Testing of High Temperature Tempering of Laminated Spring Steels by Pulsed Magnetic Method

V.F. MATYUK, M.A. MELGUI, D.A. PINCHUKOV, Institute of Applied Physics of National Academy of Sciences of Belarus, Minsk, Republic Belarus

Abstract - The results of investigation of possibility to use the curve parameters of the gradient of the normal component of the residual-magnetization field strength, of its hysteresis loop and of the recovery curves at local magnetization and magnetization-reversal of the article under test by series of magnetic field pulses, varying in time and sign for multiparameter testing are done. On the example of the specimens of silicon and chrome-manganese-vanadium spring steels it is shown, that in such case a unique dependence between these parameters and the hardness of the article can be established. Besides high correlation coefficients and acceptable values of rms deviation are available.

Introduction

Magnetic method of testing of mechanical properties and structure of articles of ferromagnetic steels [1–3] are widely used in metallurgical and machine-building plants. The physical base of that method is the availability of the unique connection between the mechanical properties under test and the measured magnetic characteristic after certain type of heat treatment.

The coercive-force-measurement methods effectively solve the problems of hardness testing of articles after hardening and low-temperature (100–300 °C) tempering of medium-carbon and high-carbon steels and of alloyed steel grades. Pulse magnetic method makes available the testing of hardness, strength, relative elongation and contraction of low-carbon cold- and hot-rolled steels after their recrystallization annealing.

But no one from these methods is suitable for the testing of mechanical properties of steel articles containing >0,3% carbon and subjected to hardening followed by high-temperature (350–600 °C) tempering. Don’t find practical use the untraditional methods of magnetic testing of such materials on height and form of Lissajous figures, magnetoelastic method, on the relaxation coercive force of body H_{rc}, on residual induction B_d^{-} or $B_d^{\sim}$ either after partial demagnetization of specimens by constant magnetic field H^{-} or by variable magnetic field $H^{\sim}$ [2].

The general difficulty in magnetic testing of the heat treatment quality of steel grades containing >0,3% of carbon is the ambiguous dependence of the standard magnetic characteristic on the tempering temperature. To eliminate the ambiguous dependence is very actual task.

Generally formulated the pulsed magnetic method consists in local pulsed magnetization of the tested article by one or several pulses of magnetic field of constant amplitude and in measurement of the gradient ∇H_{rn} of the normal component of residual-magnetization field strength (RMFS).

In the present paper the results of the search for the modes of the local pulsed magnetization and for the additional magnetic parameters, ensuring to solve the problem of unambiguous quality testing of high-temperature tempering of the considered class of materials.

1. Multiparameter Pulsed Magnetic Method

In the investigations it was determined, that the studied problem can be solved by means of local magnetization followed by magnetization reversal of an inspected article by series of magnetic field pulses varying in amplitude and sign and of measuring of the characteristic points along the variation curve of the gradient of the normal component ∇H_{rn} of residual-magnetization field strength [4, 5].

As example let us consider the process of local magnetization of article by five series of pulses, whose amplitude ΔH_p rises from pulse to pulse at a step of H_p, the sign of the amplitude increment changes after every series and the magnetic field direction alternates after every other series (Figure 1).

Curve 1 (Figure 2, a) of the gradient ∇H_{rn} change, read at magnetization by rising in amplitude at a step of ΔH_p from zero value up to H_{ps} pulses of magnetic field with given polarity of preliminary demagnetized specimen (the first series of pulses), has in contrast to the magnetization curve in the static field anomalous form. It increases first, reaches the maximum value ∇H_{rnm} and then decreases up to value ∇H_{rns} after input of the last pulse with the amplitude H_{ps}.

