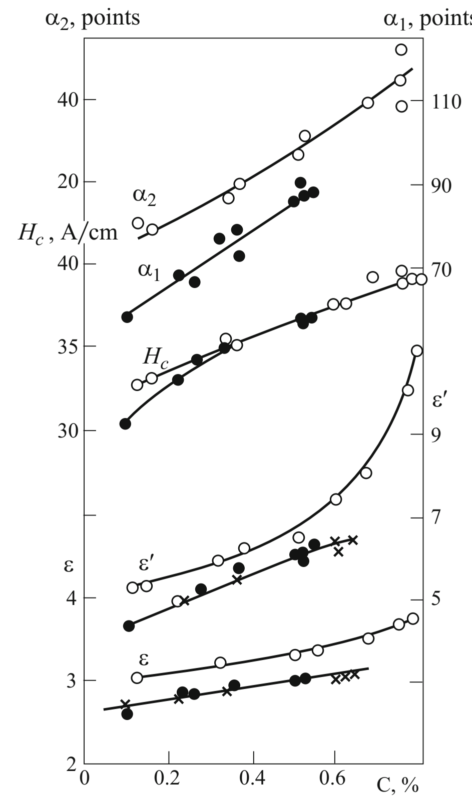

Fig. 1. Dependence of wear resistance ε (tests against corundum) and ε′ (tests against silica), of the coercive force H_c and of readings of an eddy current device α_1 and α_2 on the content of carbon in martensite of quenched and low-tempered steels: ●, ×) 65G; ○) U8; ○, ●) quenching after heating in the furnace; ×) laser hardening [13].

magnetic fields for particular loops of magnetic hysteresis at maximum magnetic induction $b_{max} \leq 0.1$ T is even more sensitive to friction treatment. This characteristic has grown in experiments by 100% [12].

Actually, surface deformation hardening is also applied to parts with a structure of tempered martensite. In this case metering of the coercive force is complicated, because cold plastic deformation of the surface of a preliminarily heat treated steel does not cause noticeable growth in the coercive force H_c but frequently causes its decrease [8].

It is shown in [13, 14] that the method of coercive force metering is effective for estimating the wear resistance of structural and tool steels including those subjected to carburizing and laser hardening. This approach has been developed on the basis of the high sensitivity of coercivity to the content of carbon in the α-solid solution. It is known that it is just the content of carbon in the α-solid solution which determines to a considerable degree the resistance of hardened steels to abrasive and adhesive wear [15]. The possibility of estimation of the wear resistance of steels 65G and U8 from growth in coercive force H_c is illustrated by Fig. 1 [13]. The coefficient of correlation between the values of H_c and wear resistance in tests against corundum for both steels is 0.98.

The detected similarity of the dependences of wear resistance and coercive force on the content of carbon in martensite has made it possible to develop a nondestructive method for checking the wear resistance of hardened and low-tempered steels [16] from the value of the coercive force.

Eddy-Current Method

Eddy-current inspection of articles hardened by methods of surface engineering is aimed primarily at determining the thickness of the heat-hardened layer on steels [17, 18] or cast irons [19]. The authors of [20] have suggested a method for eddy-current estimation of the thickness of coatings of the Cr – Ni and Cr – Ni – Co systems formed on steel St3 by the method of gas-powder laser deposition. It is known [21] that at a fixed frequency and weak excitation fields corresponding to the Rayleigh domain, the eddy-current parameter α of ferromagnetic materials is determined by the values of effective magnetic permeability μ_{eff} and electric resistivity ρ, i.e.,

$$\alpha \sim \sqrt{\frac{1}{\mu_{eff}\,\rho}}\,. \tag{1}$$

Decrease in the permeability by more than tens of times upon transition from a highly ferromagnetic matrix to a weakly magnetic γ-solid solution based on nickel or to an α-solid solution (Co – Ni) of the coating prevails over growth in the electric resistivity of the material. For this reason the values of the eddy-current parameter for all the studied types of laser facings grow continuously with the thickness of the coating.

In works [13, 14, 22] the eddy current method is applied successfully not only for estimating the structural state and the hardness but also for predicting the wear resistance of steels subjected to laser hardening followed by heat treatment. Work [13] is devoted to determining a linear relation between the parameter α and the content of carbon in martensite for steels 65G and U8 (Fig. 1). This has been used as a physical foundation for estimating the wear resistance of articles from steels 65G and U8 by the eddy current method.

