

MAGNETIC TESTING OF MECHANICAL PROPERTIES MICROALLOYED HARDENED COLD-ROLLED SHEET STEELS AFTER ANNEALING

Vladimir MATYUK, Alexander OSIPOV, Vladlen PIUNOV
INSTITUTE OF APPLIED PHYSICS OF NATIONAL ACADEMY OF SCIENCES
Minsk, BELARUS

INTRODUCTION

At cold extruding of articles of deep and extra intricate drawing the sheet cold-rolled low-carbon steels are used, the fitness of what at least on their mechanical properties and microstructure can be determined. The main influence on the microstructure and mechanical properties of steel take the chemical composition, the mode of cold rolling and of the recrystallization annealing of coils (in the kiln or in the on-stream furnace) and of the mode of subsequent skin-rolling. Besides the conditions of the previous hot-rolling have serious effect.

Among the physical methods of testing the structure and mechanical properties of heat-treated steel articles wide use in world have found the magnetic and electromagnetic methods. They are based on the general rules of influence of structural factors on the magnetic and mechanical properties of steel articles, that give the assumptions for indirect determination of strengthening characteristics of steels on their magnetic parameters.

Early was shown the possibility [1-4] and was widely introduced in practice the pulsed magnetic method for nondestructive testing of mechanical properties of sheet low-carbon steels after their recrystallization annealing on the value of the gradient H_m of residual magnetization field strength.

Now thanks the modern technologies it is possible to produce the micro-alloyed cold-rolled steels without the defects of inner structure (IF-steels) and high-strength steels (IFHS) having very content of carbon (about 0,001%) [5-7]. The sheet steels being degased in vacuum have very high extruding ability. Their ability to shaping is to be explained from one side by that their ductility is increased at decrease of the elements of interstitial points (carbon and nitrogen) up to ultra-low level; from the second side, introduction of the stabilizing elements (for example, titanium and niobium) allows to bind the remaining carbon and nitrogen. For full fixation of the introduced atoms of carbon and nitrogen the elements titanium and niobium in the combination with aluminium are used. As a result the IF-steel has the free from the interstitial defects (interstitial atoms) volume-centered cubic matrix. After the cold rolling with high level of deformation and after annealing this matrix is transformed in the structure with the intensive $\{111\}$ recrystallization structure. Such texture is the cause of high coefficient value of middle plastic deformation r , what corresponds for good shaping of IF-steels. Typical for IF-steels is the chemical composition: 0,002 % C; 0,01 % Si; 0,15 % Mn; 0,01 % P; 0,01 % S; 0,0025 % N; 0,04 % Al; 0,016 % Nb; 0,025 % Ti. Typical composition for the rimming steel 08кп : 0,08 % C; 0,01 % Si; 0,33 % Mn; 0,01 % P; 0,02 % S. The steel 08Ю has the same chemical composition but aluminium, that is introduced of 0,02 up to 0,07 %. The main difference of the chemical composition of the IF-steels from the earlier investigated low-carbon steels of type 08Ю-08кп is in significant decreasing of carbon content and the presence of micro-addition of titanium and niobium.

As for the attainment of the ability to deep drawing at manufacturing and microalloying of IF-steels the fixation of the interstitial atoms (the absence of the interstitial defects) is used, than for the increase of the strength characteristics of the cold-rolled and annealed strip of so named micro-alloyed HSLA (MA) high-strength low-alloyed steels the reinforcement is to be attained using the milling of grains and age hardening. This is attained by introduction of the microalloying elements (niobium, vanadium and/or niobium, each up to 0,1 %), which form the fine carbides and nitrides. After the cold rolling and annealing the effect of the age hardening of these elements becomes decrease owing the grain increase, but the MA-steels have good combination of strength and mouldability. The annealing is made in the charging furnace or continuous. Having the high yield strength these steels are characterized by low content of carbon and alloying elements, and that reinforces

such functional properties as the weldability and the suitability for the application of coating. Moreover, the MA-steels have high fatigue strength and impact elasticity. Such their properties are produced not thanks the fine granular structure, but thanks the testing of the chemical composition. One more steel, that we have studied – the two-phase steel DP600z having microstructure ferrite and martensite, that belongs to the class of the improved high-strength steels. It has low ultimate strength, but very high mechanical breaking strength.