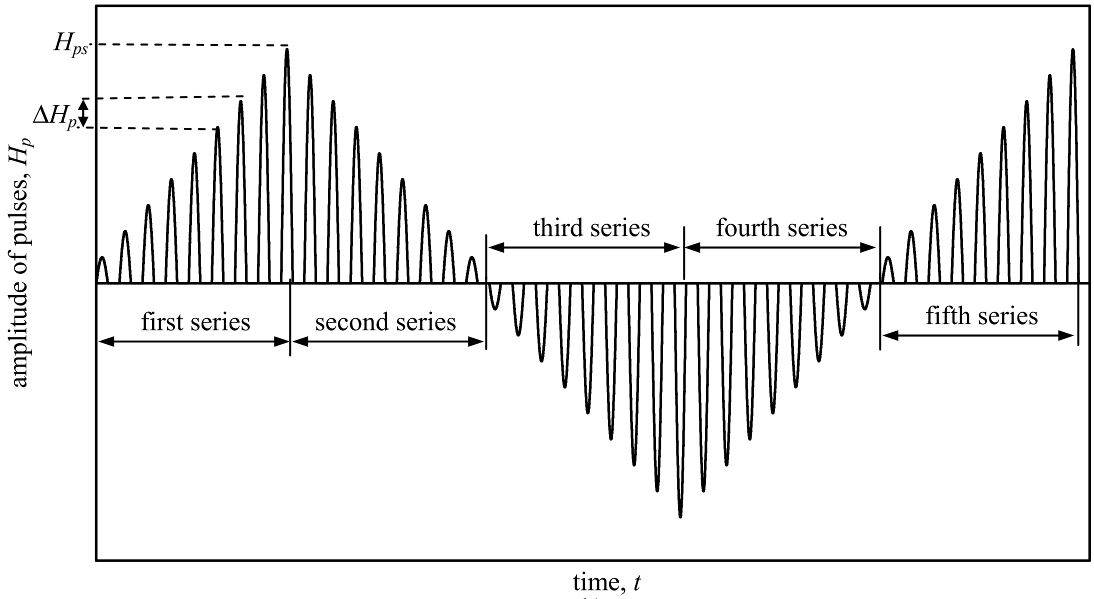
At magnetization by second series of pulses of magnetic field (Figure 1), whose amplitude decreases with the same step from H_{ps} up to zero (practically up to 0,01 H_{ps}), the gradient ∇H_{rn} don't remain constant, as at magnetization in the uniform magnetic field, but increases along the curve 2 (Figure 2), run into value ∇H_{rn0} at minimum amplitude of magnetizing pulse.

Anomalous run of the curves 1 and 2 is caused by that at local pulsed magnetization the residual magnetization of an article depends not only on the static magnetic characteristics of a material, determined by the structure of a material, but on the value of eddy current, exciting in the article at the rise and decrease of the magnetizing pulses. Simultaneously action on the material both of the magnetizing field and of the eddy current field takes to that outer and inner layers of the material opposite polarity have [5]. Besides the value of the eddy current is defined by the sharpness of the leading and trailing edges of the wave front, which rises with the rise of the amplitude of pulses.

With the rise of the amplitude of the magnetizing pulses rises the magnetization of the inner layers of the material with the opposite relative to the outer layer polarity. As a result the total magnetization and as the sequence the gradient of the residual-magnetization field strength begins to decrease. Followed by subsequent amplitude decrease of H_p the contribution of the layers with the opposite polarity of the magnetization decreases and that all takes to the total increase of the gradient ∇H_{rn}.

If after action of the first two series of pulses keep acting by the third series of pulses of magnetic field, whose direction opposite to the magnetic fields of the first two series is, and increase the amplitude H_{pd} of that pulses (Figure 1), the process of magnetization and magnetization reversal goes along the curve 3 (Figure 2). At $H_p \rightarrow -H_{ps}$ the gradient ∇H_{rn} tends to the negative value of ∇H_{rns}.

a)



b)