An important advantage of laser hardening is the possibility to eliminate subsequent tempering and to find application for hardened steels with a structure possessing maximum wear resistance [23]. However, tempering may occur in subsequent welding, grinding, or friction heating. A marked decrease in readings α of the eddy current device allows us to predict lowering of the wear resistance of steels ShKh15 [14] and 65G [13] hardened after laser heating due to tempering in the range of 100 – 300°C as a result of the production process or operational effects.

Analysis of Field Dependence of Differential Magnetic Permeability

The problem of separate certification of the hardened surface layer and of the core of an article can be solved in many cases with allowance for the special features of reversal magnetization of two-layer ferromagnetics. It is known that the loops of magnetic hysteresis of a two-layer ferromagnetic have characteristic inflections, and the dependences of the differential magnetic permeability μ_d on the intensity of the reversal magnetization field H has as many maximums as many different ferromagnetic layers the article has [24]. The field of maximum differential permeability $H(\mu_{d\max})$ of a layer virtually coincides with the value of its coercive force H_c.

Field dependences of differential permeability $\mu_d(H)$ are commonly obtained using standard three-point differentiation with respect to the field of descending or ascending branches of the major loops of magnetic hysteresis, i.e.,

$$\mu_d = \lim_{\Delta H \to 0} \frac{\mu_0\,\Delta M}{\Delta H} = \frac{\mu_0\,dM}{dH}\,, \tag{2}$$

where $\mu_0 = 4p \times 10^{-7}$ H/m is the magnetic constant, M is the magnetization, and H is the intensity of the magnetic field.

The principles for analyzing the field dependence of differential permeability $\mu_d(H)$ have been developed in the works of E. S. Gorkunov with coauthors in the 1980s. According to them the height of the peak and the field of the peak of magnetic permeability are suitable for estimating the thickness and the hardness of the respective layer; the thicker the layer the higher the higher the respective peak other conditions being equal; the higher the hardness (and the magnetic hardness) of the layer the stronger the magnetic field in which its peak of differential magnetic permeability is localized. The same principles have been used by American authors in [26] for determining the thickness of a layer obtained by induction hardening (up to 3.3 mm thick) or carburizing (up to 1.6 mm thick) on a number of low- and medium-carbon low-alloy steels.

Figure 2 presents the ascending branches of major loops of magnetic hysteresis and the field dependences of the differential magnetic permeability of cylindrical test pieces of steel 45 after normalizing and heat hardening by irradiation of a continuous CO_2-laser [27]. Here and below we present only those parts of the field dependences where the permeability maximums form.

Figure 3 [28] presents the special features of the obtained layer responsible for the observed bimodal field dependence of differential magnetic permeability $\mu_d(H)$ in a field of 1.3 kA/m corresponding to a hardened surface layer and in a field of about 0.6 kA/m corresponding to a ferrite-pearlite core. The presence of a transition zone between the layer and the core smears the boundary between the two peaks, where the permeability remains considerably higher than the background value. This can be proved by successive removal of a thin layer from the surface of the test pieces. Figure 4*a* presents the field dependences of differential magnetic permeability of steel 45 at different distances from the surface of a test piece after laser treatment. It can be seen that as a result

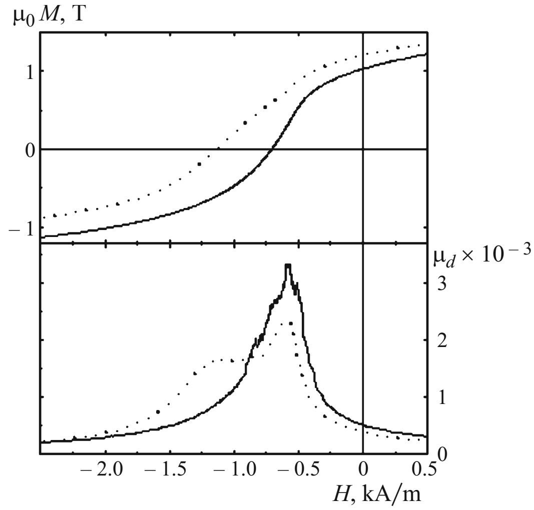

Fig. 2. Descending branches of major loops of magnetic hysteresis and field dependences of differential magnetic permeability $\mu_d(H)$ for steel 45 in normalized condition (the solid lines) and after laser heat hardening (the dashed lines) [27].

of removal of a layer the peak in the region of stronger force fields is much lower, because the volume of the hardened layer decreases and so does the coercive force H_c of the test piece (Fig. 4*b*). Similar changes have been observed as a result of removal of a layer with a thickness of 0.8 and 1.5 mm from the surface of carburized test pieces of steel 20 [29].

