TESTING OF MECHANICAL PROPERTIES OF THE LIGHT-GAUGE ROLLED PRODUCTS OF LOW-CARBON STEELS IN THE ZINC GALVANIZING LINE BY THE PULSE MAGNETIC METHOD

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Abstract: The paper describes the pulse magnetic method and its implementation in the IMPOC measurement systems for the non destructive on-line control of the mechanical properties of cold rolled low-carbon steels. Practical results of industrial application of the IMPOC-1B installation on the hot dip galvanizing line Nr. 1 at the EKO Stahl company (Germany) are presented. Finally are given some results of experimental investigations for further improvement of the devices for the magnetic pulse control in production lines.

Introduction: Material strength and plasticity are main technical characteristics of the light-gauge cold rolled low-carbon steels. The traditional sampling and the standardized destructive tensile tests of the strip are both time and cost consuming and can not guaranty the quality over the whole length of the coil. Therefore the use of these tests results for characterisation of the process and product stability is restricted. A practical solution of this technological problem is targeted at the installation of non destructive measurement devices for online control directly in the production lines.

The conception of such measuring systems is based on the correlation between the metal structure and the composition on the one hand and the electrical and magnetic properties of the material on the other hand. A detailed analysis of the relationship between these parameters and the strength of different steel grades is given in [1, 2]. In dependence on the selected magnetic parameter and the method of managing of disturbing factors, inevitable during the control of the moving strip (speed, lift-off from the pass line, strip tension deviation and other) different methods and devices for the prediction of the mechanical properties of the rolled material in the production lines are developed. Their classification and detailed analysis are described in [3]. Among the presently existing on-line control means the analysis specially stresses the measurement systems, based on the higher harmonics method [4], the two-frequency magnetization method [5] and the pulse magnetic method [6, 7].

Because of to the high robustness, especially concerning the tolerable lift-off of the strip from the pass line during the strip processing the pulse magnetic method is the most promising method for industrial use. It is widely used in Magnitogorsk, Cherepovets, Novolipetsk (Russia), Mariupol (Ukraine) as well as in EKO Stahl company (Germany).

Method of control: In generally the pulse magnetic method is characterized by a local magnetization of the material to be controlled by one or more pulses of a magnetic field and the measurement of the gradient of the residual magnetization field strength. Main problems in its application for the control of moving strips are the displacement of the strip during its motion, the considerable lift-off of the strip from the pass line (up to ± 10-20 mm), the tension deviation and so on. The elimination of the influence of the moving strip is possible by separation of the processes of the local pulse magnetization and the measurement of the gradient of the normal component of the residual magnetization field strength in space and time. The influence of the strip speed on the results of the local magnetization process of the strip can be eliminated with the help of the right choice of the magnetization pulse duration. The speed effect on the result of the measuring process is removed through the measurement of the maximum of the gradient of the normal component of the residual magnetization field strength (the locally magnetized section has a bell-shaped curve).

Since for the pulse magnetization a coreless solenoid is used a proper choice of the solenoid configuration and the amplitude of the pulse make sure the influence of the measuring clearance on the results of the magnetization is relatively weak. An still higher reduction of the lift-off effect can be realized if the magnetization solenoids are arranged on both sides of the moving strip. Because the strip due to the high demagnetizing factor is magnetized by the tangential components of the field the solenoids must be counter-connected. In this case the magnetisation field of the coupled two solenoid system is directed along the strip length and equal to the double value of the tangential component of the field of one solenoid.

The influence of the strip lift-off is more essentially during the measurement timing of the gradient of the normal component of the residual magnetization field strength, than during the magnetization timing (about 2% of the measured gradient for every 0,1 mm of clearance). The measurement of the maximum of the gradients of the normal component of the residual magnetization field strength from both sides of the moving strip and their averaging allow to decrease this influence considerably. At a distance between the end-faces of the ferroprobe-gradient gauges of 50 mm it is possible to decrease by 5% the influence of a lift-off in a range of ±10 mm when using the arithmetic mean of the maximums of the measured gradients. The same effect can be reached for a lift-off in the range of ±20 mm applying the geometric mean.
Taking into account the results of this perturbation analysis the pulse magnetic method for on-line control of the mechanical properties of steel strips is characterized by the local magnetization of the moving strip from both sides by two axial- aligned counter-connected solenoids, arranged on opposite sides of the strip and by the measurement of the maximum values of the normal component of the residual magnetization field strength from both sides of the strip. After averaging of the measured signals the mechanical properties of the material are predicted on the base of the correlation between the magnetic and mechanical parameters that is determined in advance.
The principle of the on-line control of steel strip by pulse magnetic method is depicted in Fig.1.