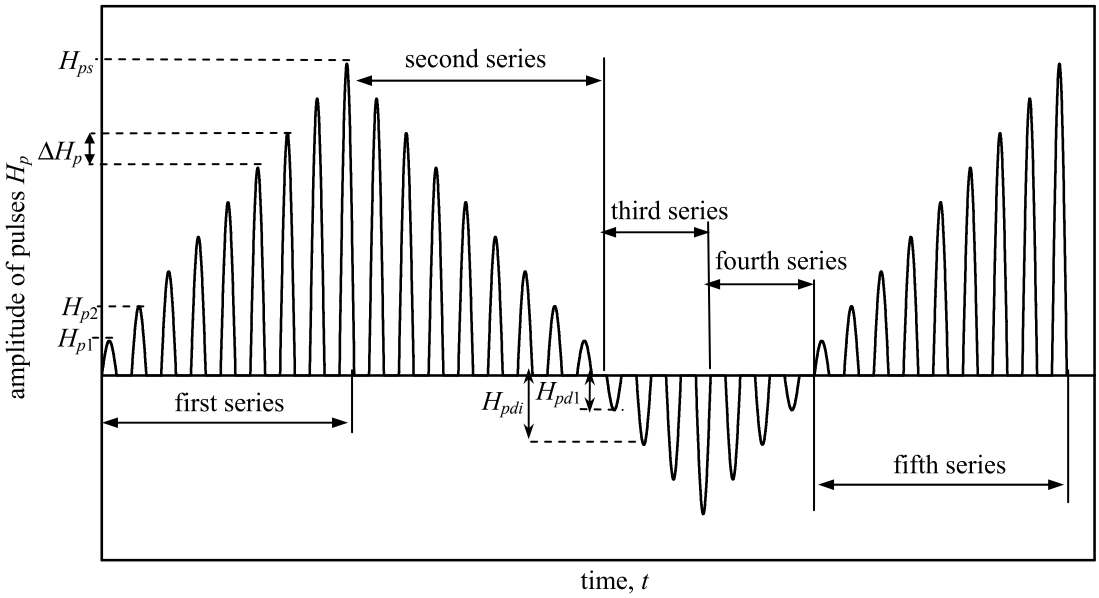


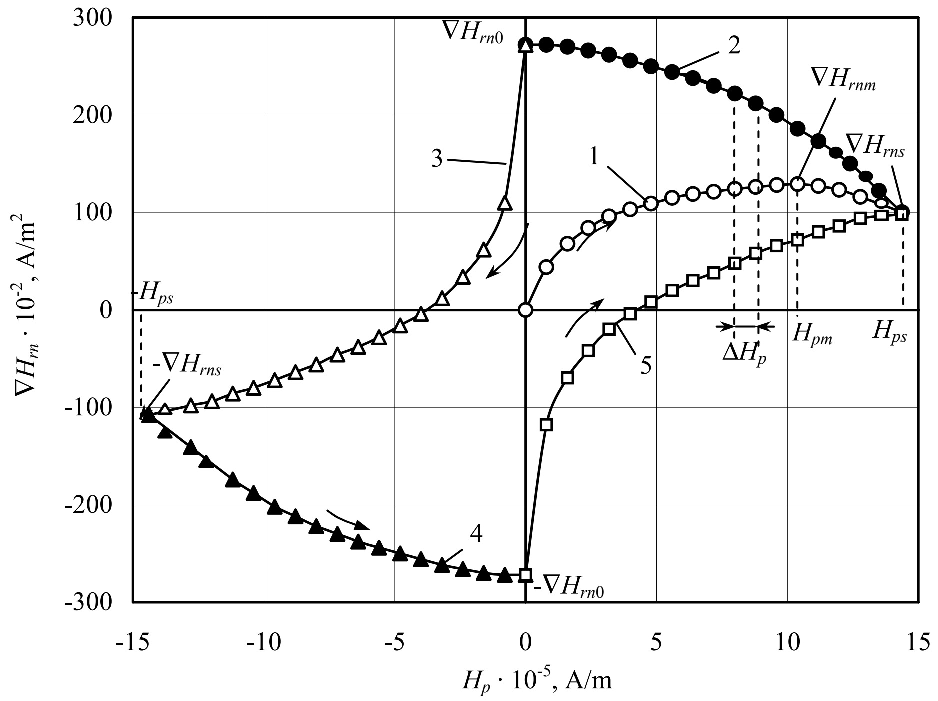
Figure 1. Variation of the amplitude of magnetizing pulses in time for receiving the curve of the gradient of normal component of residual-magnetization field strength or its hysteresis loop (a) and return curve (b)

The subsequent decrease of the amplitude of the pulses of the field of the reverse direction (the fourth series of pulses) takes to the change of ∇H_{rn} along the curve 4 (Figure 2, a) from negative value of ∇H_{rns} up to negative value of ∇H_{rn0}.

The action with the fifth series of magnetic field pulses, whose amplitude varies from zero up to H_{ps} with original direction (Figure 1, a), closes the hysteresis loop of the field gradient of the residual magnetization field strength at local pulsed magnetization along the curve 5 (Figure 2, a).