At present the microalloyed cold-rolled steels are produced by the Russian ferrous metallurgy plants (for example, “Severstal”, NLMK) and by the foreign producers (Arcelor – France, Thyssen-Krupp – Germany, Nippon Steel – Japan) and by others. Their steelmaking increases, the new plants of flow-line production of zinc-plated strip for the motor industry are building.

Having such premises as the experience of reliable magnetic testing of very close to the microalloyed steels by the chemical composition low-carbon steels for the successful magnetic testing of the microalloyed steels we must know the behaviour of the magnetic and the mechanical properties in the production process, as not for every class of steels the interrelationship between the magnetic and the mechanical properties is single-valued.

The aim of present paper is the investigation of the complex of magnetic and mechanical characteristics of the specimens from microalloyed steels in the dependence on the heat treatment mode (annealing) after the cold rolling in comparison to the behaviour of low-carbon steels and the finding of such magnetic parameters, which can allow to test the heat treatment mode and to determine the mechanical properties by the nondestructive method of testing, among them using the devices of pulsed magnetic testing.

MAIN RESULTS

At studying the possibilities of the nondestructive testing of mechanical properties of microalloyed steels by magnetic method were used the specimens, prepared in the metallurgy plant EKO-Stahl, Eisenhuttenstadt, Germany.

The results are described using the specimens of IF-steels. There were prepared the specimens of two dimensions: $450 \times 500 \times 1 \text{ mm}^3$ and $100 \times 150 \times 1 \text{ mm}^3$ after hot rolling and skin rolling. In the test laboratory the specimens were investigated metallographically and the mechanical properties of the heat treated specimens were determined. The dependence of the ultimate strength R_m and the yield strength $R_{p0,2}$ on the duration of annealing are done in the Table and in the Figure 1a. In the Figure 1b are done the early investigated dependencies of that parameters on the annealing temperature of the steel 08кп. The analysis of the results for the IF-steels, as for the other microalloyed steels show, that the heating for duration of 6 minutes slightly influences the mechanical properties, that are sensitive to the structural changes, and are changed very faint with the remove of internal stresses, that take place in the beginning of heating, up to the metal is not heated to the temperature of 400°C .

On the sixth minute of heating the recrystallization of metal begins (that show the metallographical analysis) and is completed in short time. At that the hardness and the strength decrease sharp with simultaneous increase of the ductility. It must be noted, that the static recrystallization of the microalloyed steels in comparison to the cold-rolled plain carbon steels takes more significant time and demands twice as many activation energy as the killed steels do [7].

Table – The results of mechanical tests of the IF-steel specimens

NN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$t_{ann, \text{min}}$	5,0	5,5	6,0	6,5	7,0	7,5	8,0	8,25	8,5	8,75	9,0	9,25	9,5	9,75	10,0
R_m, MPa	602,3	599,3	520,3	297,3	290,7	288,3	289,0	287,0	289,0	285,3	286,3	285,3	285,3	285,7	287,0
$R_{p0,2}, \text{MPa}$	550,3	556,0	511,0	104,0	93,3	92,3	98,0	92,7	98,7	91,3	88,7	90,3	108,7	89,3	95,3