Effect of Force Loading of Surface-Hardened Steels on Field Dependence of Differential Magnetic Permeability

It is known that the deformation behavior of surface-hardened materials differs from that of homogeneous ones [30]. The total strains on the surface and in the bulk of a material under a load and after unloading are the same but the arising stresses differ [31]. To design multilayer components of structures (shells) by methods of building mechanics we should have accurate data on the stress state of every layer, which may vary in operation. This problem can be solved by measuring magnetic characteristics with the aim to determine the relation between them and the active stresses and then to estimate the remaining life. However, measurements of the coercivity H_c give little relevant information, because H_c of a multilayer ferromagnetic is not a physical parameter of the material in the conventional sense but is a quantity characterizing the demagnetization current at which the magnetic fluxes of the layers are mutually compensated [32].

Until recently, plotting of dependence $\mu_d(H)$ has been a complex methodological problem due to the long time and low accuracy of measurements. Modern facilities for magnetic measurements make it possible to record magnetic hysteresis loops fast and in detail and the applied softwares provide accurate plotting of functions $\mu_d(H)$. This allows us to study the evolution of peaks of differential magnetic permeability under force loading in order to monitor the state of every layer of an article in operation.

Figure 5*a* generalizes the evolution of the field dependence $\mu_d(H)$ under the action of applied tensile stresses normalized to the value of the yield strength for a series of test pieces of steel 45 after laser heat hardening [27 – 29]. The magnetic measurements were performed when the specified values of the tensile stress were attained and the test piece was unloaded. It can be seen from Fig. 5*a* that under the action of $0.95\sigma_{0.2}$ the permeability of the core decreases substantially, while that of the surface layer increases. To explain this interesting effect we should understand that in fact

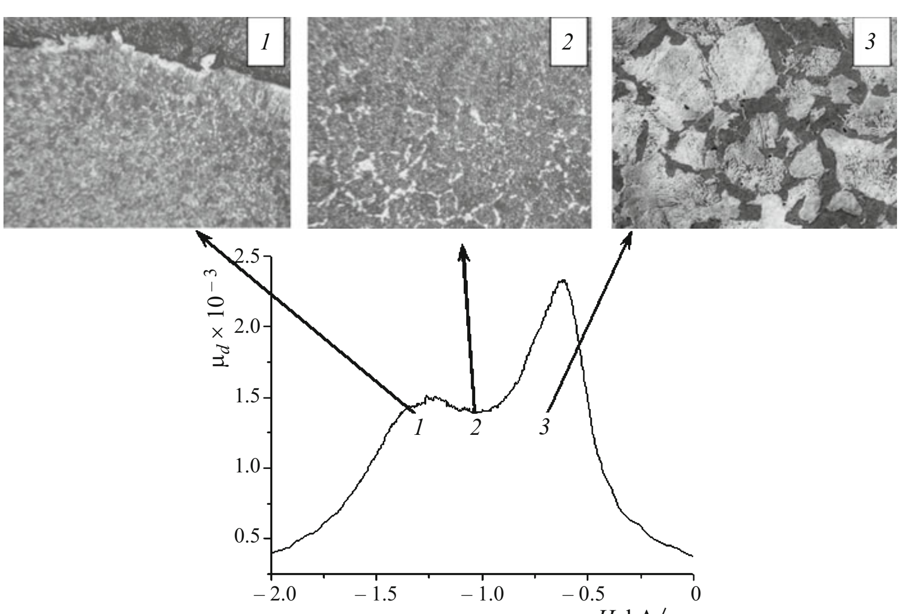

Fig. 3. Microstructure magnified to × 240 (*1*, *2*) and × 1500 (*3*) and field dependence of differential magnetic permeability $\mu_d(H)$ for steel 45 after laser heat hardening [28]: *1*) surface layer; *2*) transition zone; *3*) core of the test piece.