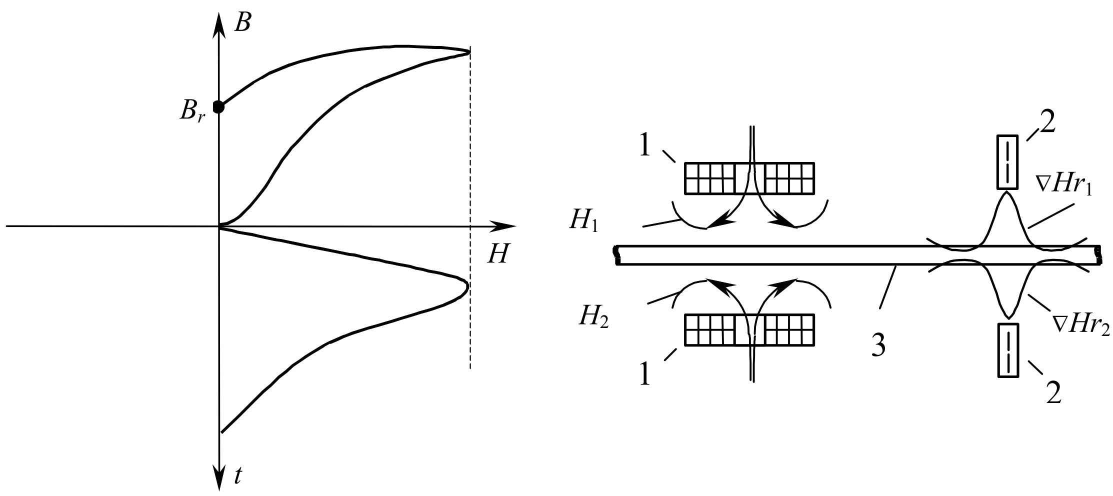

Fig. 1 Measurement principle: 1 – magnetizing solenoids;
2 – ferroprobe-gradient gauges; 3 – strip

The normally used ferroprobe-gradient gauges for measurement of the gradients of the magnetic field strength by direct measurement of the second harmonic don't provide the high metrological characteristics due to their low thermal and temporal stability of the ferroprobes and the nonlinearity of their transformation characteristics. Additionally in such measuring method increased demands to the stability of the excitation current of the ferroprobe and of the measuring channel are required. In this case the multiplicative deviation can amount to several percents.
The application of the well-known compensation methods for improvement of the mentioned characteristics in pulse magnetic on-line control is difficult due to the small spot of the magnetized section and the high speed of the test sample. High metrological characteristics and the avoidance of the influence of external parameters as well as of slowly changing magnetic fields can be achieved when the determination of the gradients of the residual magnetization field strength doesn't use the signals from the ferroprobe-gradient gauge but the value of the current through the compensation coils by means of separation in time the comparison of the signals from the magnetized section and the compensation coils.