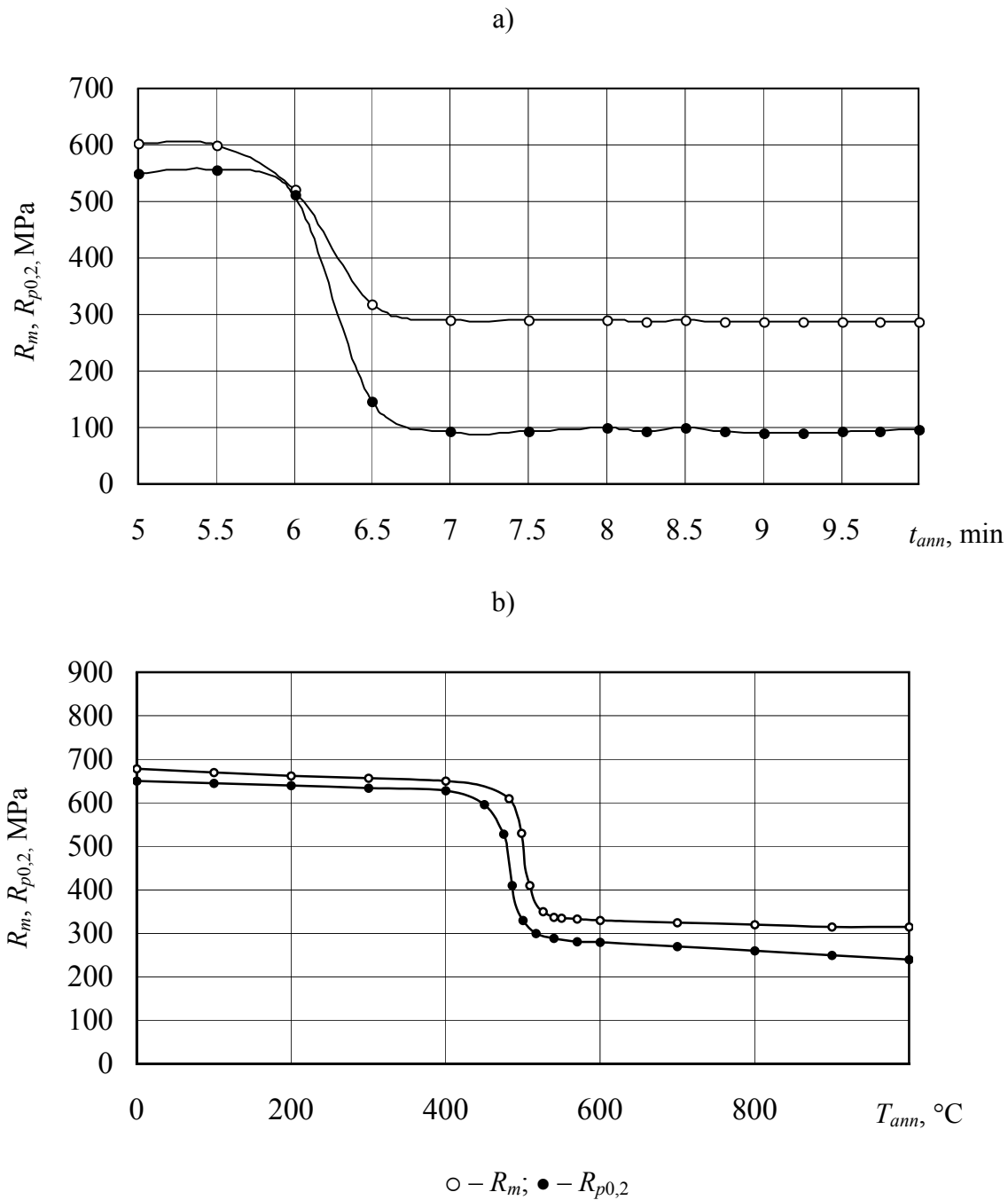


Figure 1. Ultimate strength R_m and yield strength $R_{p0.2}$ in dependence on the annealing time of the IF-steel specimens (a) and on the temperature of annealing of the 08кп steel specimens (b)

Our earlier investigations have concern the specimens of usual plain cold-rolled low-carbon steels' annealed at different temperatures in the range from 200 up to 900 °C with the endurance time in the furnace according the standard production procedure. The dependences of mechanical properties were analogous to the curves from Figure 1, the dependences were on the annealing temperature at standard endurance time, but not on endurance time at standard annealing temperatures. At that for the steel 08Ю the ultimate strength R_m change from 320 up to 680 MPa, the yield strength $R_{p0.2}$ change from 240 up to 650 MPa, and that can be seen as the confirmation of justice of such analogies.

The measurement of magnetic characteristics of specimens were made in the quasi-static mode of magnetization using the laboratory magnetic measuring device УИМКН (УИМХ) [8]. On the specimens in the form of ring (in the closed magnetic circuit) the next magnetic characteristics of the material were measured:

- coercive force for induction H_c , as the value of field strength H , at which the induction B on the descending branch of hysteresis loop is equal to zero;
- residual magnetization for magnetic hysteresis loop M_r ;
- maximum magnetization M_m , as the value M at $H = H_m$;
- maximum magnetic permeability μ_m , as $(B/H)_m$;
- the value of differential magnetic permeability $\mu_{d,H = H_c}$ for the hysteresis loop, as $(dB/dH)_m$ at $H = H_c$.