If the magnetization-reversal of an article particularly is, for instance with the amplitude $H_{pdi} = i\Delta H$, where i is the number of pulses of opposite sign, but not complete one along the curve 3 (Figure 1, b), then the amplitude of the magnetic field pulses in the fourth series is decreased up to zero value, we become the return curve, that goes not in the direction of the gradient ∇H_{rn} rise, as it at magnetization in uniform static magnetic fields is, but decreases from the value ∇H_{rndi} up to ∇H_{rn0i} (i-th curve, Figure 2, b).

a)



b)

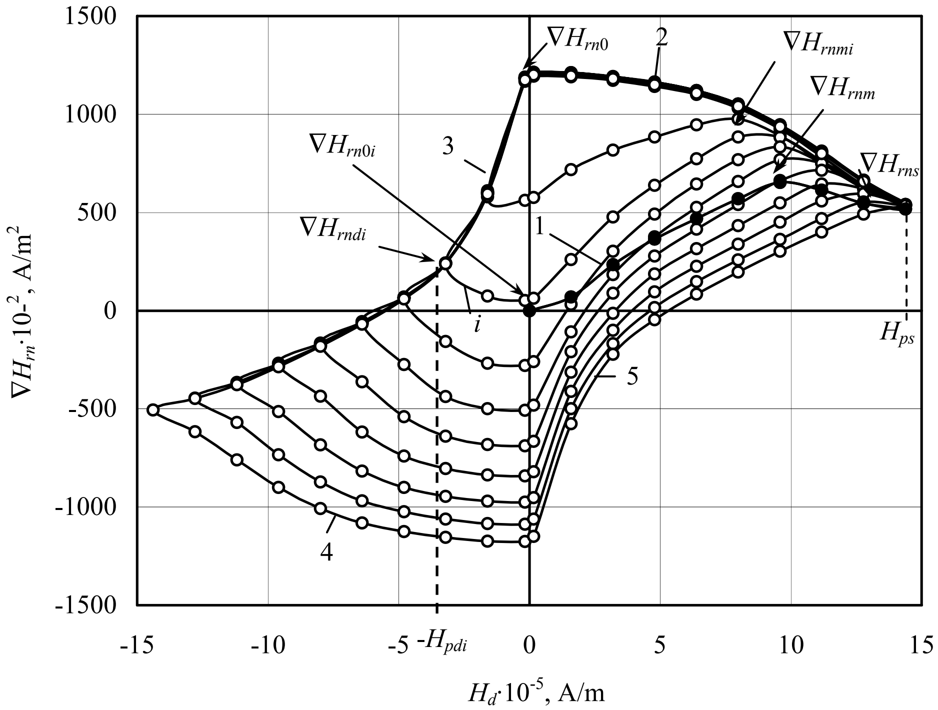


Figure 2. Normal magnetization curve (1) of the gradient of the normal component of the residual magnetization field, of branches (2, 3, 4, 5) of its hysteresis loop (a) and the return curves (b)

At magnetic field direction reversal the gradient ∇H_{rn} with the rise of the pulse amplitude increases first, reaches the maximum of ∇H_{rnmi} and at $H_p = H_{ps}$ decreases up to the value of ∇H_{rns} (Figure 2, b).

To every value of pulses number *i* corresponds its own return curve. By ongoing magnetization reversal on any closed loop the process goes along the same curves (curves 2–3–4–5 in Figure 2, a or curves 2–3–*i* in Figure 2, b).

Thus the anomalous relative the static mode of magnetization reversal shape of branches of hysteresis loop and return curves of the gradient of residual magnetization field strength at local pulsed magnetization reversal makes possible to receive a number of additional magnetic parameters, which can be used for multiparameter magnetic testing of the quality of quenching and tempering of steel articles, testing of which on one parameter (on the gradient of normal component of residual magnetization field strength ∇H_{rn} after the magnetizing by series of pulses with constant amplitude) impossible is.

