

ELECTROMAGNETIC TESTING OF PHASE COMPOSITION, HARDNESS AND WEAR RESISTANCE ON NITROGEN- AND CARBON-CONTAINING HIGH-CROMIUM STEELS

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Introduction

The development of the steels with increased nitrogen content (“high nitrogen steels – HNS”) is a promising direction of creation of economically alloyed high strength wear- and corrosion-resistant materials [1-4]. The casting under nitrogen pressure (counter-pressure casting technique) allows to avoid using of expensive alloying elements (first of all, nickel) and, due to addition of strong austenite former nitrogen, form in Fe-Cr-N system steels fully austenitic structure with no deterioration of corrosion behavior and providing with low magnetic conductivity of austenitic steels. There is a great deal of data stored in scientific literature about strength, corrosive and tribological properties of HNS [1-7]. However, insufficient attention is devoted to physical properties of HNS and the possibilities of nondestructive testing of their chemical and phase composition, hardness and wear resistance.

In the present work electromagnetic properties, phase composition, hardness and abrasive wear resistance of two high-nitrogen steels produced with counter-pressure casting technique are investigated. The steels are Kh19A1.0 cast steel (in wt.%, 1.00 N, 0.07 C, 19.02 Cr, 0.17 Mn) and Kh22GA1.24 hot deformed steel (in wt.%, 1.24 N, 0.08 C, 22.20 Cr, 1.38 Mn). For the purpose of comparison the industrially produced carbon-containing 95Kh18 steel (in wt.%, 1.00 C, 17.72 Cr, 0.48 Mn) is studied. Specimens with dimensions of 5.4×5.4×61 mm were oil quenched from temperatures of 950-1200°C. Hardness of the specimens was measured using Rockwell technique. The basic magnetic characteristics were determined by means of Remagraph C-500 setup, the electrical resistivity – using technique described in [8], the parameters of signal of double resonance electromagnetic-acoustic transduction (EMAT) – using technique described in [9], eddy-current characteristics – using technique described in [8]. Phase composition was determined using magnetic analysis method. Relative abrasive wear resistance (with respect to wear resistance of armco-iron) was investigated under wear over fixed abrasive (electrocorundum with 160 µm grain).

Results

Experimental results are presented in Fig. 1 and Fig. 2. Fig. 1a shows that hardness of the steels changes nonmonotonically with the increase of quenching temperature and has its maximum at $T_{\text{quench}}=1050-1100^{\circ}\text{C}$. Quenching temperature rise causes the increase of residual austenite portion up to 100 vol.% (Fig. 1b). While the austenization temperature of the investigated high-chromium steels increases, it is observed the decrease of saturation magnetization (Fig. 1c), maximal magnetic conductivity (Fig. 1d), remanence (Fig. 1f), informative parameters of EMAT – the amplitude of resonance signal and the velocity of null mode of longitudinal normal acoustic wave (Fig. 2a, b), initial magnetic conductivity (Fig. 2c) as well as the increase of coercive force (Fig. 1e) and readings of eddy-current instrument (Fig. 2e). Likewise hardness, the electrical resistivity changes nonmonotonically with the increase of quenching temperature (Fig. 2d) Abrasive wear resistance of the steels increases with quenching temperature rise. However, at maximal quenching temperatures one can see some decrease of abrasive wear resistance of the steels (Fig. 2f).

Fig. 3 shows, that eddy-current method can be used for evaluation of changes of abrasive wear resistance of high-chromium steels for quenching temperature range of $T_{\text{quench}}=950-1125^{\circ}\text{C}$ for which unambiguous correlation relationships between wear resistance ε and the readings of eddy-current instrument α of Kh19A1.0 and 95Kh18 steels are established. Eddy-current method

can be also used for testing of wear resistance of high-chromium steels after quenching from higher temperatures (1150-1200°C) causing formation of fully austenitic metal matrix with different stability to deformation $\gamma \rightarrow \alpha'$ transformation under wear, different amount of undissolved nitride phases and, correspondingly, different wear resistance level.