The same magnetic parameters were measured in the open magnetic circuit on the specimens in the form of plates having dimensions $100 \times 10 \times 1 \text{ mm}^3$. In Figure 2 are done the dependencies of coercive force H_c , residual magnetization M_r , differential magnetic permeability $\mu_{d,H = H_c}$ and maximum magnetization M_m on the ultimate strength of the ring specimens from IF-steel (closed magnetic circuit). The results of investigations of IF-steel in the form of plates having dimensions $100 \times 10 \times 1 \text{ mm}^3$ in the quasi-static mode in Figure 3 are done.

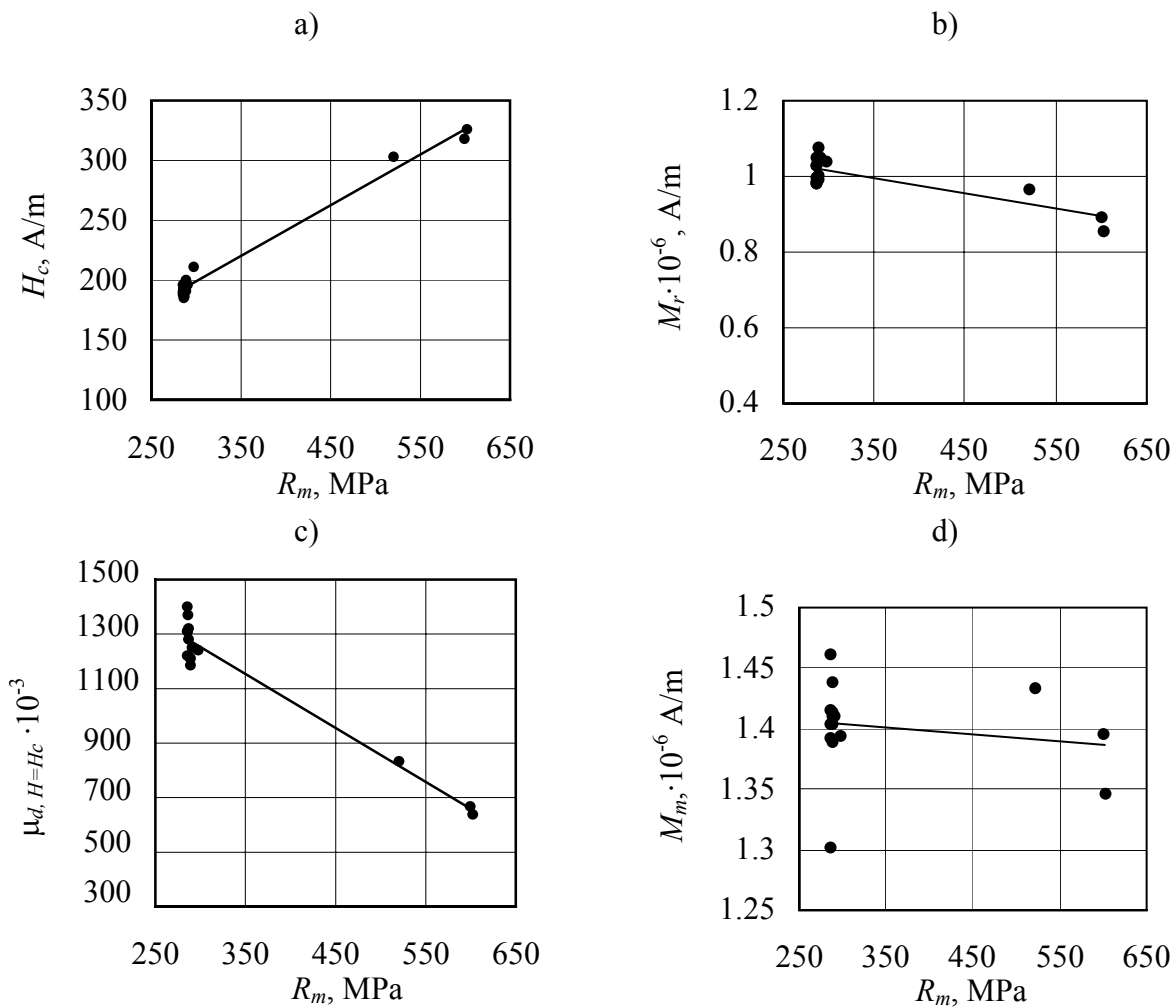


Figure 2. Coercive force H_c (a), residual magnetization M_r (b), differential permeability $\mu_{d,H = H_c}$ (c) and maximum magnetization M_m (d) of ring IF-steel specimens in dependence on the tensile strength R_m