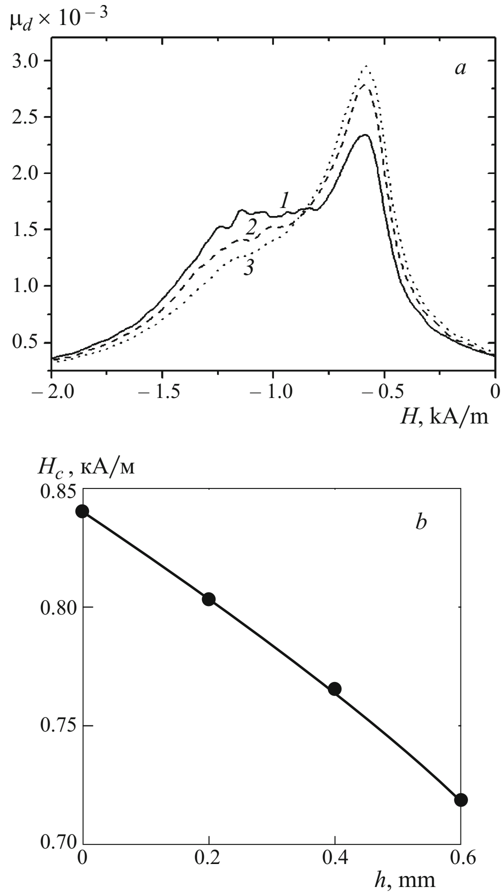

Fig. 4. Field dependences of differential magnetic permeability $\mu_d(H)$ (*a*) and variation of coercivity H_c over the thickness of the surface layer (*b*) of steel 45: *1*) after laser heat hardening; *2*, *3*) after removal of a surface layer with thickness $h = 0.4$ and 0.6 mm, respectively.

a specimen with a hardened surface consists of two different materials, i.e., a hardened surface layer and a ferrite-pearlite core, the mechanical properties of which differ. The yield strength $\sigma_{0.2}$ determined for such a specimen does not match either of these materials but represents a mean value. For this reason, the stresses below the yield strength $\sigma_{0.2}$ in a laser-treated test piece can exceed the yield strength of its core. This is proved by the results of structural studies and hardness metering and by computations of stresses in each of the layers [33], which have shown that under the action of stresses equal to $0.95\sigma_{0.2}$ the core is strain hardened and its magnetic permeability decreases regularly.

In the plastic tension range ($\sigma \geq 1.05\sigma_{0.2}$) the permeability of the whole of the material decreases considerably and the bimodal field dependence $\mu_d(H)$ transforms into a curve with one maximum (Fig. 5*a*) typical for homogeneous specimens not subjected to surface hardening. It has been shown that the bimodal field dependence $\mu_d(H)$ is lost against formation of numerous microcracks and micropores in the surface layer and in the transition zone of the specimens tested for the action of tensile stresses $\sigma = 1.05\sigma_{0.2}$ (Fig. 5*b*); then the contribution of the hardened layer into the processes of reversal magnetization is lowered. Weakening of the contribution of the hardened surface layer into the measured magnetic characteristics upon growth in the total level of deformation of the test piece has been detected [12] under cyclic loading for steel St3 after a hardening friction treatment.

CONCLUSIONS

Principles and examples of the use of coercive force metering and of the eddy current method for certifying the thickness, hardness and wear resistance of hardened layers including their subsequent temperature loading are considered. It is shown that analysis of the field dependence of differential magnetic permeability $\mu_d(H)$ for monitoring the states of the hardened surface layer and of the core of an article under force loading is more advantageous than measurement of the coercivity H_c. The loss of bimodal dependence $\mu_d(H)$ is an indicator of accumulation of damage under the action of stresses exceeding the yield point.

