The Plant for Pulse Magnetic On-Line Testing of Mechanical Properties of Rolled Products

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Abstract - In the paper the information about the special features of construction and of working principle of the plant IMPOC-1BM and the results of its testing in laboratory and under production-line-conditions are done. The plant is intended for on-line nondestructive testing of mechanical properties of sheet steels at strip velocity up to 10 meters per second.

Introduction

Pulse magnetic method of on-line testing of mechanical properties of rolled products is widely used in metallurgy. It is based on the presence of significant correlation between the residual magnetization and the general mechanical properties of rolled products from low-carbon, some medium-carbon and low-alloyed steels undertaken to different heat treatment (annealing) conditions. The method consists in cyclic local magnetization of the sheet in motion from both sides by pulse magnetic field of system consisting in two axially connected solenoids, the normal components of which fields are compensated, and the tangential components are added, in the subsequent measuring of maximum values of the gradients of the normal components of the residual magnetization field strength from every side of the sheet and their averaging (the arithmetic mean or the geometric mean) (Figure 1) [1].

In comparison with other methods of nondestructive on-line testing of mechanical properties of steel rolled products the pulse magnetic method has some advantages:

- the method offers the scope for testing of rolled products having thickness from 0,15 up to 12 mm;
- the acceptable displacement of the sheet from the rolling plane is allowed up to ±20 mm;
- the wide range of velocities of sheet's movement (0,5–25 m/s), at which the testing can be realized;
- the absence of the influence of zinc or aluminum plating on the testing results;
- the availability of reliable metrology support.

The basic model for the realization of pulse magnetic on-line testing is the plant IMPOC-1B (PULSE MAGNETIC ON-LINE CONTROLLER) [2]. It enables to test the mechanical properties both of continuously moving at the velocity from 0,5 up to 5 m/s metal strip and of separately moving sheets having thickness from 0,15 up to 12 mm. The measuring points are disposed every 5 meters away. The dimensions of each transducer are

550×220×220 mm. At this time the plants IMPOC-1B are used in galvanizing and pickling lines of many metallurgical works.

But for the hot-rolled products exists the necessity the decrease the distance between the testing points (especially at the ends of coil). At some production lines the velocity of sheet moving reaches 7–10 m/s. Sometimes it is difficult to find the place of the transducers of the plant IMPOC-1B disposition. Besides, in case of light-gauge metal (0,15–3 mm) the potentials of the magnetizing system of plant IMPOC-1B are exploited not completely, as the magnetizing system is intended for more wider range of thickness of rolled goods (from 0,15 up to 12 mm).

Having in mind that all in the Institute of Applied Physics of National Academy of Sciences of Belarus at support of Forschungs- und Qualitätszentrun Brandenburg GmbH was the new model designed – Pulse Magnetic On-Line Controller IMPOC-1BM. It is intended for automatic on-line testing of mechanical properties of rolled goods from low-carbon steel from 0,15 up to 3 mm in thickness with control points on distance of every 2 meters. The velocity of strip in production line can be from 0,1 up to 10 m/s. Besides the measuring characteristics up-grading in the IMPOC-1BM the transducers dimensions were diminished.

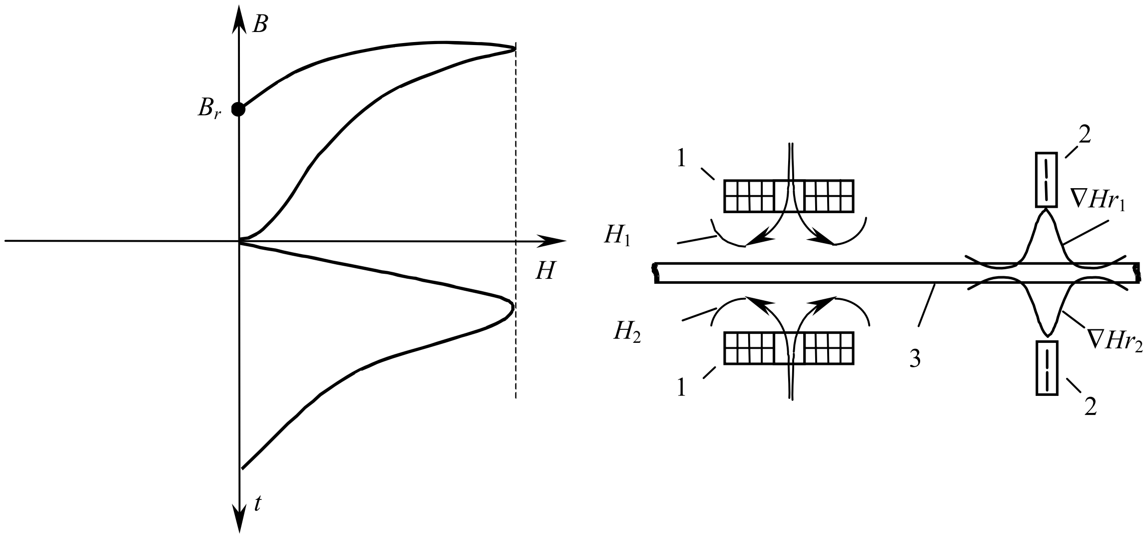


Figure 1. Measuring principle: 1 – magnetizing solenoids; 2 – ferroprobes gradientmeters; 3 – the sheet in motionт

1. Selection of magnetizing pulse parameters

Having in mind the special features of construction and of electric circuit of the plant IMPOC-1BM to ensure the testing of the moving strip with the velocity of 10 m/s with simultaneous decreasing of the distance between the measuring points up to 2 m it is necessary to increase the maximum frequency of the magnetizing pulses up to 5 Hz, what must increase fivefold the supply power of the plant and the heating of the magnetizing solenoids. At the same time the limitation on thickness of the rolled goods by the value of 3 mm enables the decrease of the amplitude and of the duration of the magnetizing pulses and by such way to decrease the dissipated power and to improve the energy characteristics of the plant.

