PULSED MAGNETIC MULTIPARAMETER ANALYZER IMA-M

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INTRODUCTION

Pulsed magnetic method of testing of mechanical properties of rolled products and articles from ferromagnetic steels and the devices for its realization are used in many metallurgical and machinebuilding plants for the sampling testing (devices type IMA) and for testing in the production flow (devices type IMPOC) [1, 2]. It consists in local magnetization of the article under test by the heterogeneous pulsed magnetic field of solenoid or of system of solenoids with the given amplitude in one direction and in measurement of the gradient ∇H_{rn} of the normal component of the residual magnetization field strength after the termination of the magnetization cycle, on the value of what the mechanical properties were determined. But the devices type IMA are not able to test the articles from the medium-carbon and alloyed steels, that are undertaken to the hardening with the following tempering in the temperature range from 350 up to 600^{o}C. This is caused by that the measured gradient ∇H_{rn} has not the unambiguous dependence on the tempering temperatures of such articles.

The aim of this paper is the design of the new device of pulsed magnetic testing, which can ensure unambiguous testing of hardness of the articles of machinebuilding from steels containing more than 0,3 % of C, after their hardening and medium- and high-temperature tempering.

MAIN RESULTS

For the quality testing of the medium-temperature and high-temperature tempering of the articles from the upgraded steels in the IAPH Of National Academy of Sciences of Belarus was designed the pulsed magnetic multiparameter analyzer IMA-M. It realized the multiparameter pulsed magnetic method of testing [3]. Its distinguish consists in that the magnetization is realized by five series of pulses, the amplitude changes from one pulse to the next with the permanent step. The amplitude in the first series rises with the step $\Delta H_{и}$ from zero up to the maximum value of $H_{иs}$, in the second series the amplitude decreases from $H_{иs}$ down to zero, in the third series the field direction is reversed and the amplitude rises from zero up to given value of $H_{иpi} = i\Delta H_{и}$ (where i is the number of steps), in the fourth series the amplitude decreases from $H_{иpi}$ down to zero, in the fifth series the direction of the field is reversed to the initial and the amplitude rises from zero up to $H_{иs}$. The number of pulses in every series does not exceed 10, an their duration is not longer than 3,5 ms. At magnetization of the preliminary demagnetized specimen by the first series of pulses (Figure 1), the amplitude of which rises with the step $\Delta H_{и}$ from zero up to $H_{иs}$, the gradient ∇H_{rn} of normal component of residual magnetization field strength changes by contrast to the magnetization in static homogeneous field not on the tending to the saturation curve, but on the anomalous curve 1 (Figure 2, a), it is the gradient ∇H_{rn} rises, approaches its maximum ∇H_{rnm} and then decreases down the value ∇H_{rns} after the termination of the last pulse with the amplitude of $H_{иs}$. At subsequent magnetization of article by the second series of pulses (Figure 1, a) the amplitude of which decreases from $H_{иs}$ down to zero (in practice up to 0,01 $H_{иs}$) with the same step $\Delta H_{и}$, the gradient ∇H_{rn} don't stay constant, as at magnetization in homogeneous magnetic field, but increase on curve 2 (Figure 2, a), having approach the value ∇H_{rn0} at minimum amplitude of the magnetizing pulse. It is caused by that at pulsed magnetization the gradient depends both on the static magnetic characteristics of material, determined by the structure of the material and on the eddy current, excited in article at rise and decrease of the magnetizing pulses. Investigation of the topography of ∇H_{rn} above the separate layers of plane articles has show, that at magnetization by pulses with high amplitude the upper layers have the residual magnetization of opposite sign as the inner layers, that takes to the decrease of the value of the gradient ∇H_{rn0}. At subsequent decrease of the pulse amplia)