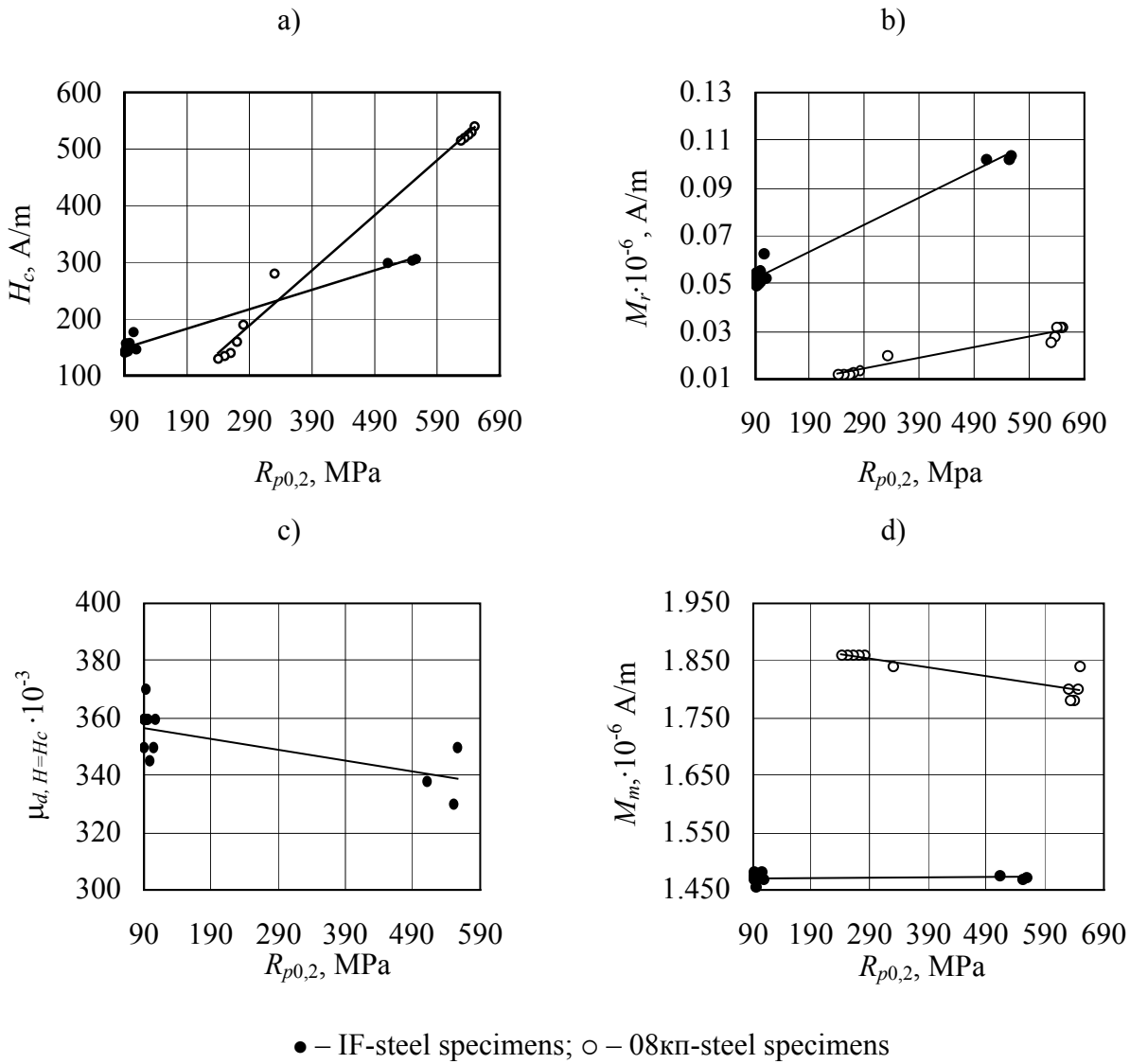


Figure 3. Coercive force H_c (a), residual magnetization M_r (b), differential permeability $\mu_{d,H=H_c}$ (c) and maximum magnetization M_m (d) of the specimens in the form of plates with dimensions $100 \times 10 \times 1 \text{ mm}^3$ in dependence on the yield strength $R_{p0,2}$