The diminishing of the transducers' size is possible on account on the decrease of the magnetizing solenoids and the decrease of the distance between them and the magnetic sensitive elements.

But the decrease on size and the change of the configuration of the magnetizing pulses are acceptable up to that level till the local portion of the sheet under test is magnetized to the state close to the magnetic saturation state. They can take to the change of the configuration of the locally magnetized portion of the sheet and hence to the change of the dependencies of the measured parameter on the tested properties and of the range of tuning out on the influence of the sheet offset at its moving the test results. To the same result can take the change of the dimensions of the magnetizing solenoids, which is the sequence of the requirement to decrease the dimension of the transducer. The decrease of the distance between the solenoids and the magnetic sensitive elements is limited on the blocking time of the measurement for the duration time of the strong magnetizing pulse.

As the transducer of the plant IMPOC-1B along the rolling plane is extended then in the first turn the sizes of solenoids in that direction must be diminished. With such aim it would designed the round solenoids to replace by the solenoids of rectangular configuration (such configuration of solenoids have the modifications IMPOC-1, IMPOC-1A and IMPOC-2) having placed their major axis transverse to the rolling plane [3].

It was determined earlier, that the main contribution in the magnetization of flat ferromagnetic materials take the amplitude and the rate of the magnetizing pulse decay [4]. That is why at optimization of the magnetizing solenoids we have attempt to accelerate the rate of magnetizing field increase on account of the induction decrease and of the pure resistance decrease of solenoids and the decrease of the capacitance of storage battery, and the slope of pulse decay rate by introduction of the damping circuit consisting from in series connected diode and resistor. As a result of the optimization for every of two solenoids were chosen following parameters: size 80×29×200 mm^3 (width×height×length), inductance of 800 mcH, pure resistance of 0,1 Ohm. On Figure 2 the comparison of the form of magnetizing pulses of plant IMPOC-1B (capacity of storage battery is 400 mcf, charging voltage is 580 V) and plant IMPOC-1BM (capacity of storage battery is 200 mcf, charging voltage is 800 V, damping resistor is R_D = 0,6 Ohm) is done.

2. Special features of the plant IMPOC-1BM

The plant IMPOC-1BM like its analogues consists of following units: two transducers, generator and measuring unit. It provides for possibility of connection of the velocity measuring element and has potential, current and digital outputs of measuring signal. The specific features of the electric circuit of the plant IMPOC-1BM in contrast to its analogues are connected first of all with the increase for 5 times of the frequency of magnetizing pulses repeating, which takes to significant increase of the output power of the charge-discharge circuit and the power of the system for cooling the magnetizing solenoids and the increase of the velocity of sheet motion. That all demand the increase of the fast-acting of the measuring system.

Each transducer includes the magnetizing solenoid, the ferroprobe-gradientmeter and the compensating coil. Owing the significant increase of the scattered by the solenoids power there are provided both oil and air cooling. The transducers are located from both sides of sheet symmetrically relative to the mid-plane of its movement, that is to the plane of rolling. The clearance (the distance) between the transducers is 50 mm. The error of the clearance setting must be not more than 1 mm, the misalignment of the transducers must be not more than 2 mm.

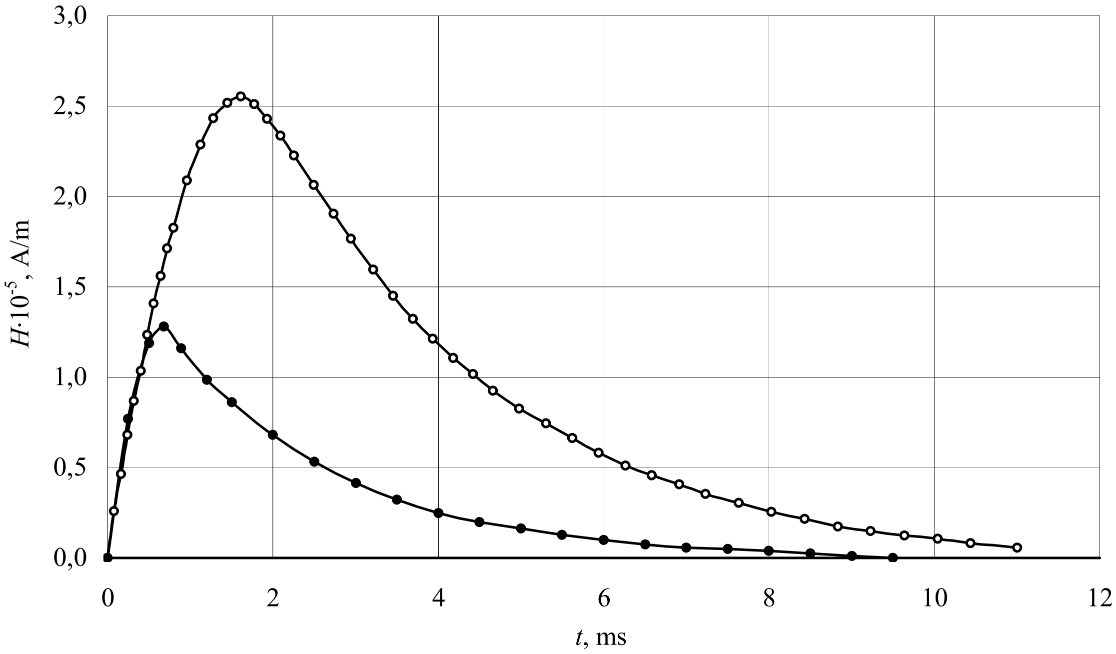


Figure 2. Form of the pulse of normal component of the magnetic field strength on the end face of the transducer of plant IMPOC-1B (○) and plant IMPOC-1BM (●)