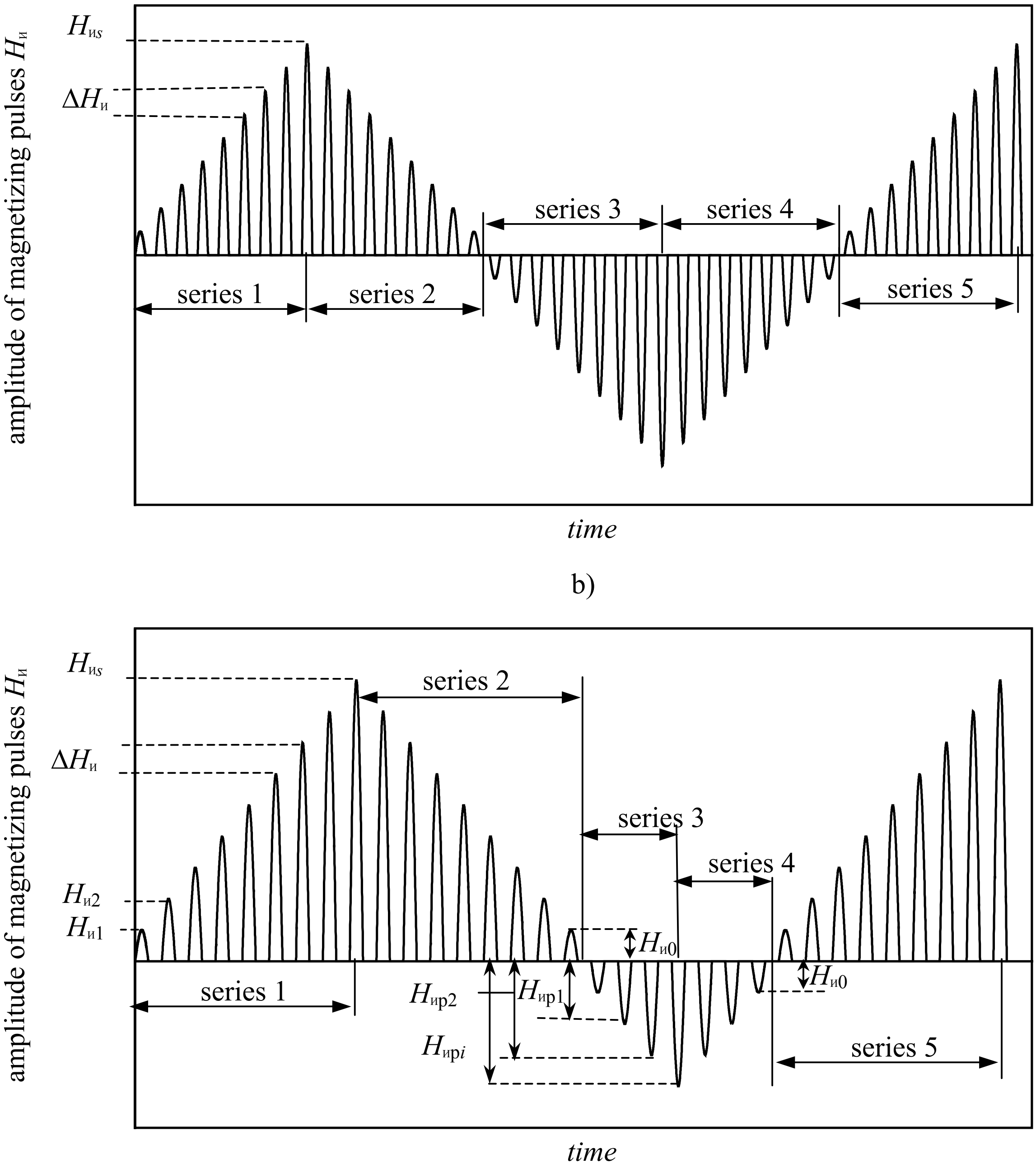

Figure 1. The change of the amplitude of magnetizing pulses during the time for receiving the anomalous major curve and hysteresis loop of the gradient of residual magnetization field strength (a) and the return curve of the gradient of residual magnetization field on the *i*-th cycle (b)