The influence of the magnetic prehistory on the test results was considerably reduced as a result of the pulse magnetization with an amplitude higher than 10^5 A/m. The edge effect of the strip was found depending not only on the amplitude of the magnetizing pulses and the sizes of the solenoid, but also on the material thickness. With an increase of the thickness the edge effect rises too. The assessment of the IMPOC systems revealed, that the edge effect doesn't exceed 0,5 m.
Concerning the influence of the strip tension it was observed that not the value of the applied tension stresses but its deviation in the time interval between the magnetization and the measurement of the gradient of the residual magnetization field strength has to be taken into account. The deviation of the strip movement relating to the elements of the transducer by an angle of up to 20° has no influence on the measurement results.
IMPOC family: On the base of the discussed control method a family of pulse magnetic on-line controller of type IMPOC-1, IMPOC-1A, IMPOC-1B, IMPOC-2 and IMPOC-3 was developed where each of the devices is different by its functionality and circuit design. The IMPOC-1 device guaranties the independence from the influence of strip lift-off in the range of up to ±10 mm, where the systems IMPOC-1A, IMPOC-1B, IMPOC-2 and IMPOC-3 - in the range of up to ±20 mm. The control of the material can be executed at a strip speed from 0,5 m/s to 5 m/s (IMPOC-1, IMPOC-1A, IMPOC-1B) and from 1 m/s to 25 m/s (IMPOC-2 and IMPOC-3).
The main specification of the IMPOC systems are shown in table 1.

Table 1. The specification of the systems type IMPOC

Strip thickness, mm	
IMPOC-1, IMPOC-1A	0,15-10
IMPOC-1B	0,15-12
IMPOC-2, IMPOC-3	0,15-15
Strip speed, m/s	
IMPOC-1, IMPOC-1A, IMPOC-1B	0,5-5
IMPOC-2, IMPOC-3	1-25
Permissible strip lift-off from the pass line, mm	
IMPOC-1	±10
All the others	±20
Amplitude of the magnetic field pulses, A/m	
IMPOC-1, IMPOC-1A	$1,3\cdot10^5$
IMPOC-1B	$3,2\cdot10^5$
IMPOC-2, IMPOC-3	$5\cdot10^5$
Upper range of measurement of the gradient of magnetic field, A/m^2	
IMPOC-1, IMPOC-1A	$3,2\cdot10^4$
IMPOC-1B	$5\cdot10^4$
IMPOC-2, IMPOC-3	$3\cdot10^4$
Weight, kg	
IMPOC-1	68
IMPOC-1A	70
IMPOC-1B	84
IMPOC-2	145
IMPOC-3-	150

IMPOC-1B: For prediction of the mechanical properties of rolled strip at a speed of up to 5 m/s the most promising system is IMPOC-1B (Fig. 2).
Structurally the system consists of two transducers, generator and measuring unit. Each of the two transducers includes the magnetizing solenoid and the ferroprobe-gradient gauge, fixed on a distance of 300 mm from the centre of the magnetizing solenoid in the direction of strip motion. The distance is chosen considering that the centre of the magnetized section over the whole range of the applied strip speed approaches the ferroprobes after

termination of the magnetizing pulse. The magnetizing solenoid and the ferroprobe are mounted in a textolite base. The transducers are arranged from both sides of the strip symmetrical to the mean plane of its motion (the pass line).