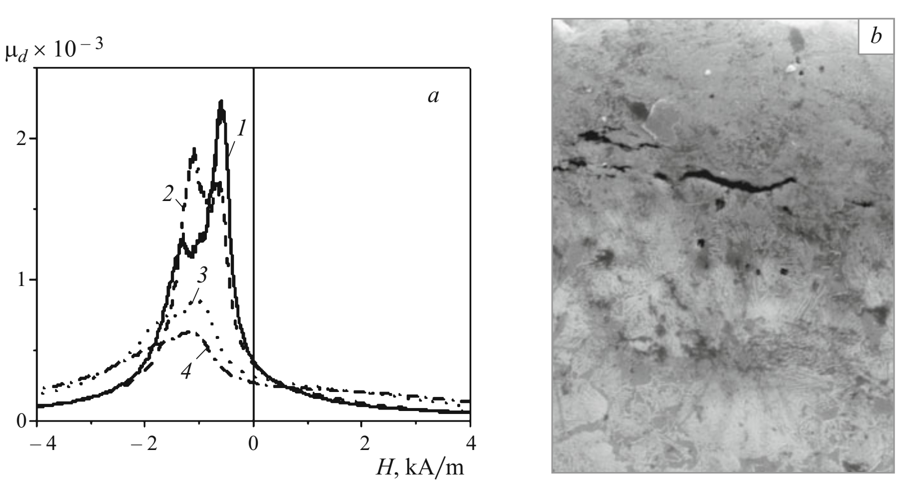

Fig. 5. Evolution of the field dependence of differential magnetic permeability $\mu_d(H)$ (*a*) and a microcrack in the surface layer (*b*, × 3000) formed due to tensile deformation of steel 45 after laser heat hardening: *1*) prior to loading; *2*, *3*, *4*) after loading at $0.95\sigma_{0.2}$, $1.05\sigma_{0.2}$, and $1.3\sigma_{0.2}$, respectively.