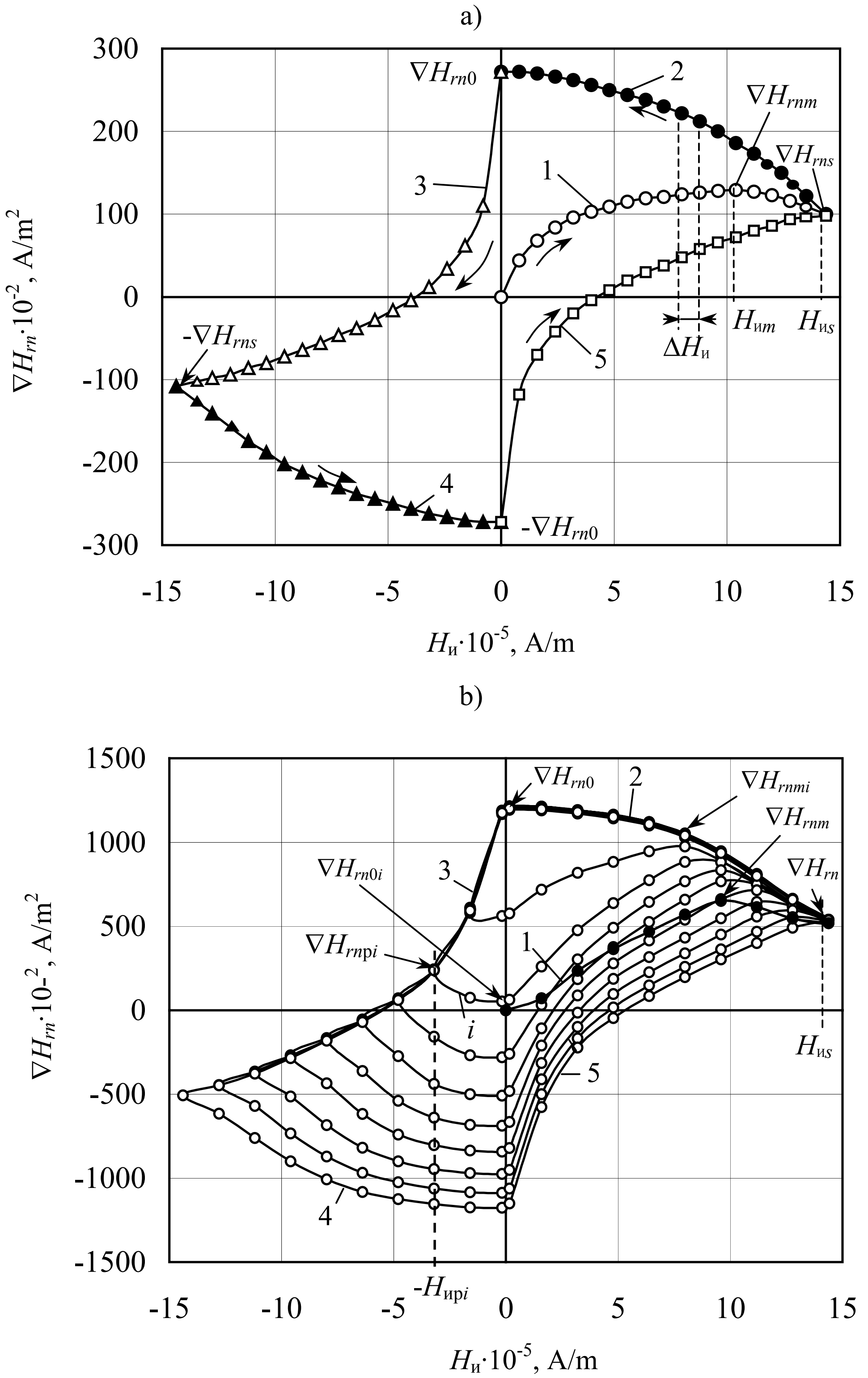

Figure 2. Major magnetization curve (*1*) and branches of hysteresis loop (*2*, *3*, *4*, *5*) – (a) and return – (b) of the gradient ∇H_{rn} of normal component of the residual magnetization field strength at local pulsed magnetization reversal with the variable amplitude