The magnetizing solenoids of the transducers are connected between them in series-opposing and are hooked up to the discharge electronic switch of the generator. At such connection of the magnetizing solenoids the normal components (relative the rolling plane) of created by them fields in the clearance between the transducers are compensated, but the tangential components are added together, and in such a way the maximum magnetization of the local portion of the sheet is achieved. The frequency of the magnetizing pulse repeat is specified by the program of the microcontroller of generator proportional to the velocity of the sheet motion: the velocity of 10 m/s corresponds the frequency of magnetizing pulses 5 Hz, the velocity of 0,1 m/s corresponds to the frequency 0,05 Hz. At such function the distance between the magnetized portions of strip is 2 m.

The frequency setting of magnetizing pulses can be executed both in manual and automatic operating mode (in response with the signal from the external velocity measuring element).

Under conditions of external synchronization the frequency of pulse rate (and as sequence the distance between the magnetized portions of the strip) is set up in response with the signal from the external source.

The generator generates the current pulses, which, passing through the magnetizing solenoids of transducers, magnetize with prescribed frequency the local portions of the moving strip. It can operate in one of the four modes:

1 – the mode of generation the isolated current pulses in response with the operator command;

2 – the mode of generation the periodic following current pulses in accordance with the preset velocity of the strip motion;

3 – the mode of generation the periodic following current pulses in response with the signal of the velocity measuring element;

4 – the mode of generation the isolated current pulses in response with the signal of external synchronization .

Generation of the current pulses is realized by the charge of the main storage battery up to the preset voltage and by its subsequent discharge through the magnetizing solenoids of the transducers.

For generation of current pulses with the repeat rate of 5 Hz and for diminution of the voltage of the power transformer in the generator the additional storage battery of high capacitance is used. This makes possible to have in the system at all times the energy, which is higher in comparison to that needed for the charge of the main storage battery. The charging of the main battery can occur both from the additional storage battery and from the rectifier unit partial by way of multiple opening-closing of the electronic switch. The cycles of charging-recharging are repeated until the voltage on the main storage battery reaches the level needed. The level is monitored by the microcontroller.

Such circuit allows to charge the main storage battery having the capacitance of 200 mcF up to voltage of 700 V and to discharge it through the magnetizing solenoids during the time less than 200 ms. This all provides the required frequency of the magnetizing pulses with preset amplitude and duration at relative small voltage of the power transformer.

Through the control panel the required operation mode shall be introduced in the microcontroller and is indicated on the LCD. In response with the introduced information the microcontroller selects and controls the required program and generates the signals that control the charge-discharge of the main storage battery, processes the external signals (the mode of external synchronization and operating mode in response with the velocity sensor) and generates the synchronizing signals for the operation of the measuring unit.

The measuring unit is intended for the service of the ferroprobes of both transducers, for extraction and compensation of the second harmonic component of their signals, for measuring the maximum value of the compensating signal from every channel, for determination of their averaged values (arithmetic mean and geometric mean) and for indication of the results of averaging.

Closing the plant the microcontroller of the measuring unit generates the single-polar square pulses in the form of meander (the relative pulse duration is equal to 2) having the frequency of 5 kHz. These pulses are conversed into the bipolar signal in form of a triangle, which is applied on the exciting windings of ferroprobes.

The signals picked off every ferroprobe are processed in separate channels. In every channel from the signals from ferroprobes the second harmonic component is derived (10 kHz) that is proportional to the gradient of the field strength of the magnetized portion of the sheet.

Following the amplifier the second harmonics is demodulated by the detector, the commutation pulses of which are generated by the microcontroller. For the time of current pulse travelling through the magnetizing coils the commutation of the synchronous detector is disabled by the microcontroller.

The integrated signal proportional to the second harmonic component of the signal from ferroprobe, hence proportional to the value of the applied magnetic field (to the gradient of its normal component), is applied to the compensation coil in such polarity that the magnetic field created by the coil has direction opposite to the direction of the measured magnetic field, that is the feedback on the gradient of the normal component of the residual field strength is realized. As the coefficient of amplification of the measuring circuit of the second harmonics is high (not less than 10^4), the field of the compensation coil controls the change of the measured field and compensates it completely. Besides the current through the compensating coil is proportional to the measured gradient of the normal component of the residual magnetization of the field, acting on the ferroprobe.

The signal, proportional to the current through the compensating coil, is applied to the input of the according analog-digital converter (ADC) of the microcontroller. The maximum signals of every channel are registered by the microcontroller for the time of the travel of the neighbouring magnetizing pulses. The microcontroller computes the arithmetic mean or the geometric mean (the according mode is preset using the panel of the input unit in response with liquid-crystal device – LCD). The results of computation are put out on LCD and through the digit-analog converter (DAC) and electronic switch are applied to the amplifier, from output of which the amplified signal through the current source can be applied on the external current gauge.