The analysis show that the better magnetic parameter of testing in both cases (in closed and in open magnetic circuit) the coercive force H_c is, the residual magnetization M_r can serve as the testing parameter in the open circuit only owing the big demagnetizing factor, which causes the slope of the magnetic hysteresis loop and is responsible for the linear portion of the loop starting from the field of coercive force up to the field of residual magnetization. The sheet material has large demagnetizing factor. That is that between the residual magnetization and the coercive force for the specimen in the form of narrow plate in the open magnetic circuit exists the linear dependence. Thus, the residual magnetization not less effective as the coercive force can be used for the reliable magnetic testing of mechanical properties (tensile strength, yield strength) of IF and others microalloyed steels. More, the process of residual magnetization measurement is more simply and its results are more stable. Such magnetic parameter as the value of differential magnetic permeability $\mu_{d,H=H_c}$ for the hysteresis loop can be used for the nondestructive testing, but in practice it is influenced by many hindering factors. The technique for its measurement is complex enough and the reliability is not high. The investigations undertaken have show that the maximum magnetic susceptibility χ_m and the saturation magnetization M_m in this case can not serve as the testing parameters of the heat treatment mode, as they don't have the interrelationship with its change. In Figure 3 are done the

results of our earlier investigation of low-carbon steel (08кп) in static mode by ballistic method using the ballistic device БУ-3 [9] for the specimens in the form of narrow plates of $200 \times 220 \times 1 \text{ mm}^3$. Their magnetic properties, as for the steel IF, with the increase of the temperature of annealing and with the start of recrystallization change essential, the magnetic permeability increases, the coercive force and the residual magnetization decrease. As the process of recrystallization is finished, the grain growth is stopped, and both the magnetic parameters and the mechanical are changing weak. The best connection with the mechanical parameters change demonstrates the coercive force, which in our concrete case is the optimum parameter of testing. Analogous results are received by measuring the magnetic characteristics of specimens in the quasi-static mode of magnetization for other microalloyed steels (IFHS, MA (ZStE 340z) and two-phase steel DP (DP600z).

The investigation of the magnetic properties of the microalloyed steels under test in the pulsed mode of magnetization were made using the device ИМА-4М [10], and by two-sides pulsed magnetization – using the device ИМПОК-1Б [11].

On the specimens with dimensions $450 \times 500 \times 1 \text{ mm}^3$ the gradient of the residual magnetization field strength was measured using the probe having the base of 30 mm after their local magnetization in static from one side of the plate by the superimposed solenoid with diameter of 16 mm and the amplitude of pulses of $2,1 \cdot 10^5 \text{ A/m}$ (device ИМА-4М), the results in Figure 4 are done. Using the device ИМПОК-1Б such measurements were carried out from both sides of plate with the solenoid having the dimensions $145 \times 15 \times 15 \text{ mm}^3$ and the amplitude of pulses of $3,2 \cdot 10^5 \text{ A/m}$.

The analysis show that in both cases are clear detected that the specimens, the recrystallization of which at the annealing was not completed because they stay in the furnace for smaller time as it must be. Besides the device ИМА-4М thanks its high locality the zones of metal heterogeneity, which are caused by different level of recrystallization of some zones of specimen, are detected.

At studying the interconnection of the magnetic parameter of testing H_{rn} and the tested mechanical properties (tensile strength, yield strength) we have analyzed the opportunity to merge in one statistical file results of measurements for all tested steels (IF, IFHS, MA, DP). In Figure 5 the correlation connections between the value H_{rn} , measured using the device ИМПОК-1Б, and the tensile strength R_m of these steels are done.