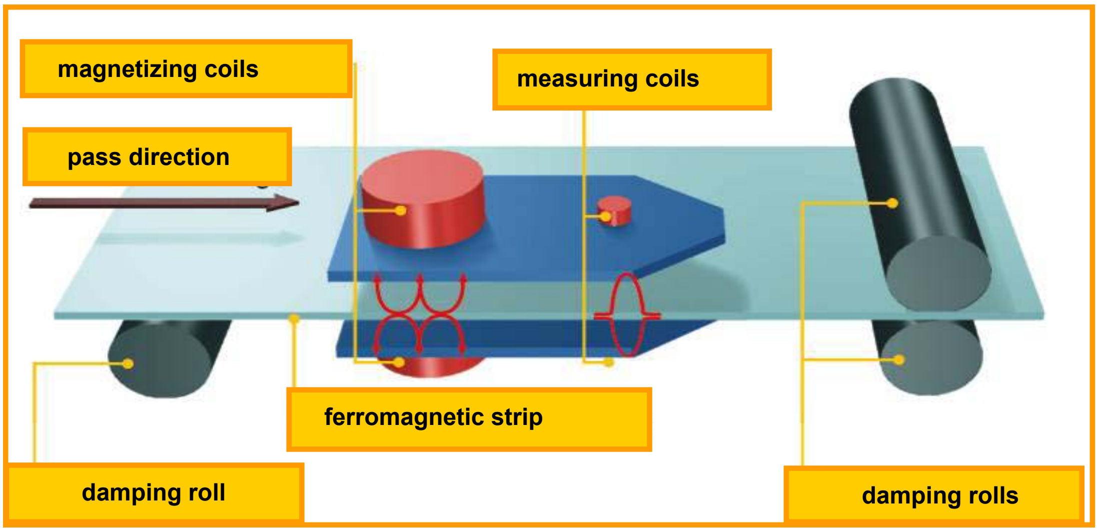

Fig. 2 Structure and measuring arrangement of IMPOC-1B system

The clearance between the transducers is equal to 50 mm. The pulse amplitude of magnetizing field on the end-face of each transducer is $3{,}2\cdot10^5$ A/m, the pulse duration is 10 ms. In order to avoid the interference of the magnetizing pulse on the measuring circuit the measuring cycle is blocked during the pulse duration. The frequency of the magnetizing pulses is specified proportional to the strip speed: a strip speed of 5 m/s corresponds to a magnetizing pulse frequency of 1 Hz, a strip speed of 0,5 m/s - to 0,1 Hz. In this case the distance between the magnetized sections is equal to 5 m.
The control is carried out by using the arithmetic or the geometric mean of the maximum values of the gradients of the normal component of the residual magnetization field strength, measured from both sides of the sheet.
For measurement of the gradients of the residual magnetization field strength the compensation method is applied. That allows to increase the temporal and thermal stability of the measurement and to improve the linearity. Additional to the determination of the arithmetic mean the IMPOC-1B system makes the control by the geometric mean of the measured gradients possible. In this way the tolerance of the permissible lift-off of the strip could be increased by twofold (up to ±20 mm).
Beyond the control of steel strip the IMPOC-1B system can be used for prediction of the mechanical properties of single sheets. In this case the edge effect has to be taken into account. That means that the magnetization of the single sheet must be executed on a distance of 0,5 m from its edges. Therefore the length of the sheet should be higher than 1 m.
Other additional features of the IMPOC-1B system are the increased amplitude of the magnetizing pulses by 2,5 fold (in comparison to IMPOC-1 and IMPOC-1A) and the modified shape of the magnetizing solenoids that makes possible to extend the thickness range of the tested material up to 12 mm. At the same time the permissible lift-offs of the moving strip can be increased up to ±30 mm even in the case of a clearance between the elements of the transducer of 100 mm.
Metrological support: For the metrological support of the IMPOC systems a sophisticated calibration method without use of control samples was developed. The calibration is carried out by a special measure of the gradient of the magnetic field (MGPD) and a pulsating current source (simulator). A magnetic field is simulated in space and time the gradient of which is similar to the gradient of the field of the locally magnetized strip when moving

between the ferroprobes.

The MGPD measure is based on the principle of setting up a magnetic field using axial-aligned ring coils. The special feature of these measures is that they create a magnetic field with a constant gradient in the two working zones. The value and the sign of this field in each working zone coincide with the value and the sign of the magnetic field of the both sides magnetized specimen.

The working principle of the simulator is based on the generation of a current pulse through the MGPD measure by sequential search of $2N$ values of the gradients of the residual magnetization field, measured on a fixed sheet and stored in the memory of the simulator at a rate that is proportional to the speed of the strip.

Industrial tests and application: The industrial tests and application of IMPOC-1B systems were carried out in strip cut-to-length lines and in hot dip zinc and aluminium galvanizing lines. The practical interest for IMPOC application include both the improvement of the actual product and/or process control systems and the optimisation of the technological processes.

As a part of the product control system the IMPOC installation allows to set up a statistical process control by monitoring the mechanical properties over the whole strip length. Although the destructive tensile test is normally defined as the final quality inspection test, the IMPOC measurement gives a valuable additional documented information about the tolerance field of the mechanical properties in the coil. In agreement with the customer the IMPOC display can be used as final material test reducing in this way the material inspection costs.