Such parameters can be (Figure 2):

∇H_{rnm}– the maximum value of the gradient ∇H_{rn} upon magnetizing with series of pulses having rising amplitude (curve 1);

∇H_{rns} – the value of the gradient ∇H_{rn} after termination the process of magnetization by first series of pulses with maximum pulses amplitude H_{ps};

∇H_{rn0} – the value of the gradient ∇H_{rn} after termination the process of magnetizing with second series of pulses, whose amplitude decreases from H_{ps} up to zero (practically up to $0{,}01H_{ps}$);

∇H_{rndi} – the value of the gradient ∇H_{rn} upon magnetization reversal by *i*-th pulse of third series, whose amplitude is equal to H_{pdi};

∇H_{rn0i} – the value of the gradient ∇H_{rn} along *i*-th return curve after magnetization reversal by pulses of forth series, whose amplitude decreases from H_{pdi} up to zero (practically up to $0{,}01H_{ps}$);

∇H_{rnmi} – the maximum value of the gradient ∇H_{rn} along *i*-th return curve upon the magnetization by fifth series of pulses, direction of what with the initial direction of magnetization complies and its amplitude increases from zero (practically from $0{,}01H_{ps}$) up to H_{ps}.

The parameters ∇H_{rnm}, ∇H_{rns}, ∇H_{rn0} (for prescribed values of H_{ps} and ΔH_p) don’t depend on the magnetization reversal, and on the contrary the parameters ∇H_{rndi}, ∇H_{rn0i}, ∇H_{rnmi} vary with change of H_{pdi} substantially.

Choice (discretion)of the *i*-cycle of magnetization reversal for testing of real article execute (realize) upon studying of dependence of all abovementioned parameters for different modes of magnetization reversal on the tempering temperature, and the choice of the correlation relation between the measured hardness and the hardness calculated on the optimum cycle of magnetization reversal – proceeding from receiving the greatest correlation coefficient *R* and the least value of rms deviation S_n.

2. Examples of Realization of the Method

As an example let us consider the use of multiparameter pulsed magnetic method for solving the problems of hardness testing after high-temperature tempering which can not be solved at magnetization by series of unipolar pulses with constant amplitude.

2.1. Silicon steel

Spring silicon steel containing 0,57 up to 0,62% carbon and 1,5 up to 2,0% silicon is used for manufacture of automobile springs. As in [6] is shown, none from the magnetic parameters (coercive force H_c, maximum magnetization M_s, magnetization value M_c along the normal magnetization curve at $H = H_c$, differential and initial susceptibility), measured in static mode, show the unique dependence on the tempering temperature after quenching at the temperature of 870 °C, at the same time the hardness with the rise of tempering temperature decreases monotonous.

For investigation of possible use of pulsed magnetic method for testing the hardness of that steel were used the specimens having cross-section 90×12 mm^2 120 mm in length. They show that at magnetization by series from 6 pulses having constant amplitude (0,86·10^6 A/m) and duration of 3,5 ms the gradient of normal component of residual magnetization field strength ∇H_{rn} in the temperature range 100 up to 350 °C decreases monotonous with the rise of temperature (Figure 3), but then the maximum is observed at temperature 400–450 °C, weak rise and maximum at 520 °C and further decrease of ∇H_{rn} up to 650 °C. Because of such ambiquity the testing in response to ∇H_{rn} after magnetization by series of pulses with constant amplitude in the temperature range 300–600 °C impossible is, since to one measured value of ∇H_{rn} three different values of hardness *HRC* correspond, which decreases unambiguous with the rise of the tempering temperature.

For specimens of the same steel grade the hysteresis loops and the return curves along the gradient ∇H_{rn} of the normal component of residual magnetization field strength for all tempering temperatures are studied. Their analysis has shown that the best cycle which is to use for testing that steel is the magnetization cycle at $i = 2$, because in that case the parameters ∇H_{rnd2} и ∇H_{rn02} have unique dependence on the tempering temperature.