tude $H_и$ the contribution of layers with the opposite signs decreases, that takes to the rise of the gradient ∇H_{rn}.
When after the two first series to undertake the article to the third series with the opposite sign and to increase the amplitude $H_{ир}$ (Figure 1, a) then take place the demagnetization and the magnetization reversal on the curve 3 (Figure 2, a) and at $| H_{ир} | \to H_{иs}$ the gradient ∇H_{rn} tends to the value minus $\nabla H_{rn\mathrm{s}}$. The subsequent decrease of the pulse amplitude of reversed direction (fourth series of pulses) takes to the change of ∇H_{rn} on the curve 4 (Figure 2, a) from minus $\nabla H_{rn\mathrm{s}}$ up to minus ∇H_{rn0}. Exposure of the fifth series with the amplitude changing from zero up to $H_{иs}$ of the original derection (Figure 1, a) takes to closing of the loop of anomalous hysteresis on the curve 5 (Figure 2, a).
If the magnetization reversal is not complete on the curve 3, but partial for example with amplitude $H_{ирi} = \Delta H_и$ (Figure 1, b), where i is the number of pulses of opposite sign, then to decrease the pulse amplitude in the fourth series down to zero, we receive the return curve, which goes not up to ∇H_{rn}, as at magnetization in homogeneous magnetic static fields, but decreases from ∇H_{rnpi} down to ∇H_{rn} 0i (i-th curve). After the partial magnetization reversal at change of the magnetic field direction for the origin the gradient ∇H_{rn} rises, goes through maximum ∇H_{rnmi} and at $H_и = H_{иs}$ reaches again the value ∇H_{rns} (Figure 2, b). To every value of the pulse number i corresponds its own return curve. At continuation of the reversal magnetization on the every closed cycle the process repeats the same curves (2-3-4-5 or 2-3-i curves).
Thus the anomalous run of curve of branches of hysteresis loop and of the return curves of the gradient of the residual magnetization field strength at local pulsed magnetization reversal of the ferromagnetic article allow to receive the additional magnetic parameters, which can be used for the multiparameter testing of the quality of hardening and tempering of steel articles, the testing of what on the single parameter (the gradient of normal component of the residual magnetization field strength) is not possible.
As the testing parameters can be used (Figure 2):

∇H_{rnm} – the maximum value of the gradient ∇H_{rn} on the major magnetization curve (curve 1);

∇H_{rns} – the value of ∇H_{rn} after the termination of the first series with the maximum amplitude $H_{иs}$;

∇H_{rn0} – the value of ∇H_{rn} after the termination of the second series, the amplitude of what decreases from $H_{иs}$ down to zero (in practice up to 0,01 $H_{иs}$);

∇H_{rnpi} – the value of ∇H_{rn} after magnetization reversal by the i-th pulse of the third series with the amplitude $H_{ирi}$;

∇H_{rn0i} – the value of ∇H_{rn} on the i-th return curve after termination of the fourth series, the amplitude of what decreases from $H_{ирi}$ down to zero (in practice up to 0,01 $H_{иs}$);

∇H_{rnmi} – the maximum value of ∇H_{rn} on the i-th return curve at magnetization by the fifth series, the direction of which corresponds to the original magnetization and the amplitude increases from zero (in practice from 0,01 $H_{иs}$) up to $H_{иs}$.