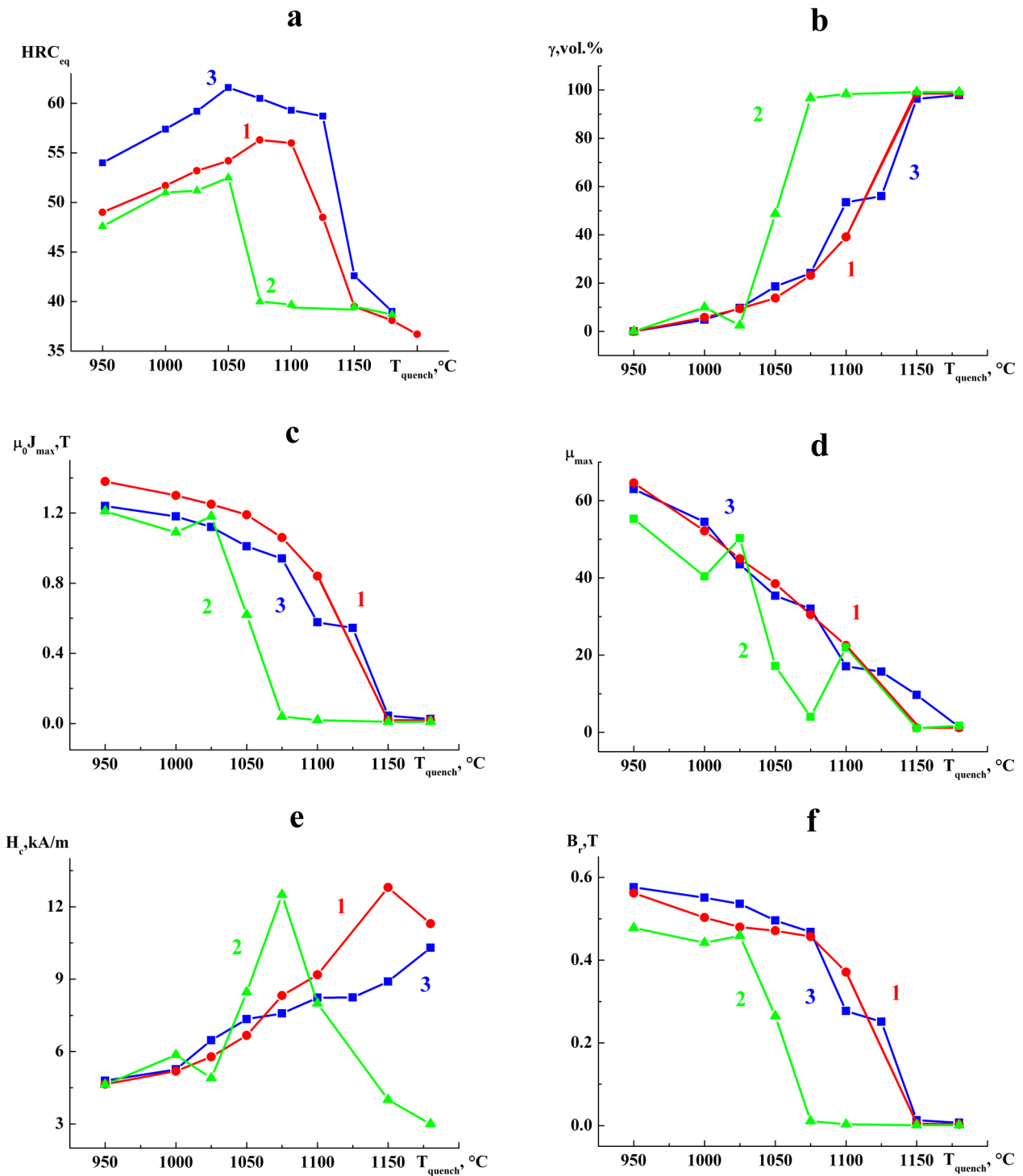


Fig. 1. The influence of quenching temperature on hardness HRC_{eq} (a), amount of residual austenite γ (b), saturation magnetization $\mu_0 J_{\text{max}}$ (c), H_c maximal magnetic conductivity μ_{max} (d), coercive force (e) and remanence B_r (f) of Kh19A1.0 (1), Kh22GA1.24 (2) and 95Kh18 (3) steels: μ_0 is the magnetic constant