The upkeep of the needed measuring range (one of the three: $5 \cdot 10^2$ A/m^2, $5 \cdot 10^3$ A/m^2 and $5 \cdot 10^4$ A/m^2) is realized by the microcontroller by establishing the required coefficient of amplification. The discretion of the range can be realized both automatically and manual (it is established by user using the panel of the input unit in response with LCD).

The operation of the measuring unit is synchronized by the external pulses from the generator of the plant or from the special-purpose SIMULATOR at its calibration.

3. Tests of the plant IMPOC-1BM under the laboratory conditions

The suitability of the new conditions for local magnetization of the light-gauge rolling products was tested on the specimens of most widely used rimming low-carbon steel containing 0,08 % of carbon, which were heat-treated in different conditions. The distance between the end-faces of transducers was 50 mm (the distance between the end-faces of solenoids was 70 mm).

In the Figure 3 the testing results of above mentioned specimens having thickness of 3 mm, annealed at temperatures 200 °C and 600 °C are done. It is evident, that the state close to the magnetic saturation of locally magnetized portion of a sheet is reached at the pulse amplitude of $(0,9\text{-}1,0) \cdot 10^5$ A/m for both specimens: for magnetically soft and for magnetically hard.

The received results have shown, that the chosen topography, amplitude and configuration of the magnetizing pulses ensure the reliable magnetization of the specimens of low-carbon steel 3 mm in thickness and high sensitivity to the changes of the heat treatment conditions (the difference between the values of the gradient of the residual magnetization field strength of the non-recrystallized and the recrystallized specimens was 2,5-fold). Fir the specimens of less thickness such mode of magnetization ensures more better suitability.

On Figure 4 the topography of the gradient of normal component of the residual magnetization field strength at magnetization of the same specimens in direction along and transverse to the rolling plane by the plants IMPOC-1B and IMPOC-1BM is done. It is shown that the configuration of the magnetized by the solenoids of plant IMPOC-1BM portion along the rolling direction is like to the analogous form, received at magnetization by the plant IMPOC-1B. Small difference in the value of the maximum is connected with lesser length of the solenoid in the rolling direction and with lesser duration of the magnetizing pulses, and that all in the aggregate diminish the size of the magnetized portion in this direction and, hence the value of the created magnetic field along the axis, that passing over its center perpendicular to the sheet surface.

At the same time the extent of the magnetized by the solenoids of plant IMPOC-1BM portion transverse to the rolling direction is more wider in comparison with the magnetization by solenoids of plant IMPOC-1B. This allows to diminish the error of measurements of the maximum of the magnetized portion at vibration fluctuations of the sheet in the rolling plane perpendicular to the motion direction.

At on-line testing of the sheet the important technical characteristic is the value of measuring error because the displacement of the sheet in motion relative the rolling plane. In the Figure 5 the dependencies of the arithmetic mean and of the geometric mean of the