The parameters ∇H_{rnm}, ∇H_{rns}, ∇H_{rn0} (for the given $H_{иs}$ and $\Delta H_и$) don't depend on the magnetization reversal cycle, which by the value of $H_{ирi}$ is determined, and the parameters ∇H_{rnpi}, ∇H_{rn0i}, ∇H_{rnmi} change essential (down to the sign change) at the change of $H_{ирi}$.
The selection of the i-th cycle of magnetization reversal (where i is the number of pulses in the third series) for the testing of the specifies article is curried out after the investigation the dependencies of all abovenamed parameters for different cycles of magnetization reversal on the tempering temperature, the selection of the correlation equation between the measured hardness and the hardness, calculated on the optimum cycle magnetization reversal proceeding from the highest correlation coefficient R and the lowest nonnormality of root-mean-square S_n is curried out.
The hardness or the tempering temperature of articles tested by this method is determined on the equations of multiple correlation.

The analyzer IMA-M consists of (Figure 3) transducer *1*, including the magnetizing solenoid *1-1* and incorporated in it the ferroprobe-gradientmeter *1-2*, the channel of pulses generation *2*, including the step-up transformer *2-1*, the communication condenser *2-2*, the bridge rectifier *2-3*, the charge switch *2-4*, the detector *2-5* of the charging current, the store condenser *2-6*, the detector *2-7* of voltage and the discharging switch *2-8*, the measuring channel *3*, including the separating condenser *3-1*, the amplifier *3-2*, the detector *3-3* of the compensation current, the band filter *3-4*, the programming amplifier *3-5*, the synchronous detector *3-6*, the restrictive amplifier *3-7*, the integrators *3-8* and *3-9*, the control unit *4*, including the microcontroller *4-1*, the output on the USB-port *4-2* for the connection with the PC, the liquid-crystal display *4-3*, the push button *4-4* and the power source *5*.