The application of IMPOC system for process optimisation is as manifold as the technological parameter effecting the mechanical properties of the material. Irregularities in the temperature regimes during slab heating, hot rolling and annealing processes can be revealed. The IMPOC system detects inhomogeneities in the material behaviour resulting from unplanned line stoppages or from the deviation of technological parameter at the coil ends. This information is practical useful for optimisation of the strip cropping length or the coil cutting preconditions.

The arrangement of an IMPOC-1B system in the continuous hot dip galvanizing line Nr.1 of EKO Stahl company is depicted in Fig. 3. This line is intended for galvanizing of LC, HSLA , construction and IF steels in the range of 0.35 - 3,0 mm in thickness and 660 - 1600 mm in width. The mass of the coil is max. 34 t (entry) and 16t (exit) . The maximum processing speed of the strip is 180 m/min. The annual production capacity is about 450 kt.

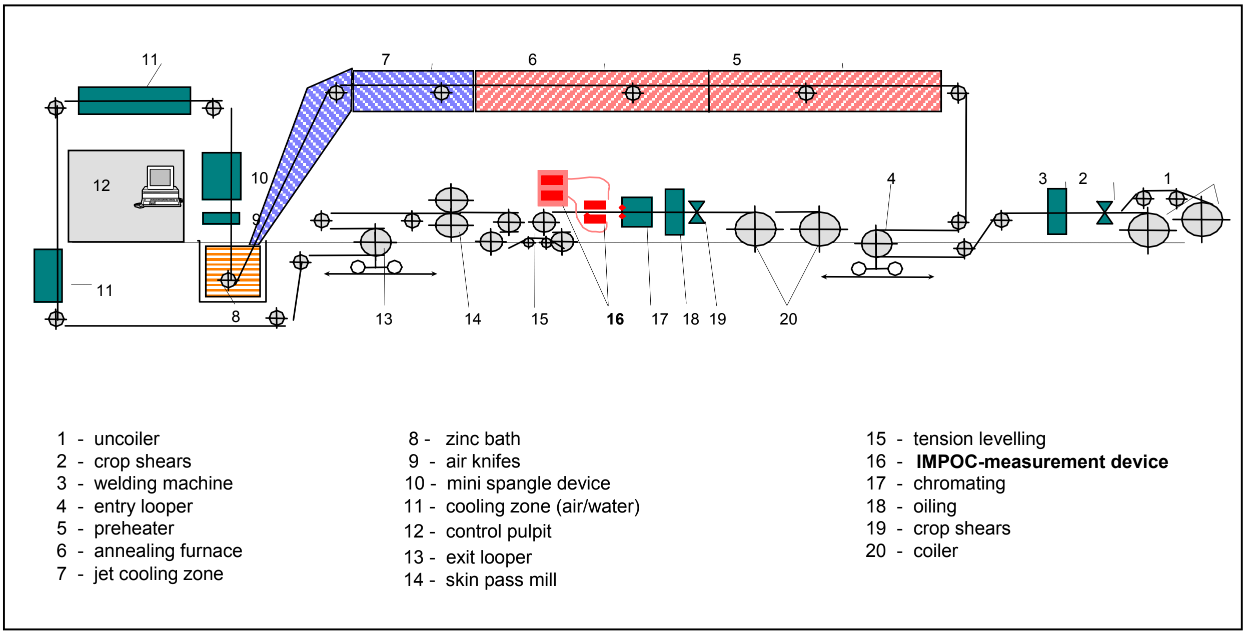

Fig. 3 Layout of the hot dip galvanizing line Nr 1 with IMPOC-1B application

The installation of the transducers was chosen at the exit of the line after the shin pass mill and the tension levelling line, where the mechanical properties of the galvanised steel strip are fully pronounced. The PC for data collection and processing of the measured IMPOC signals is located in the main pulpit at the production line. Here arrive all information characterizing the strip under processing (e.g. strip identification code, steel grade, dimension), the technological process (e.g. processing speed, skin pass and levelling deformation) as well as the IMPOC signal, proportional to the gradient of the residual magnetization field strength. On the PC monitor in the main pulpit of the galvanizing line are continuously depict the graphs of the mechanical properties of the running strip, which are calculated from the IMPOC signals using steel group related regression equations and other technological parameters by choice. The actual mechanical properties, normally the tensile and yield strength, are compared on-line with the standard values of the steel grade or the customer related limits. The measuring error in prediction of the mechanical steel properties is 5 % for yield strength and 10 % for tensile strength.
At the end of each coil the PC generates a statistical analysis of the measured data of the final coil and a record of the mean value and standard deviation of the mechanical parameters as well as of the product capability is stored.
Figure 4 depicts a typical record of the mechanical properties of a hot dip galvanized steel strip predicted by the IMPOC-1B system.