The search for optimum correlation between the hardness (*HRC*) measured using the direct method and hardness (HRC_c) computed using the results of magnetic measurements shows, that in the range of tempering temperatures from 100 up to 320 °C the use of four parameters ∇H_{rnm}, ∇H_{rn0}, $\nabla H_{rnd2,}$ ∇H_{rnm2} позволяет весьма точно определить твердость *HRC*. Besides the correlation coefficient is R = 0,99, the rms deviation is S_n = 0,03 *HRC* (Fig. 4), and the correlation equation has the form

$$HRC_c = 47{,}004 - 5{,}259 \cdot 10^{-5} \nabla H_{rnm} + 3{,}934 \cdot 10^{-4} \nabla H_{rn0} - 1{,}767 \cdot 10^{-4} \nabla H_{rnd2} -$$

$$- 3{,}127 \cdot 10^{-4} \nabla H_{rnm2} . \quad (1)$$

For the temperature range 300–600 °C (the range of the middle- and high-temperature tempering) preferably is the testing using three parameters, which ensures the hardness determination with the correlation coefficient of 0,98 and rms deviation of S_n = 1,34 *HRC*. Besides

$$HRC_c = 48{,}975 - 3{,}298 \cdot 10^{-4} \nabla H_{rnd2} - 3{,}013 \cdot 10^{-4} \nabla H_{rns} + 7{,}606 \cdot 10^{-4} \nabla H_{rnd2} . \quad (2)$$

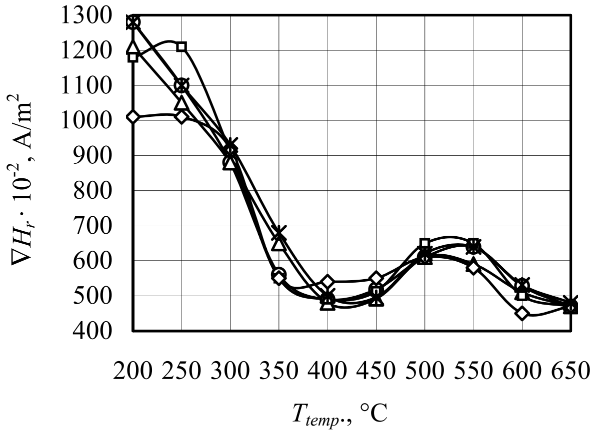


Figure 3. Gradient of normal component of residual magnetization field strength of the silicon steel in dependence on tempering temperature at the quenching temperatures:
◊ – 800, □ – 840, Δ – 870, × – 900, ○ – 930 °C (H_p = 0,86·10^6 A/m^2)