The investigations have confirmed the opportunity of the sampling testing of mechanical properties of microalloyed steels both in static (device ИМА-4М) and in the on-line production (device ИМПОК). The opportunity is shown to carry out the magnetic testing of steels IF, IFHS, MA and DP using the results of statistical processing in unified file. In spite of the additional error, caused by the wrong annealing of the specimens in the furnace, the correlation coefficients R are good (high) enough.

DISCUSSION

The investigation of main magnetic characteristics (coercive force, residual magnetization, saturation magnetization and others) of microalloyed heat-treated cold-rolled sheet steels after annealing using the laboratory magnetic measuring device in the quasi-static mode in closed (using the specially prepared specimens in form of ring) and in open circuit (using the narrow rectangular plates) are carried out. Its results show, that the reliable testing of mechanical properties (tensile strength R_m and yield strength $R_{p0,2}$) for the coercive force and residual magnetization of these steels after annealing is possible.

The behaviour of magnetic and mechanical properties of usual cold-rolled low-carbon steels and of microalloyed steels in the process of annealing don't differ one from another.

The opportunity of testing of mechanical properties of such steels on the value of the gradient of the residual magnetization field strength, measured using the ferroprobe, is confirmed by multiple investigations in static using the devices of pulsed magnetic testing with the transducer type superimposed solenoid. At that the measurements using the device with high locality (ИМА-4М) enable on the given specimens to detect local zones of heterogeneity of metal in form of zones with different level of recrystallization.