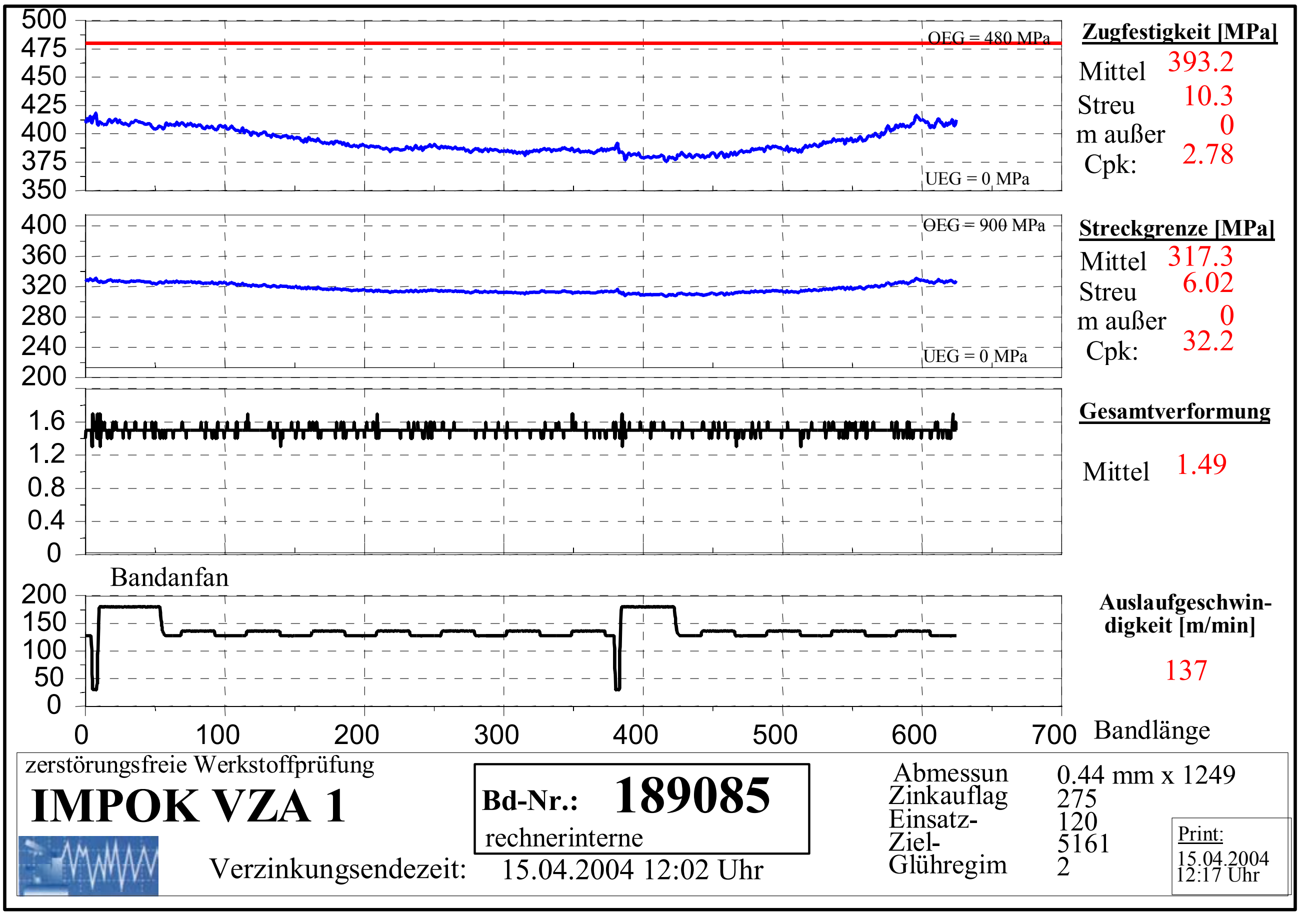

Fig. 4 Quality record of coil Nr. 189085 from the EKO Stahl hot dip galvanizing line 2

