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Magnetic inductive on-line measurement system for mechanical properties within a hot-dip galvanizing line

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As quality demands for rolled flat steel products increase, there is a growing need for on-line processes to characterize material properties in strip plants. Fullest-possible monitoring of important product properties during production is the key to maintaining high quality levels and process stability. On-line measuring of yield point and tensile strength is possible using commercially available equipment and is already practiced in some steel industry strip plants. Physical measuring processes are used to determine material characteristics which correlate with mechanical properties.
The article describes how the magnetic inductive measuring system Impoc works and reports on operating experience after extended use in a hot-dip galvanizing line at ThyssenKrupp Stahl AG. Based on examples, the measuring accuracy attained with various steel grades is described and possibilities of detecting coarse grain are illustrated.

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The capacity of modern strip plants in the steel industry such as hot-dip galvanizing lines and the high quality demands in terms of material characteristics increasingly call for qualitative on-line process monitoring. While plant technology has become highly developed as regards automatic process control, on-line processes to characterize material properties have, for some years now, been adopted by the companies at an ever increasing pace. Full monitoring of important product properties during production is required in order to maintain a high level of quality. Various layer thickness measurements, surface inspection processes, and roughness measurement methods are just a few examples. On-line information on mechanical properties is also becoming increasingly important. On-line measuring of yield point and tensile strength is, to some extent, still at the exploratory stage [1]. Some strip plants, however, are already fitted with integrated systems that provide valuable information for plant operators. Physical methods of measurement are used to determine material parameters which correlate with mechanical properties.

The EMG Impoc equipment is such a system working on the principle of magnetic induction. Two of these devices have been successfully used over a period of time in the two hot-dip galvanizing plants at Eko Stahl GmbH. The following report portrays the functioning of the measuring process and describes experience with a new Impoc device gathered in the Ferndorf hot-dip galvanizing plant of ThyssenKrupp Stahl AG.

Impoc measuring system

Principle of operation. The Impoc measuring system comprises two identical measuring heads positioned one on the upper and one on the lower side of the strip, **figure 1**. Each measuring head is made up of a magnetizing coil to periodically magnetize the strip and a probe to detect the gradient of residual magnetic intensity (residual magnetic gradient).

Magnetizing coil. A measuring cycle starts with the local magnetization of the moving strip using the two magnetizing coils. They are connected in series so that the pulsed current generates magnetic fields in the two coils isochronously.

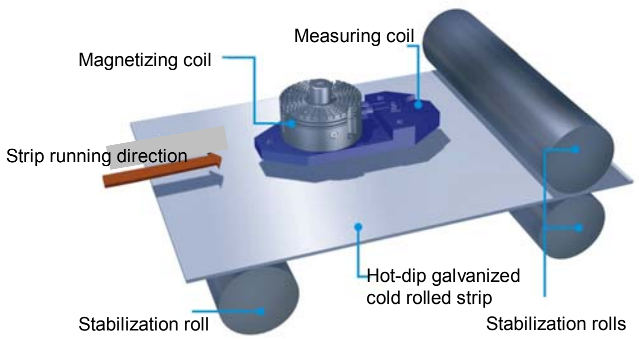

Fig. 1 Schematic design of the Impoc measuring system

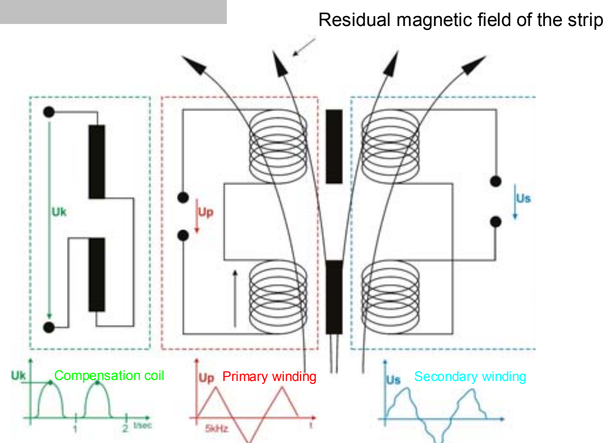

Fig. 2 Operating principle of the Impoc probe

The main direction of propagation of the field which extends for only approx. 15 ms is vertical to the coils. Due to the high amplitude of the magnetizing pulse, the moving ferromagnetic strip is magnetised to saturation.

The magnetizing coils are supplied with generator electronics which also permits strip length synchronous sampling with a maximum pulse frequency of 1 Hz. The design of the measuring head ensures that once the magnetizing pulse decays the probes detect only the residual field of the strip.

Probe. In addition to the magnetizing coil, each measuring head is fitted with a probe to detect the gradient of the normal component of the residual magnetic intensity (remanence) of the moving strip.

The basis for field intensity measurement is a flux-gate magnetometer, the so-called Förster probe, **figure 2** [2]. The operating principle is that of a transformer, the coils of which are switched against each other on the secondary side. If there is no field or a homogeneous external field, the voltage induced by the primary winding is identical in both secondary coils and the measuring signal is zero. When an external field intensity gradient is present, one coil core is more strongly penetrated by the external field than the other so that a measuring signal is generated.

The primary winding is supplied with triangular supply voltage of 5 kHz. The first harmonic wave (10 kHz) is filtered from the actual measuring signal, as this is a measure for the magnetic induction (residual magnetic field) [3]. After synchronisation of the supply voltage and the harmonic wave, the measuring signal is rectified. Using a third differentially wound coil which is also installed in the probe, see **figure 2**, the external strip field is compensated for using the modified measuring signal.