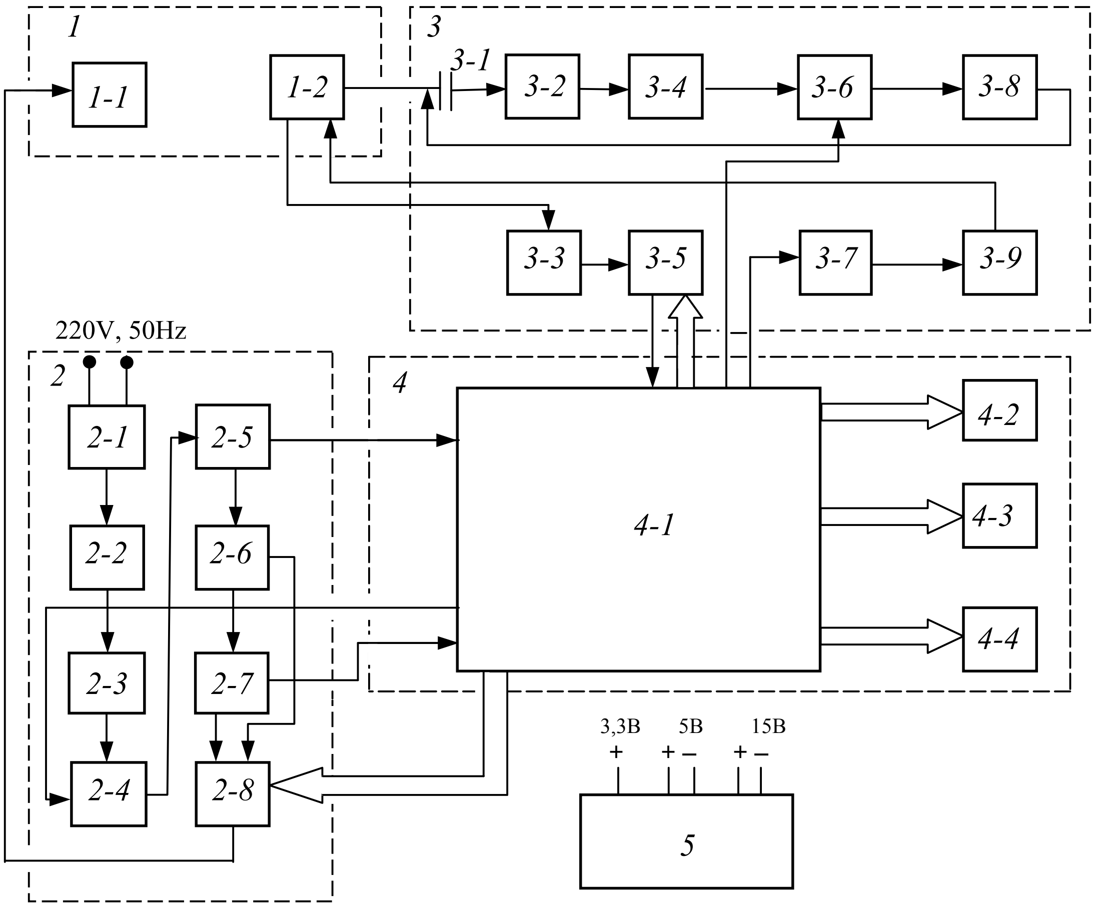

Figure 3. Function scheme of the analyzer IMA-M

At positioning the transducer of the analyzer on the surface of the article under test and pressing the button START the channel *2* generates the sequence of pulses according the mode, entered in the microcontroller from the control buttons of PC. The current pulses, going through the magnetizing solenoid, locally magnetize the article. In the analyzer the compensation circuit of measuring of the electromotive force of the second harmonic of the ferroprobe-gradientmeter is realized.
The value of the compensation current, flowing through the measuring winding of the ferroprobe-gradientmeter is proportional to the gradient of the normal component of the residual magnetization field strength after the next magnetizing pulse. In according with the selected mode the microcontroller determines the values of ∇H_{rnm}, ∇H_{rns}, ∇H_{rn0}, ∇H_{rnpi}, ∇H_{rn0i} and ∇H_{rnmi} and puts they out to the display or to PC. In the analyzer it is provided the opportunity for conversion the measured data into the values of hardness for each particular article.

Main technical performance data of the analyzer IMA-M

– maximum amplitude of the magnetizing field on the end face of the solenoid H_{us} = (5,2; 5,9; 6,5; 7,2; 7,8) $\cdot 10^5$ A/m with the error of ±5 %;
– the step of change of the pulse amplitude ΔH_{u} = (1/9 H_{us} ±5 %) A/m;
– the range of the measurement of the gradient of residual magnetization field strength ± (1–180) $\cdot 10^3$ A/m^2;
– relative measuring error is not more than ± [5 + 0,07(1,5$\cdot 10^5 \nabla H_{rn}$ –1)] %;
– the duration of single measurement is not more than 30 s.

DISCUSSION OF RESULTS

The analyzer IMA-M is effective used for the testing of hardness of medium-carbon steels after hardening and following high-temperature tempering.

Availability of some magnetic testing parameters for one measuring cycle ensures the opportunity of use both the pair and multiple linear correlation of type

$$HRC_{\text{p}} = a_0 + \sum_{k=1}^{N} a_k \nabla H_{rnk} \ ,$$

where a_0 is the free member of correlation, ∇H_{rnk} are the measured magnetic parameters, N is the number of parameters included in the equation, a_k are the coefficients at corresponding parameters.

For determination of the optimum number of measured parameters, that ensures the highest correlation coefficient R and the lowest nonnormality of root-mean-square S_n we have using the program product NCSS-2000 computed the regression equations of all possible models: one-, two-, three-, four-, five- and six-parametric for the cycle i = 2. The number of equations for each model is equal to the number of combinations from 6 elements according the number of parameters used. Thus for the one-parameter model we have 6 equations, for the two parameters – 15, for three-parameters – 20, for four-parameters – 15, for five-parameters – 6 and for six-parameters – 1. For each of the models were selected such regression equations, that ensure the highest correlation coefficients and the lowest error variance.