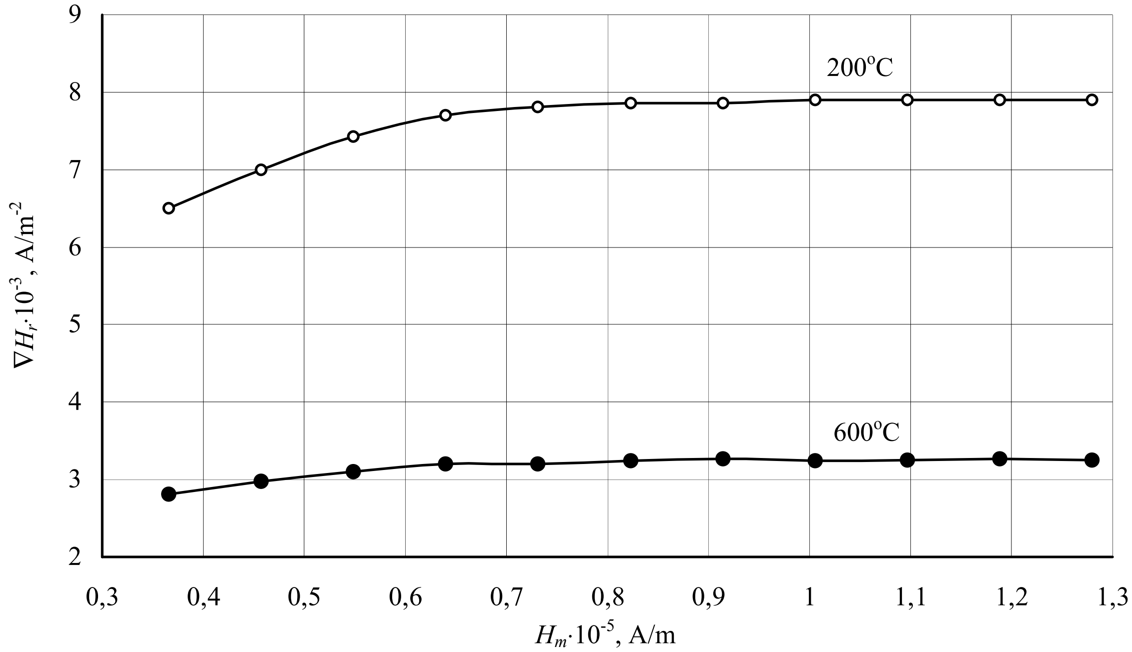
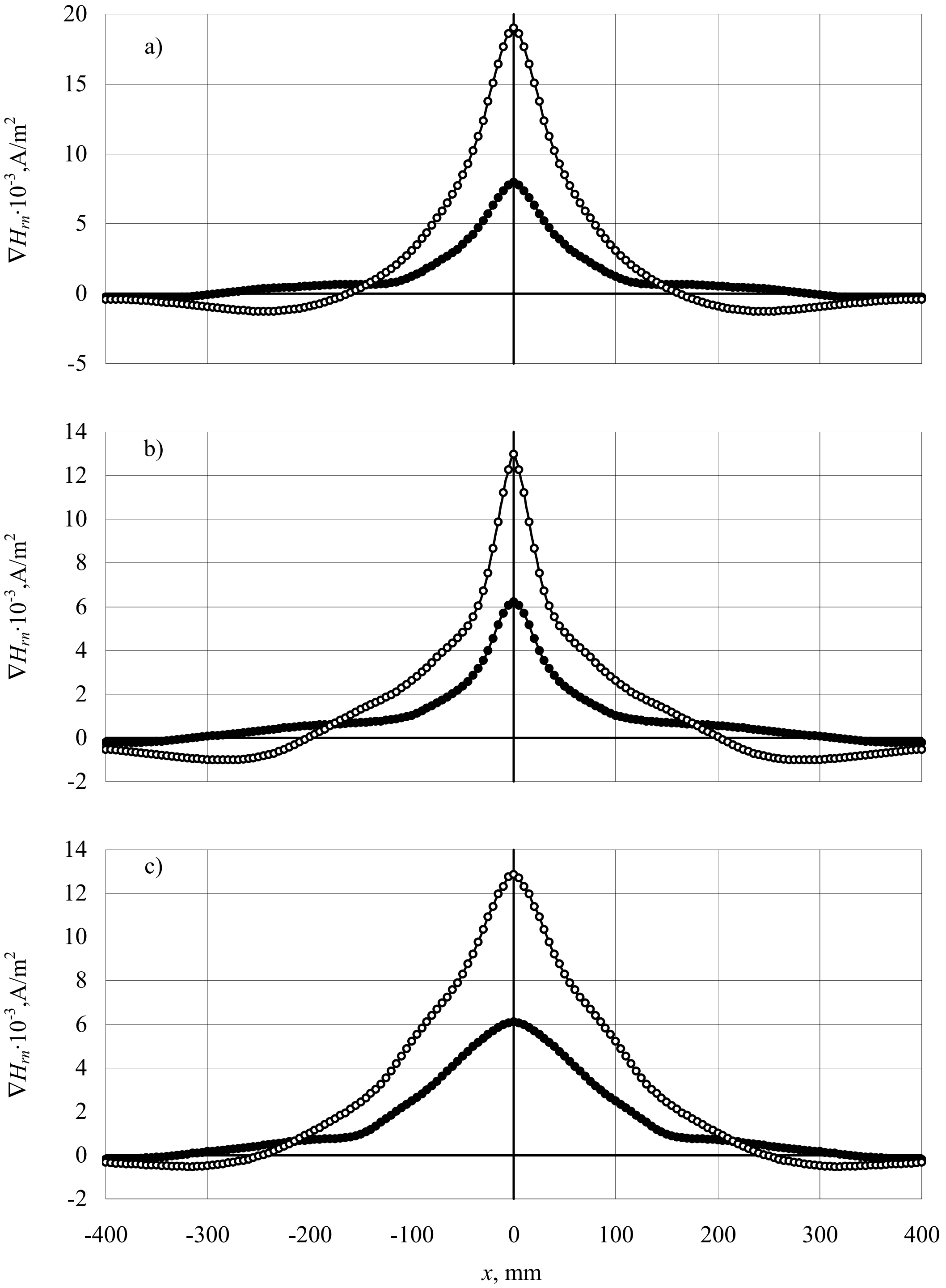


Figure 3. Dependence of indications of the plant IMPOC-1BM on the amplitude of magnetizing pulses for the specimens of steel, containing 0,08 % of carbon, 3 mm in thickness, annealed at temperatures 200 °C and 600 °C.

gradients of normal component of the residual magnetization field strength, measured from both sides of locally magnetized sheet on the value of its displacement Δh relative the rolling plane are done. The show, that at calculation of the arithmetic mean of the measured from both sides gradients the measuring error because the sheet displacement for ± 10 mm of magnetically hard specimen reaches for IMPOC-1B 1,2 %, but for IMPOC-1BM it is 0,5 %. For magnetically soft specimen the error is not higher than 2,2 % and 1 % for plants IMPOC-1B and IMPOC-1BM accordingly. The calculation of the geometric mean of the measured gradients at sheet displacement relative the rolling plane for ± 20 mm provides the measuring error on the magnetically hard sheet not more than 1,9 % for the plant IMPOC-1B and 1,6 % for the plant IMPOC-1BM. For the magnetically soft specimen the error by calculation the geometric mean don’t exceed 4,5 % for the plant IMPOC-1B and 3,2 % for the plant IMPOC-1BM.

The change of parameters of the magnetizing field in the plant IMPOC-1BM in comparison with the plant IMPOC-1B don’t change the character of the dependence of the measuring results on the temperature of annealing of the rolling goods (Figure 6).