REFERENCES

1. B. A. Proskuryakov, *Technological Reference Dictionary on Surface Engineering* [in Russian], Mashinostroenie, Moscow (2006), 368 p.
2. T. Bell, “Fundamentals of surface engineering,” *Mater. Eng.*, **1**(1), 37 – 52 (1989).
3. N. N. Mikheev, “A magnetic method for controlling the thickness of quenched, carburized, nitrided and decarburized layers on steel parts,” *Izv. Akad. Nauk SSSR (OTN)*, Nos. 5 – 6, 53 – 68 (1943).
4. M. N. Mikheev, “Magnetic properties of carburized and nitrided steels,” *Zh. Teor. Fiz.*, **15**(9), 677 – 680 (1945).
5. M. N. Mikheev, P. I. Zimnev, and K. E. Miloslavskii, “Control of the depth of carburization and quality of heat treatment with the help of a coercive force meter,” *Vestn. Mashinostr.*, Nos. 6 – 7, 70 (1945).
6. V. V. Klyuev (ed.), *Devices for Nondestructive Inspection of Materials and Articles. A Handbook* [in Russian], Mashinostroenie, Moscow (1986), Book 2, 488 p.
7. V. E. Shcherbakov and E. S. Gorkunov, *Magnetic Control of the Quality of Metals* [in Russian], UrO RAN, Ekaterinburg (1996), 264 p.
8. G. V. Bida, “Magnetic control of the depth and hardness of surface-hardened layers on articles,” *Defektoskopiya*, No. 5, 10 – 28 (2006).
9. G. V. Bida and A. P. Nichiporuk, “Coercive force measurement in nondestructive checking,” *Defektoskopiya*, No. 10, 3 – 28 (2000).
10. M. N. Mikheev, G. V. Bida, V. N. Kostin, et al., “Checking the depth and hardness of HFC-hardened layers on automotive crankshaft necks,” *Defektoskopiya*, No. 8, 12 – 17 (1985).
11. I. M. Shif and B. M. Neizvestnov, “Magnetic control of hardening of the surface plastically deformed layer of steel parts,” *Defektoskopiya*, No. 6, 27 – 35 (1965).
12. A. V. Makarov, R. A. Savray, E. S. Gorkunov, et al., “Effect of hardening friction treatment on the special features of magnetic and eddy-current control of annealed structural steel subjected to cyclic loading,” *Defektoskopiya*, No. 7, 75 – 92 (2008).
13. E. S. Gorkunov, V. M. Somova, A. V. Makarov, et al., “Magnetic and electromagnetic methods of estimation of wear resistance of steel articles,” *Defektoskopiya*, No. 6, 33 – 39 (1995).
14. A. V. Makarov, E. S. Gorkunov, L. Kh. Kogan, et al., “Eddy-current and coercivity-metering control of abrasive wear resistance of steel ShKh15 subjected to laser and volume heat treatment,” *Defektoskopiya*, No. 10, 3 – 16 (2006).
15. L. G. Korshunov, A. V. Makarov, and A. L. Osintseva, “A study of wear resistance and structural transformations in abrasive wear of laser-hardened steel U8,” *Trenie Iznos*, **9**(1), 52 – 59 (1988).
16. E. S. Gorkunov, A. V. Makarov, L. G. Korshunov, et al., “A method for determining the wear resistance of steels and alloys, RF Patent 2069343, MKI G 01 N 3/58,” *Byull. Izobr. Polezn. Modeli*, No. 32 (1996).
17. I. I. Mal’ko, N. N. Zatsepin, and V. E. Maksimkov, “Eddy-current control of the depth of a layer hardened after laser treatment on articles from steels Kh12M, 45, U10, and ShKh15,” *Defektoskopiya*, No. 1, 95 – 96 (1989).
18. D. Schneider and B. Brenner, “Zerstörungsfreie Bestimmung der Einhärtungstiefe des lasergehärteten Stahls X20Cr13 mit Ultraschall-Oberflächenwellen,” *Neue Hütte*, **34**(10), 374 – 378 (1989).
19. S. Kahrobaee and M. Kashefi, “Hardness profile plotting using multi-frequency multi-output electromagnetic sensor,” *Nodestr. Test. Eval. Int.*, **44**, 335 – 338 (2011).
20. A. V. Makarov, E. S. Gorkunov, I. Yu. Malygina, et al., “Eddy-current control of the hardness, wear resistance and thickness of coatings obtained by the method of gas-powder laser deposition,” *Defektoskopiya*, No. 11, 68 – 78 (2009).
21. V. V. Dyakin and V. A. Sandovskii, *The Theory and Design of Attached Eddy-Current Converters* [in Russian], Nauka, Moscow (1981), 136 p.
22. A. V. Makarov, L. Kh. Kogan, E. S. Gorkunov, Yu. M. Kolobylin, “Eddy-current control of wear resistance of carburized chromium-nickel steel 20KhN3A,” *Defektoskopiya*, No. 2, 67 – 78 (2001).
23. A. V. Makarov, L. G. Korshunov, and A. L. Osintseva, “Effect of tempering and friction heating on the wear resistance of laser-hardened steel U8,” *Trenie Iznos*, **12**(5), 870 – 878 (1991).
24. M. N. Mikheev and E. S. Gorkunov, *Magnetic Methods of Structural Analysis and Nondestructive Check* [in Russian], Nauka, Moscow (1993), 252 p.
25. E. S. Gorkunov, B. M. Lapidus, A. V. Zagainov, et al., “A study of differential magnetic permeability for checking the quality of surface hardening,” *Defektoskopiya*, No. 7, 7 – 13 (1988).
26. C. Zhang, N. Bowler and C. Lo, “Magnetic characterization of surface hardened steel,” *J. Magn. Magn. Mater.*, **321**, 3878 – 3887 (209).
27. E. S. Gorkunov, S. Yu. Mitropol’skaya, S. M. Zadvorkin, et al., “Effect of laser surface hardening on magnetic characteristics of carbon steel under loading conditions,” *Defektoskopiya*, No. 8, 58 – 66 (2008).
28. E. S. Gorkunov, S. Yu. Mitropol’skaya, A. L. Osintseva, and D. I. Vichuzhanin, “A study of strain and an evaluation of stresses in materials with hardened surface layers by magnetic methods,” *Fiz. Mezomekhan.*, 12(2), 95 – 104 (2009).
29. E. S. Gorkunov, S. Yu. Mitropol’skaya, E. M. Groznaya, et al., “Effect of elastoplastic loading on magnetic properties of steel 20 hardened by gas carburizing,” *Defektoskopiya*, No. 4, 3 – 16 (2011).
30. S. V. Panin, “Laws of plastic deformation and fracture at the mesolevel of materials with coatings and surface hardening,” *Fiz. Mezomekhan., Special Issue*, **7**(1), 109 – 1123 (2004).
31. M. A. Shtremel, *The Strength of Alloys, Part II, Deformation* [in Russian], MISiS, Moscow (1997), 527 p.
32. V. M. Dekhtyar, “About the coercivity of a two-layer cylinder,” *Zh. Eksp. Teor. Fiz.*, Issue 10, 2 – 7 (1946).
33. E. S. Gorkunov, S. M. Zadvorkin, I. G. Emel’yanov, and S. Yu. Mitropol’skaya, “Laws of variation of magnetic characteristics of two-layer articles from carbon steels under tension,” *Fiz. Met. Metalloved.*, **103**(6), 657 – 666 (2007).