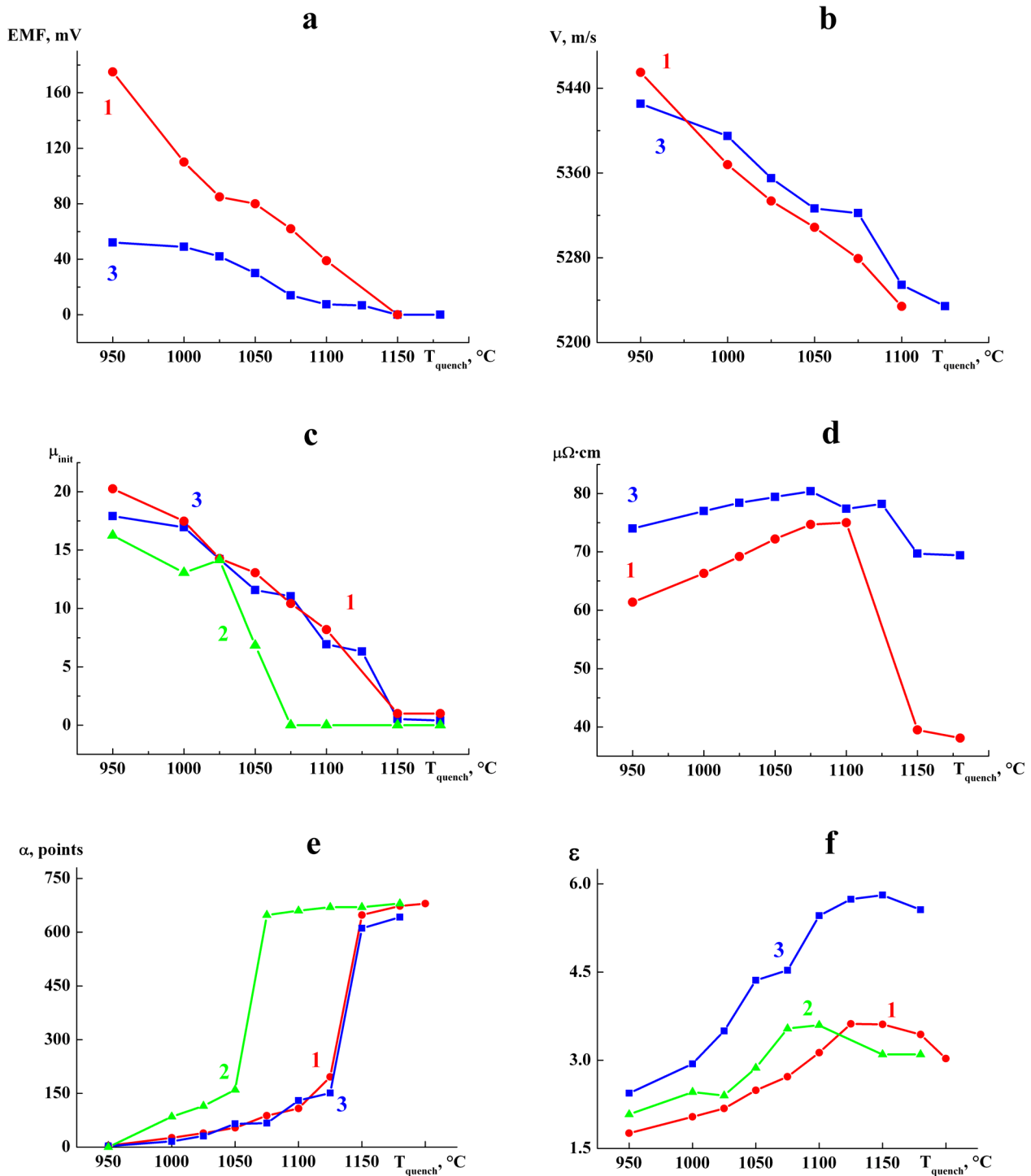


Fig. 2. The influence of quenching temperature on resonance EMAT signal amplitude (a), velocity of a longitudinal acoustic wave V (b), initial magnetic conductivity μ_{init} (c), electrical resistivity ρ (d), readings of eddy-current instrument α (e) and abrasive wear resistance ε (f) of Kh19A1.0 (1), Kh22GA1.24 (2) and 95Kh18 (3) steels.