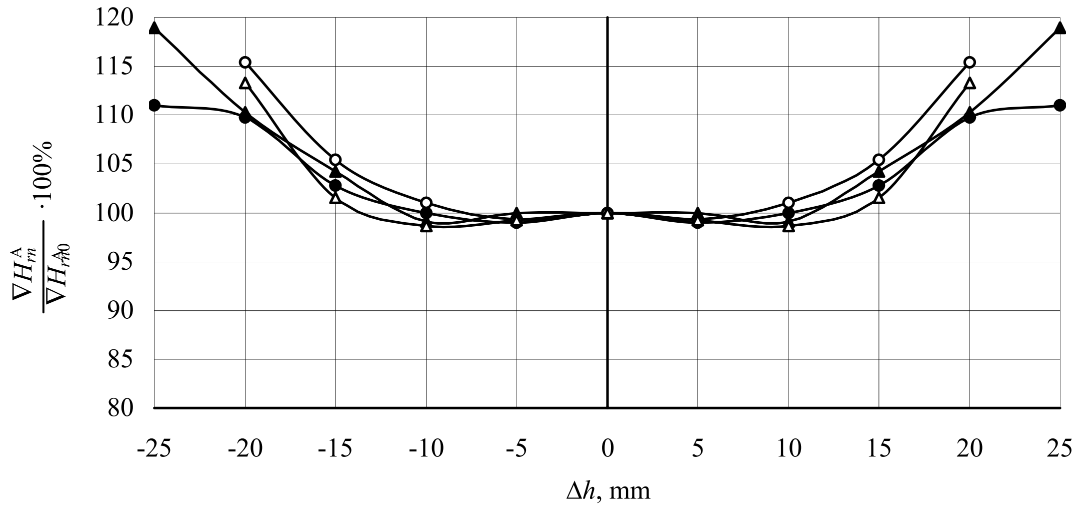
Thus, having the lesser extent along the rolling direction and lesser scattered power of one pulse of the magnetizing system of the plant IMPOC-1BM ensures for the sheets with thickness up to 3 mm the conditions of magnetization not worse, than the magnetizing system of the plant IMPOC-1B.



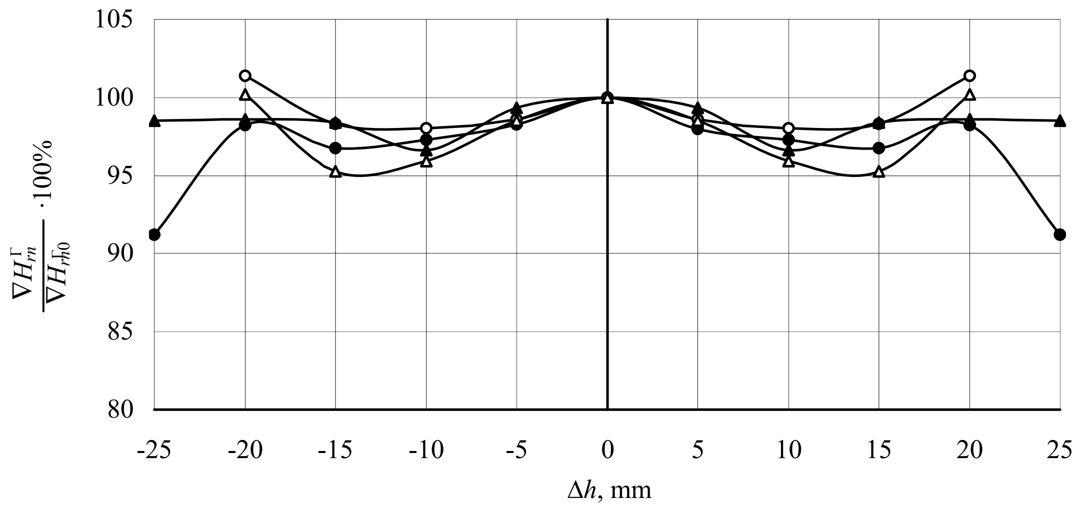
Annealing temperature: ○ – 200º C; ● – 600º C;
a – U = 580 V; C = 400 mcf; b, c – U = 700 V; C = 200 mcf; R_D = 0,235 Ohm;

Figure 4. Topography of the gradient of normal component of residual magnetization field strength on the distance of 10 mm over the sheet surface of the sheet of low-carbon steel (carbon content is 0,08 %) along (a, b) and transverse (a, c)) to the rolling plane at the magnetization by plant IMPOC-1B (a) and by plant IMPOC-1BM (b, c).

a)

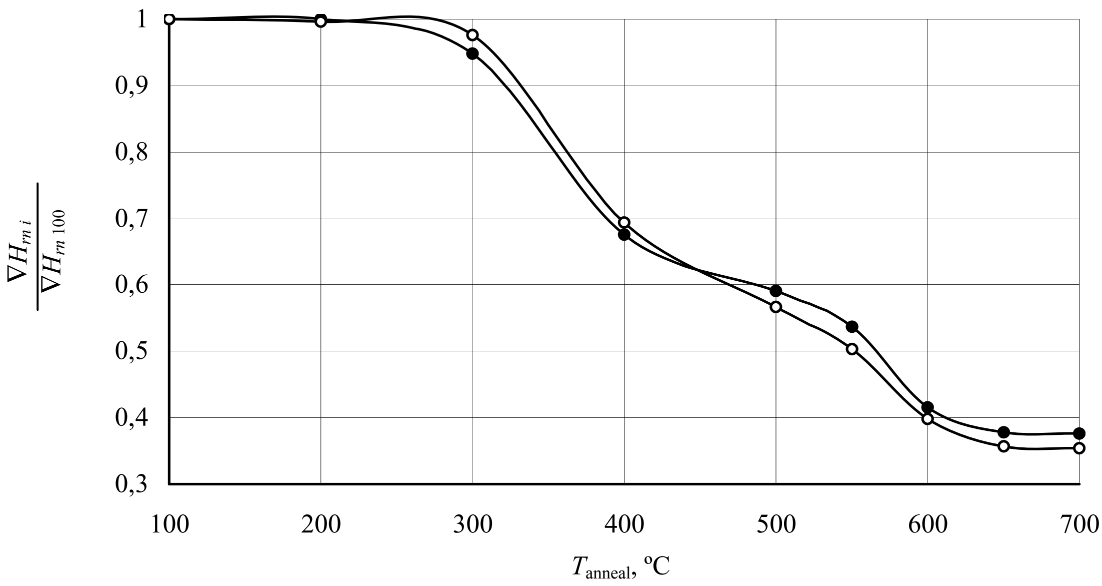


b)