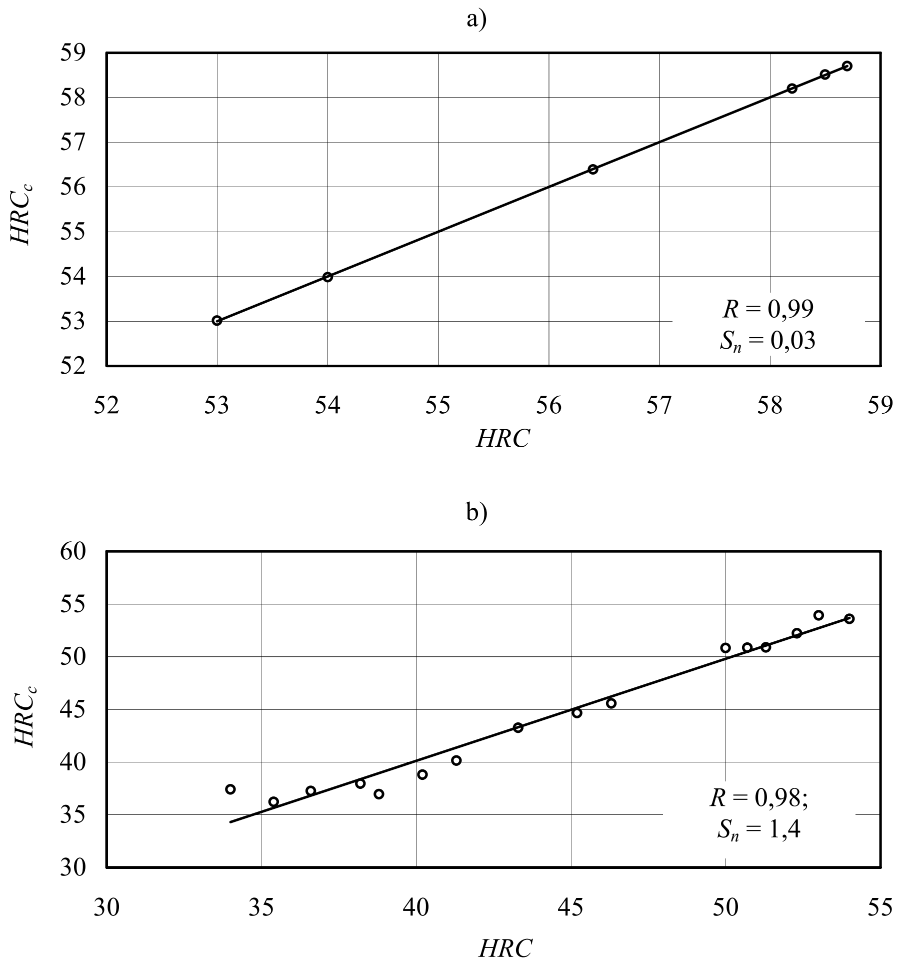


Figure 4. Correlation fields of optimum models for silicon steel.
Tempering temperature: a – 100–320 °C; b – 300–600 °C.

2.2. Chrome-manganese-vanadium steel

Chrome-manganese-vanadium first quality steel, containing 0,48–0,55 % of carbon, 0,95–1,2 % of chromium, 0,8–1,0 % of manganese and 0,15–0,25 % of vanadium, also is used for manufacture of automobile springs. It differs from the silicon steel by better processing characteristics. The increase of manganese content in the medium-carbon steel alloyed with chromium, rises its strength properties and ability to calcination. The presence of vanadium takes to its fine-grained structure and additional rises the ability to calcination. At tempering in the range of 400 up to 500 °C along the nodes of dislocation lattice the vanadium carbides are deposited (precipitated), which were dissolved at heating for quenching. This hinders the steel to become softer at tempering up to essential coagulation of carbides, which takes place at tempering temperatures above 500 °C.

The investigations of the influence of the tempering temperature after quenching on the hardness and on the value of gradient ∇H_{rn} of normal component of residual magnetization field strength after magnetization by series of pulses with constant amplitude have shown, that the gradient ∇H_{rn} monotonous decreases with the rise of temperature at low-temperature tempering only. With the rise of the temperature in the range from 300 up to 600 °C ∇H_{rn} changes ambiguous, meanwhile the hardness *HRC* monotonous decreases in the whole range of tempering temperatures. This don't allow to use the parameter ∇H_{rn} for testing the hardness after the medium- and high-temperature tempering.

At magnetization reversal of the specimens of chrome-manganese steel, exposed to heat treating in different conditions, by pulses of magnetic field with varying amplitude on different cycles (Figure 2, b) is determined, that optimum cycle is $i = 2$.

For hardness analysis in the temperature range of 100–300 °C must be used the parameters ∇H_{rnm}, ∇H_{rns}, ∇H_{rn0}, that ensure on the equation

$$HRC_c = 58{,}7 - 1{,}248 \cdot 10^{-3} \nabla H_{rnm} + 1{,}616 \cdot 10^{-3} \nabla H_{rns} - 1{,}642 \cdot 10^{-4} \nabla H_{rn0} \quad (4)$$

to calculate the hardness, besides the correlation coefficient between the calculated and measured values is $R = 0{,}99$ at rms deviation S_n not more than 0,21 *HRC* (Figure 5, a).

In the range of tempering temperatures 300–600 °C the same parameters are used, but with other coefficients of correlation equation

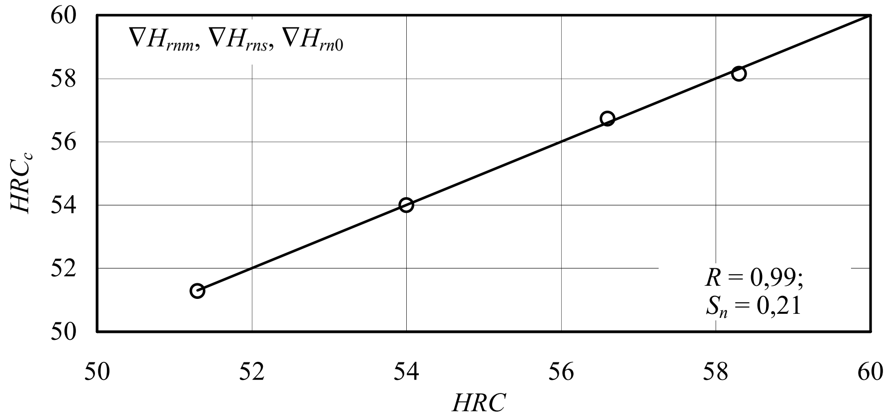
$$HRC_c = 36{,}75 + 1{,}08 \cdot 10^{-3} \nabla H_{rnm} - 1{,}711 \cdot 10^{-3} \nabla H_{rns} + 4{,}565 \cdot 10^{-4} \nabla H_{rn0} . \quad (5)$$