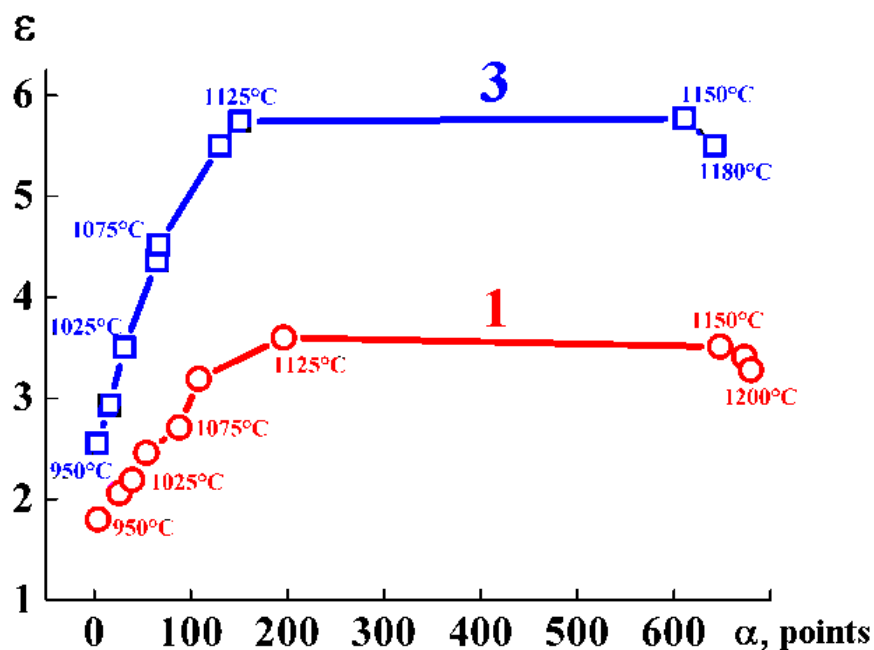


Fig. 3. Correlation relationships between abrasive wear resistance under wear over corundum ϵ and the readings of eddy-current instrument α for Kh19A1.0 (1) and 95Kh18 (2) steels: numbers beside the curves denote quenching temperatures

Discussion

The noted increase of residual austenite amount in structure of high nitrogen steels with quenching temperature rise more than 950°C (see Fig. 1b) is caused by Cr_2N nitride phase dissolution and higher saturation of solid solution with chromium and very strong austenite former nitrogen. In Kh19A1.0 cast steel with 1.00 wt.% of nitrogen fully austenitic matrix is formed during quenching from higher temperature ($T_{\text{quench}}=1150^\circ\text{C}$) than in Kh22GA1.24 hot deformed steel ($T_{\text{quench}}=1075^\circ\text{C}$, see Fig. 1b) despite the higher nitrogen content (1.24 wt.%) in Kh22GA1.24 steel. This is a consequence of delayed nitride phase dissolution in cast structure during heating of the steel for quenching. In carbon-containing 95Kh18 steel more complete Cr_{23}C_6 carbide dissolution occurs with austenization temperature increase. This lowers martensitic transformation start temperature M_s of 95Kh18 steel and leads to formation of fully austenitic metal matrix at $T_{\text{quench}}=1150^\circ\text{C}$ (see Fig. 1b). Therefore, in industrially produced 95Kh18 steel and nitrogen-containing Kh19A1.0 cast steel which contains approximately equal amount of interstitial (carbon or nitrogen) and substitution (chromium) elements, the formation of fully austenitic structure takes place at the same quenching temperature, namely $T_{\text{quench}}=1150^\circ\text{C}$ (see Fig. 1b).

The observed in Fig. 1a nonmonotonic (with maximum) trend of dependencies of high-chromium nitrogen- and carbon-containing steels hardness on heating temperature for quenching is determined by dissolution processes of nitride and carbide phases and corresponding increase of martensite strength as well as rise of residual austenite amount. Maximal hardness is achieved at $T_{\text{quench}}=1075^\circ\text{C}$ for Kh19A1.0 steel (56 HRC_{eq}) and at $T_{\text{quench}}=1050^\circ\text{C}$ for Kh22GA1.24 (52 HRC_{eq}) and 95Kh18 (61 HRC_{eq}) steels when along with high-nitrogen and high-carbon martensite, residual austenite is present in structure in amount of 10-20 vol.% (in Kh19A1.0 and 95Kh18 steels) and 45 vol.% (in Kh22GA1.24 steel). When metal matrix is fully austenitic hardness of the steels decreases to values of 37-39 HRC_{eq} (see Fig. 1a).