○, Δ:: T_{anneal} = 200 ºC; ●, ▲:: T_{anneal} = 600 ºC;

Figure 5. Dependence of the arithmetic mean (a) and geometric mean (b) of the indications of the plant IMPOC-1B (○, ●) and IMPOC-1BM (Δ, ▲) on the sheet displacement relative the middle line of the distance between the transducers.



i, °C = 100, 200 … 700.

Figure 6. Dependence of the indications of the plants IMPOC-1B (○) and IMPOC-1BM (●) on the annealing temperature.

4. Operating characteristics of the plant IMPOC-1BM

– Thickness of the tested rolling products, mm ……………………………………0,15-3
– Velocity of the rolling goods movement, m/s ……………………………………0,1-10
– Amplitude of pulses of the magnetic field strength along
  the axis on the end-face of every magnetizing solenoid, A/m …………$1{,}25 \cdot 10^5 \pm 10$ %
– Range of the measurement of the field strength gradient, A/m^2
  1 subrange ……..……………………………………..25 - $5 \cdot 10^2$
  2 subrange ……………..…………………………… $2{,}5 \cdot 10^2$ - $5 \cdot 10^3$
  3 subrange ……………………………………………$2{,}5 \cdot 10^3$ - $5 \cdot 10^4$
– Error of the field strength gradient measurement, % of
  full-scale deflection of the operating subrange, not more ……….……………………5

<u>Note.</u> Error on the first subrange is not normalized.

– Error of the measuring of the geometric mean of the measured
  gradients of the residual magnetization field strength, %, not more ……………………3
– Additional error because the sheet displacement perpendicular
  to the rolling plane in the limits for ±20 mm, % ………………………………….…..5
– Maximum number of measurements per minute ….……………………………300±10%
– Minimum number of measurements per minute …………………………….…..3±10%
– In the plant both manual and automatical subrange switching are provided.
– Indication of measuring results ………………..…………………………………digital
– Time of operating conditions setting, min, not more ………..…………………………15

– Time of continuous operation with subsequent break for 30 minutes
  for maintenance check-up, hours, not less ……………………………………………………8
– Power consumption of the plant from supply line, V·A, not higher ………………..…1000
– Overall dimensions of the plant, mm, not more
  1) generator ……………………………………………………………540×480×295
  2) measuring unit …………………………………………………..……..480×480×170
  3) transducer (one piece) …………………..415×220×205 (606 with cap screws)
– Weight of the plant, kg, not more ….……………………………………………………85

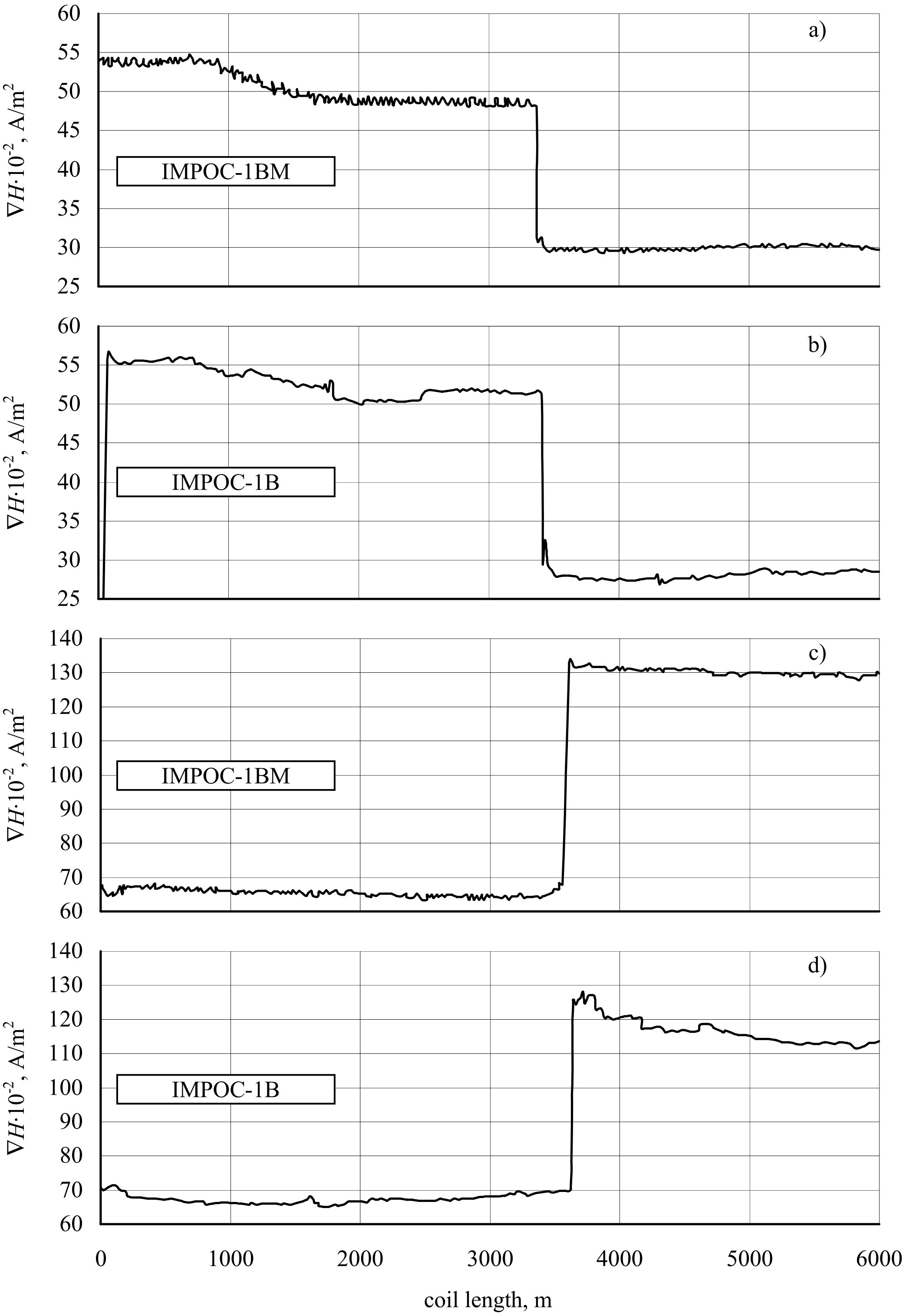
5. Tests of the plant IMPOC-1BM under the conditions of production