Further development of the pulse magnetic method: The industrial tests and application of the IMPOC control systems actually lead to new wishes and expectations for increasing their efficiency. Most important demands require the improvement of the statistical reliability of the correlation between the magnetic and mechanical properties as well as the use of this control system for determination of the steel formability (*r*-value)
To establish a better correlation between the measuring results of the IMPOC-1B system and the mechanical properties of the steel strip an investigation was undertaken to prove whether other parameters of the locally magnetized section of the strip, than the gradient ∇H_{rn} of the normal component of the residual magnetization field strength could be implemented in the statistical analysis. Thus besides the gradient ∇H_{rn} the gradients of the radial $\nabla H_{r\text{p}}$ and of the azimuthal $\nabla H_{r\varphi}$ components of the residual magnetization field strength as well as the length l_0 of the magnetized section where the related component retains the same polarity, were considered additionally. The experimental trails included the investigation of the distribution law of the mentioned above components of the residual magnetization field strength at different annealing temperatures and the determination of the influence of the strip lift-off on the measuring results.
The statistical analysis confirmed, that in the pulse magnetic control method the maximum of the gradients of the normal ∇H_{rn}, radial $\nabla H_{r\text{p}}$ and azimuthal $\nabla H_{r\varphi}$ components of the residual magnetization field strength and also the length of the positive part of the ∇H_{rn} -distribution in rolling direction can be used as statistical relevant parameters. Already the application of a two-dimensional model allows to rise the correlation coefficients *R* noticeable. The highest *R*-values (0,8344–0,9189) were observed in simultaneous measurement of ∇H_{rn} and $\nabla H_{r\text{p}}$. Three-dimensional models enable to increase the correlation coefficient by simultaneous measurement of ∇H_{rn},$\nabla H_{r\text{p}}$ and $\nabla H_{r\varphi}$ up to 0,8936-0,9446 and the use a four-dimensional model gave a rise of the correlation coefficient up to 0,9335–0,9445.
Similar experimental investigations for measurement of the anisotropic properties of the steel samples indicated, that as a consequence of the opportunity for additional measurement of the radial and azimuthal components of the residual magnetic field strength it seems to be possible to predict the texture related *r*-value by pulse magnetic IMPOC method. The statistical analysis of the correlation between the gradient of the azimuth component of the residual magnetic field strength $\nabla H_{r\varphi}$ and the coefficient of normal anisotropy *r* in rolling direction on samples from different steel companies revealed correlation coefficients in the range of R = 0,53 – 0,8. A final assessment of the of the extended IMPOC measuring method for industrial application requires further extensive statistical investigation.
Conclusions: 1. The magnetic pulse method has proved itself as a robust system for continuous online control of the mechanical properties of steel strips under industrial conditions.
2. The application of the IMPOC-1B system for product and/or process control allows:
- to improve the productivity of the production line due to the elimination of line stoppages for sampling for selective destructive and non destructive material inspections;
- to control and optimize the technological process;
- to deliver products with guarantee for the mechanical properties over the whole coil;
- to decrease time and costs for mechanical tests;
- to reduce the number of staff, employed in mechanical tests and improve their working conditions.

3. The increase of the dimension of the correlation models with the help of the additional measurement of the maximum of gradients of the normal ∇H_{rn}, radial $\nabla H_{r\text{p}}$ and azimuthal $\nabla H_{r\varphi}$ components of the residual magnetization field strength, and of the length of the positive part of the ∇H_{rn} -distribution in rolling direction substantially improves the correlation between the magnetic and mechanic properties, including the characterization of the formability.
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