The increase of non-ferromagnetic γ -phase amount and corresponding decrease of ferromagnetic α -phase portion observed with the rise of quenching temperature can be used to explain clearly seen strong decrease of saturation magnetization (see Fig. 1c), maximal magnetic conductivity (see Fig. 1d), remanence (see Fig. 1f) and EMAT parameters – the amplitude of resonance signal and the velocity of null mode of longitudinal normal acoustic wave (see Fig. 2a, b). The increase of coercive force with the rise of quenching temperature (see Fig. 1e) is caused by

saturation of martensite with carbon and nitrogen and also the rise of amount of non-ferromagnetic residual austenite inclusions which make magnetization and magnetization reversal more difficult. Higher values of coercive force at $T_{\text{quench}}=1075-1100^{\circ}\text{C}$ for Kh19A1.0 steel (see Fig. 1e) result from the presence of large amount of undissolved nitrides in the cast nitrogen-containing steel.

Shown in Fig. 2e regularities of changes with quenching temperature rise of eddy-current characteristics of the high-chromium steels correlate well with the change of residual austenite content in the steels (see Fig. 1b).

The results presented show that mentioned magnetic and electromagnetic characteristics can be used as testing parameters of phase composition and hardness of nitrogen- and carbon-containing high-chromium steels and quality of their quenching in the wide range of austenization temperatures. It is important to note that for the steel with nitrogen Kh19A1.0 higher sensitivity of resonance EMAT signal amplitude to phase composition is noticed than for 95Kh18 steel (see Fig. 2a).

The electrical resistivity change depending on quenching temperature (see Fig. 2d) coincide well with hardness change of the steels (see Fig. 1a) and can be used for determination of their strength characteristics together with magnetic ones. Fig. 2d shows that martensite-austenite-nitride structures in Kh19A1.0 steel differ in lower electrical resistivity values than martensite-austenite-carbide structures in 95Kh18 steel.

For the three steels under consideration it is established nonmonotonic (with maximum) change of abrasive wear resistance with the quenching temperature rise within the range of $950-1200^{\circ}\text{C}$ (see Fig. 2f). Abrasive wear resistance of the steels increases with the quenching temperature rise and reaches its maximal values at $T_{\text{quench}}=1075^{\circ}\text{C}$ for Kh22GA1.24 steel and $T_{\text{quench}}=1125-1150^{\circ}\text{C}$ for Kh19A1.0 and 95Kh18 steels. Thus, the highest wear resistance levels are observed if there is 50-100 vol. % residual austenite in the steels. The residual austenite forms in Kh22GA1.24 hot deformed steel at lower quenching temperatures than in Kh19A1.0 cast steel and 95Kh18 steel (see Fig. 1b). The noted increase of abrasive wear resistance of the steels with the quenching temperature rise is caused by saturation of α - and γ -solid solutions with carbon, nitrogen and chromium. The higher wear resistance of residual austenite in the high-chromium steels under consideration is connected with its intensive strengthening and partial transformation to high-strength deformation α' -martensite under wear as well as with positive influence of residual austenite on fracture toughness. The observed decrease of wear resistance for maximal quenching temperatures results from increase of stability of nitrogen austenite to deformation $\gamma \rightarrow \alpha'$ transformation under abrasive wear. For all quenching temperatures the considered high-nitrogen steels are substantially inferior in abrasive wear resistance to high-carbon 95Kh18 steel.

Conclusions

When changing the quenching temperature within the range of $950-1200^{\circ}\text{C}$ it is established nonmonotonic (with maximum) change of hardness and abrasive wear resistance of high-chromium steels containing 1.00-1.24 wt.% of nitrogen and 1.00 wt.% of carbon. The observed dissolution of nitride and carbide phases upon quenching temperature rise, which leads to saturation of solid solution with nitrogen, carbon and chromium and corresponding increase of non-ferromagnetic γ -phase amount, causes decrease of saturation magnetization, maximal magnetic conductivity, remanence and informative EMAT parameters – the amplitude of resonance signal and the velocity of null mode of longitudinal normal acoustic wave, initial magnetic conductivity as well as the increase of coercive force and readings of eddy-current instrument. Likewise hardness, the electrical resistivity changes nonmonotonically with the increase of quenching temperature. The mentioned physical characteristics can be used as testing parameters of phase composition and hardness of nitrogen- and carbon-containing high-chromium steels and quality of their quenching in the wide range of austenization temperatures. The possibility of application of eddy-current method to evaluation of abrasive wear resistance of nitrogen- and carbon-containing high-chromium steels is shown.

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