Besides the correlation coefficient is equal to 0,99, and the rms deviation is $S_n = 0{,}71$ *HRC* (Figure 5, b).

Conclusion

The pulsed magnetic testing of hardness of items of steels, containing more than 0,3% of carbon, subjected to quenching and following tempering,is possible on the parameters of the hysteresis loop and of return curve of the normal component of gradient of residual-magnetization field strength at local magnetization and magnetization reversal of the object under test by pulses of magnetic field, the amplitude and polarity of which vary with time.

a)



b)

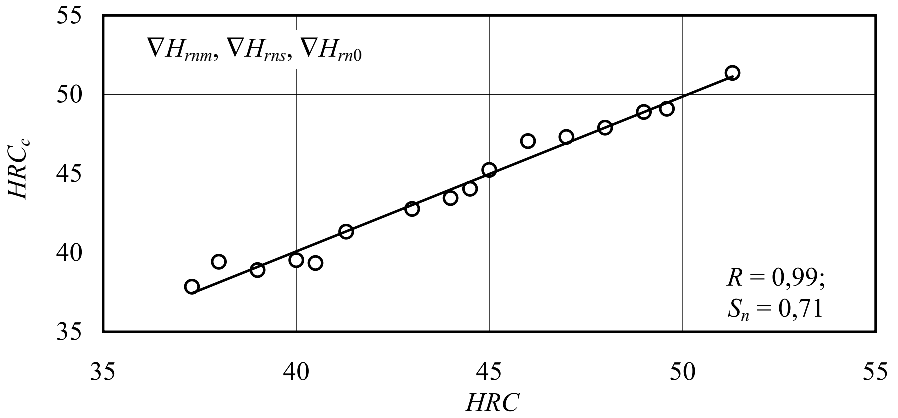


Figure 5. Correlation between the hardness *HRC*, measured by Rockwell, and the hardness HRC_c, calculated using three parameters at testing the low-temperature (0–300 °C) tempering of the steel 50ХГФА (a), and using the same parameters for the range of 300–600 °C (b).

References

[1] Melgui, M.A., *Magnitnyi kontrol' mekhanicheskykh svoistv stalei* (Magnetic Inspection of Mechanical Properties of Steels), Minsk: Nauka i Tekhnika, 1980.

[2] Mikheev, M.N. and Gorkunov, E.S., *Magnitnye metody strukturnogo analiza i nerasrushayushchego kontrolya* (Magnetic Methods of Structural Analysis and Nondestructive Testing), Moscow: Nauka, 1993.

[3] Matyuk, V.F., Goncharenko, S.A., Hartmann, H., and Reichelt, H. Present-Day Level of the Nondestructive Testing of Mechanical Properties and Punchability of the Light-Gauge Rolled Products in Production Line, *Defektoskopiya*, 2003, no. 5, pp. 19–60.

[4] Melgui, M.A. and Matyuk, V.F., Pulsed Magnetic Analyzer IMA-5, *Defektoskopiya*, 1979, no. 11, pp. 90–95.

[5] Melgui, M.A. and Kratirov, V.B.,. Anomalous Hysteresis of the Residual Magnetization Field and of its Gradient at the Magnetization of the Ferromagnetic Material by Pulsed Magnetic Field, , *Defektoskopiya*, 1986, no. 12, pp. 64–70.

[6] Matyuk, V.F., Melgui, M.A., Osipov, A.A., Kratirov, V.B.,. Lyubarets, A.L., and Shepturo, S.V., On the Possibility of Monitoring Mechanical Properties of 60C2 Laminated Spring Steel, *Vestsi Nat. Akad. Navuk Belarusi, ser. Fiz.-Tekhn. Navuk*, 2004, no. 1, pp. 112–120.