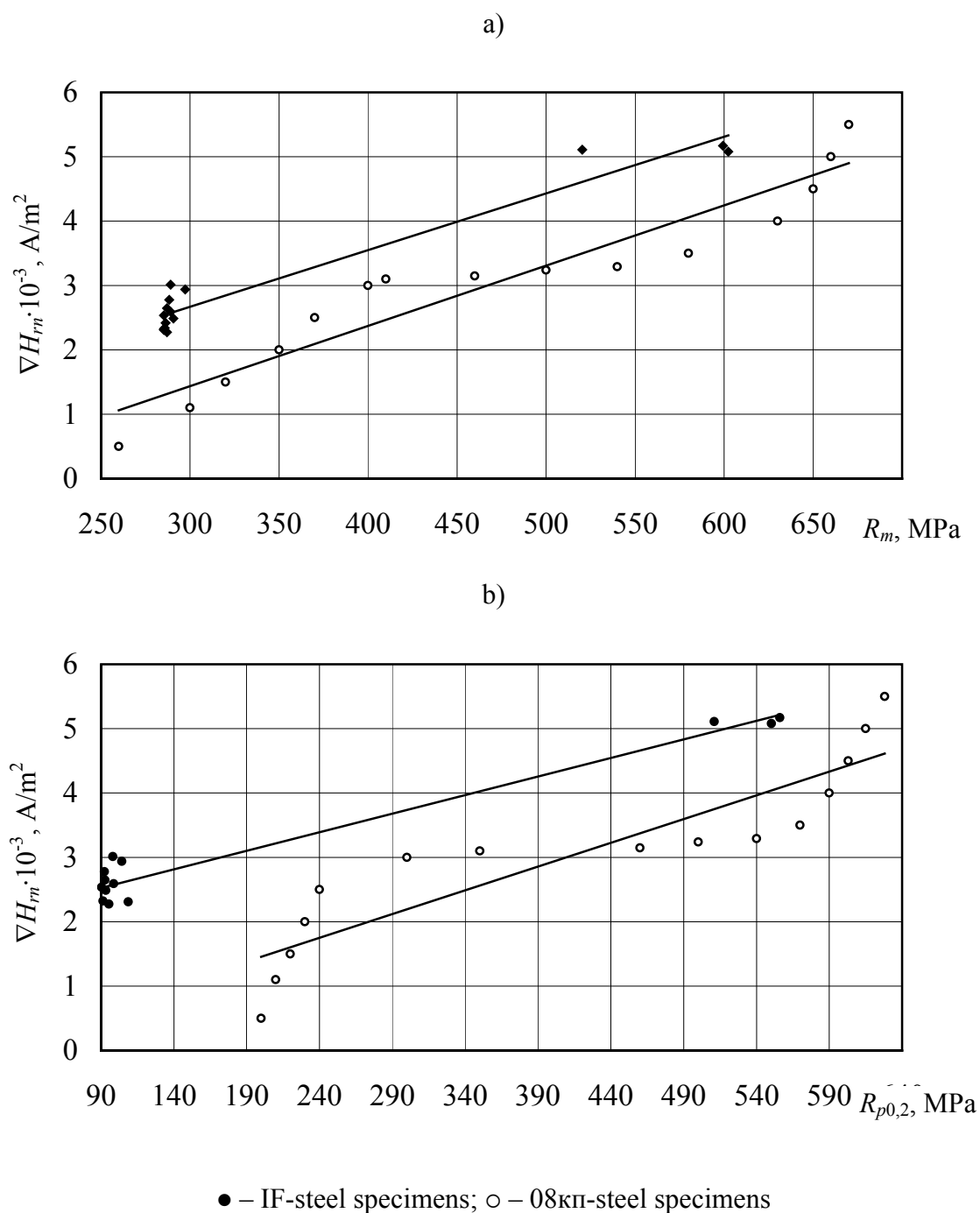
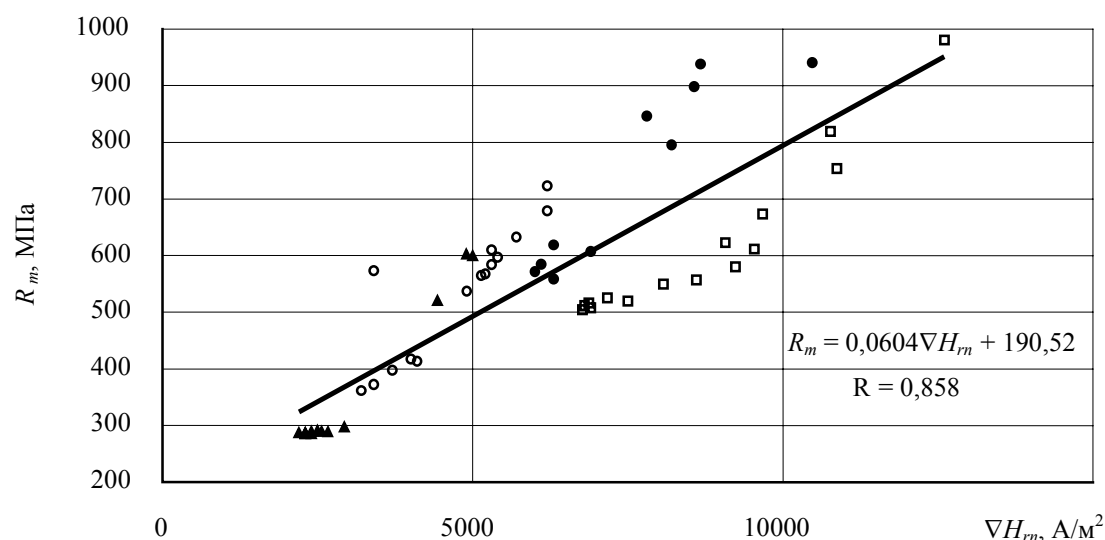


Figure 4. Gradient H_m of steel specimens at local magnetization using the solenoid with diameter of 16 mm and the amplitude of the magnetizing field of $2,1 \cdot 10^5$ A/m in dependence on the tensile strength R_m (a) and on yield strength $R_{p0,2}$ (b)

Investigations using the devices of pulsed magnetic testing with two-sides magnetization have show, that the devices ИМП ОК-1Б enable to detect the specimens, which stay in the furnace at annealing less time as it must be according the standard and which have not completed recrystallization of metal, and in such way to test the conditions of heat treatment of these steels.



▲ – IF-steel; ○ – IFHS-steel; ● – MA-steel; □ – DP-steel

Figure 5. Correlation between the gradient of residual magnetization field strength H_{rn} and ultimate strength R_m of the specimens of steels IF, IFHS, MA and DP at two-sides magnetization and measurement using the system ИМПЛОК-1Б

For the nondestructive testing of the pointed out steels in the production conditions we can advise the pulsed magnetic method of testing using the devices ИМПЛОК-1Б for the in-line testing and using the transportable devices type ИМА-4М for testing the metal in static.

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