In the table the best from this point view correlation equations of all six models for the low-temperature (100-320^{o}C), high-temperature (300-600^{o}C) and for wide region (100-600^{o}C) of tempering temperatures of steel 60C2 are done.

It is evident, that the growth of the number of magnetic parameters, used in model, takes to rise of the correlation coefficient and decrease of variance.

Thus for the low-temperature tempering the use of four-parameters model with parameters ∇H_{rnm}, ∇H_{rn0}, ∇H_{rn02} and ∇H_{rnm2} ensures the correlation coefficient R = 1 at variation S_n = 0,027 HRC. It means, that the testing of hardness of the steel 60C2 tempered in the interval from 100 up to 320^{o}C on the results of measurement of the gradient of residual magnetization field strength in four points of the cycle magnetization – magnetization reversal is possible with the accuracy not worse than the accuracy of direct measuring by the Rockwell method.

From the point view of realization the choice of measuring parameters and accordingly of correlation model is by the required accuracy and by its productivity determined. For example for hardness testing at the low-temperature tempering the three-parameters model is preferred using the parameters ∇H_{rnm}, ∇H_{rn0} and ∇H_{rn02}, that ensures sufficient accuracy at the number of magnetizing pulses reduced for 10 in the range of amplitude change from zero up to H_{us} on the ascending branch of the return curve in the comparison to the four-parameters model.

For the high-temperature tempering (300-600^{o}C) the preferred model is three-parameters, as the further growth of the number of the parameters measured don't change the correlation coefficient, and the root-mean-square deviation rises.