Production tests of plant IMPOC-1BM were carried out in the line of hot galvanizing in plant VZA2 EKO Stahl GmbH. The plant was disposed at a distance of 20 m before the skin-rolling mill and contiguous with it levelling mill. The clearance between the transducers was 50 mm.

The measuring results of the plant IMPOC-1BM were compared with the results of the plant IMPOC-1B, disposed in an outlet of the skin-rolling mill. Besides the clearance between the transducers of the plant IMPOC-1B was 66 mm. The influence of the skin-rolling on the properties of metal, difference in the topography of the magnetizing field and different clearances between the transducers don't allow to carry over the correlation dependencies between the mechanical properties and the indications of the plant IMPOC-1B to the pplant IMPOC-1BM. But the comparison of their comparison makes possible to watch how both plants sense the change of mechanical properties during the technological annealing and the change of the orange of rolled products under test.

On Figure 7 the comparison of indications of the plants IMPOC-1B and IMPOC-1BM at hot zinc-plated metal of two steel makes having different level of mechanical properties. It is seen from it that even taking into account that the metal after skin-rolling changes slightly its mechanical properties both plants sense the changes of mechanical properties during the manufacturing annealing equal.

On Figure 8 the correlation between the indications of the plants IMPOC-1B and IMPOC-1BM is done. The deviation from the straight line is caused by the above mentioned reasons.



a, b – change from the cold-rolled strip 5161 0,8 mm in thickness
to the strip 5164 0,7 mm thick
c, d – change from the cold-rolled strip 5378 0,8 mm in thickness
to the strip 5755 1,0 mm thick

Figure 7. Indications of the plants IMPOC-1BM (a, c) and IMPOC-1B (b, d) at hot zinc-plated metal.

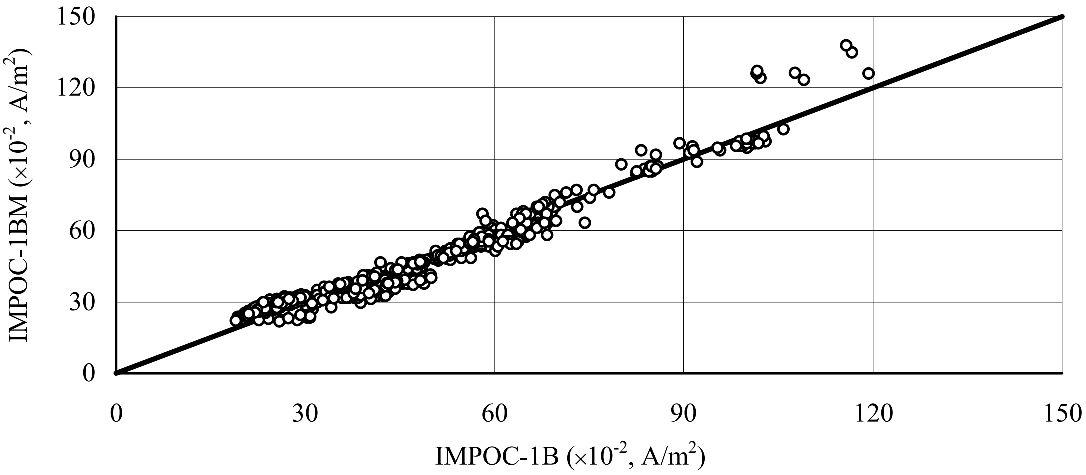


Figure 8. Correlation between the indications of the plants IMPOC-1B and IMPOC-1BM.

Conclusion

The plant IMPOC-1BM on the light-gauge rolled products of low-carbon steel (up to 3 mm in thickness) provides the operating characteristics not worse, than the base design – the plant IMPOC-1B. Besides it ensures the testing at the velocity of the strip motion up to 10 m/s every two meters and has the transducer of diminished size.

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