Table – Multiparameter correlation models for the steel 60C2

Tempering tempera-ture, ^{o}C	Model	Regressin equation	R	S_n
100–320	one-parameter	$HRC_p = 43{,}120 + 1{,}324\cdot10^{-4}\ \nabla H_{rn0}$	0,983	0,499
	two-parameters	$HRC_p = 40{,}657 - 2{,}728\cdot10^{-4}\ \nabla H_{rns} + 2{,}732\cdot10^{-4}\ \nabla H_{rn0}$	0,990	0,444
	three-parameters	$HRC_p = 38{,}508 - 2{,}637\cdot10^{-5}\ \nabla H_{rnm} - 3{,}775\cdot10^{-4}\ \nabla H_{rns} + 3{,}474\cdot10^{-4}\ \nabla H_{rn0}$	0,996	0,327
	four-parameters	$HRC_p = 47{,}004 - 5{,}259\cdot10^{-5}\ \nabla H_{rnm} + 3{,}934\cdot10^{-4}\ \nabla H_{rn0} - 1{,}767\cdot10^{-4}\ \nabla H_{rnp2} - 3{,}127\cdot10^{-4}\ \nabla H_{rnm2}$	0,999	0,027
	five-parameters	$HRC_p = 39{,}289 - 5{,}230\cdot10^{-5}\ \nabla H_{rnm} - 5{,}556\cdot10^{-4}\ \nabla H_{rns} + 4{,}062\cdot10^{-4}\ \nabla H_{rn0} + 3{,}191\cdot10^{-4}\ \nabla H_{rnp2} - 8{,}649\cdot10^{-4}\ \nabla H_{rn02}$	0,999	0,000
300–600	one-parameter	$HRC_p = 44{,}983 + 1{,}038\cdot10^{-3}\ \nabla H_{rn02}$	0,963	1,896
	two-parameters	$HRC_p = 48{,}158 - 1{,}505\cdot10^{-4}\ \nabla H_{rns} + 1{,}070\cdot10^{-3}\ H_{rn02}$	0,976	1,599
	three-parameters	$HRC_p = 48{,}975 - 3{,}298\cdot10^{-4}\ \nabla H_{rnm} - 3{,}013\cdot10^{-4}\ \nabla H_{rns} + 7{,}606\cdot10^{-4}\ \nabla H_{rnp2}$	0,984	1,355
	four-parameters	$HRC_p = 49{,}763 - 2{,}979\cdot10^{-4}\ \nabla H_{rnm} - 2{,}596\cdot10^{-4}\ \nabla H_{rns} + 5{,}804\cdot10^{-4}\ \nabla H_{rnp2} + 2{,}212\cdot10^{-4}\ \nabla H_{rn02}$	0,984	1,404
	five-parameters	$HRC_p = 47{,}885 - 3{,}134\cdot10^{-4}\ \nabla H_{rnm} - 2{,}753\cdot10^{-4}\ \nabla H_{rns} - 2{,}552\cdot10^{-4}\ \nabla H_{rn0} + 8{,}224\cdot10^{-4}\ \nabla H_{rnp2} - 3{,}016\cdot10^{-4}\ \nabla H_{rnm2}$	0,985	1,462
	six-parameters	$HRC_p = 48{,}230 - 3{,}044\cdot10^{-4}\ \nabla H_{rnm} - 2{,}702\cdot10^{-4}\ \nabla H_{rns} - 2{,}269\cdot10^{-4}\ \nabla H_{rn0} + 7{,}447\cdot10^{-4}\ \nabla H_{rnp2} + 8{,}144\cdot10^{-4}\ \nabla H_{rn02} + 2{,}752\cdot10^{-4}\ \nabla H_{rnm2}$	0,985	1,540
100–600	one-parameter	$HRC_p = 45{,}963 + 1{,}205\cdot10^{-3}\ \nabla H_{rn02}$	0,943	2,815
	two-parameters	$HRC_p = 41{,}732 + 1{,}552\cdot10^{-4}\ \nabla H_{rnm} + 1{,}237\cdot10^{-3}\ \nabla H_{rn02}$	0,964	2,326
	three-parameters	$HRC_p = 49{,}499 + 1{,}865\cdot10^{-4}\ \nabla H_{rn0} - 1{,}052\cdot10^{-3}\ \nabla H_{rnp2} + 2{,}048\cdot10^{-3}\ \nabla H_{rn02}$	0,970	2,196
	four-parameters	$HRC_p = 46{,}010 - 3{,}425\cdot10^{-4}\ \nabla H_{rns} + 3{,}528\cdot10^{-4}\ \nabla H_{rn0} - 9{,}135\cdot10^{-4}\ \nabla H_{rnp2} + 1{,}759\cdot10^{-3}\ \nabla H_{rn02}$	0,973	2,149
	five-parameters	$HRC_p = 52{,}062 - 9{,}864\cdot10^{-5}\ \nabla H_{rns} + 9{,}458\cdot10^{-4}\ \nabla H_{rn0} - 8{,}666\cdot10^{-4}\ \nabla H_{rnp2} + 1{,}768\cdot10^{-3}\ \nabla H_{rn02} - 1{,}015\cdot10^{-3}\ \nabla H_{rnm2}$	0,976	2,105
	six-parameters	$HRC_p = 51{,}908 + 3{,}798\cdot10^{-6}\ \nabla H_{rnm} - 9{,}942\cdot10^{-5}\ \nabla H_{rns} + 9{,}307\cdot10^{-4}\ \nabla H_{rn0} - 8{,}606\cdot10^{-4}\ \nabla H_{rnp2} + 1{,}768\cdot10^{-3}\ \nabla H_{rn02} - 9{,}966\cdot10^{-4}\ \nabla H_{rnm2}$	0,976	2,185

For the wide range of tempering temperatures (100-600^{o}C) the best results gives the five-parameters testing on ∇H_{rns}, ∇H_{rn0}, ∇H_{rnp2}, ∇H_{rn02} and ∇H_{rnm2}, that ensures the correlation coefficient R = 9,976 and the root-mean-square deviation S_n = 2,105 HRC.

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