This ensures that the measurement is always made at the same point (close to zero), i.e., magnetic non-linearity is compensated for. Based on the coil arrangement within the probe and the measuring principle, temperature compensation is also provided. Therefore temperature fluctuations of the strip or of the environment in which measurements are being made do not affect the result. Another benefit of measuring the field intensity gradient is the fact that any superimposed interfering field, e.g. from a drive motor or from the magnetic field of the earth does not affect the measured result.

The actual measuring cycle is started only once the magnetizing pulse has decayed. The locally magnetised strip moves through the two measuring probes. The proper measured variable, which is the compensating current per side, first rises as a function of the field intensity gradient of the strip, reaches its maximum and then decays, see **figure 2**.

The pattern of the compensating current throughout one measuring cycle is that of a bell-shaped curve with the maximum amplitude indicating the field intensity gradient of the strip. The maximum amplitudes of the compensating current are saved by the evaluation electronics and provide the central measured variables. The following calculation of the mean value from the signals of the two measuring heads largely eliminates the influence of strip vibrations that cannot be avoided within the production line.

Total system in a strip plant. Some selected technical data for the measuring system is gathered in **table 1**. The installation of measuring heads within the line is made on an electromotor-driven traversing unit with a working distance of 25 mm on each side of the moving strip.

The traversing unit first ensures that the minimum distance of 500 mm from other components is maintained in order to prevent accidental magnetisation of ferromagnetic components close to the measuring system.

Secondly, the traversing unit enables the measuring heads to be locked in an installation/safety position and at any measuring position in the line across the strip width.

The special electronic components for activation of the measuring heads are accommodated in an air-conditioned switch cabinet, close to the measuring equipment. From there, the measuring system communicates with the visualisation and control PC via Profibus. The PC location can be almost freely selected within the system. It is reasonable to have it installed in a main control stand.

The PC serves to provide on-line display of tensile strength and yield point for the moving strip. With graphic visualisation of these parameters and specific definition of warning and intervention limits to suit the particular grade of steel for on-line display, the plant operator can better support and intervene in the process (e.g. furnace control, strip speed, degree of skin-pass rolling).

Besides tensile strength and yield point, coil-related statistical parameters (mean value, standard deviation, material length outside defined warning limits) are stored in a file for permanent quality control. Furthermore, the PC enables subsequent qualitative analysis of measured data and the parameterization of the measuring system.

Strip thickness	0.15 – 12 mm
Strip width	> 500 mm
Max. strip speed	300 m/min
Working distance	50 mm between measuring heads, i.e., approx. 25 mm between strip and measuring head
Measuring frequency	synchronous with the strip length, max. 60/min
Measuring head size (L ▪ W ▪ H)	520 mm ▪ 220 mm ▪ 180 mm
Built-in length (in strip running direction)	approx. 1.5 m

Table 1: Impoc measuring system technical data

Operational experience from a hot-dip galvanizing plant

Installation. The Impoc device was installed early in 2001 at the output end of the Ferndorf hot-dip galvanizing plant of ThyssenKrupp Stahl AG. The plant produces large quantities of hot-dip galvanized strip. **Figure 3** shows the installation position of the measuring heads with respect to the moving strip. The rather large distance between the measuring heads and the strip, i.e., approx. 25 mm, ensures trouble-free operation. A plastic plate is fitted to prevent direct contact between the measuring head and the strip, so as to protect the measuring heads from strip vibrations or wavy edges. Furthermore, the system can be moved to the side at any time as a result of an escape warning signal from the strip line. The measuring heads may be positioned at any point across the strip width. In the Ferndorf plant, however, data is captured only in the strip centre. During constant operation over 18 months, the measuring system has not experienced any failures.

Visualisation of measured data and of mechanical parameters calculated using linear regression equations is made on a PC within the outlet control stand. In addition, the PC serves for the storage and analysis of measured data.

Measurement calibration. The measurement is calibrated using samples from the strip centre (transverse samples) of all tested coils. From precise assignment of the results of destructive testing an extensive data stock could be established. As a matter of fact regular steel grades are more strongly represented than "exotic" grades. This must be allowed for in statistical evaluation.

Fig. 3 Installation of the measuring system in the hot-dip galvanizing line

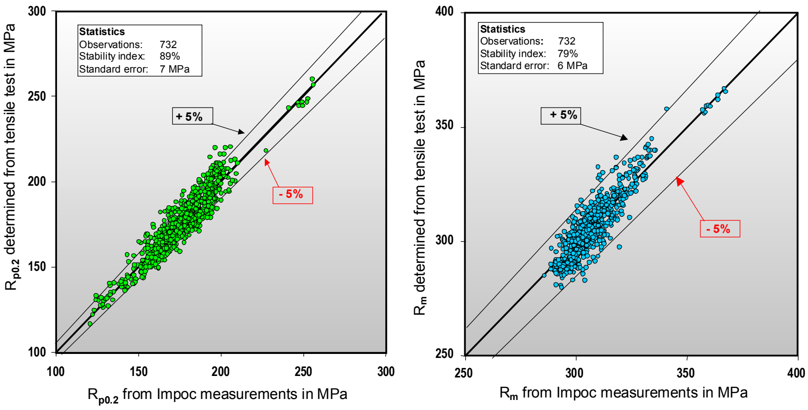

Fig. 4 Results of regression analysis for yield point and tensile strength in IF steels

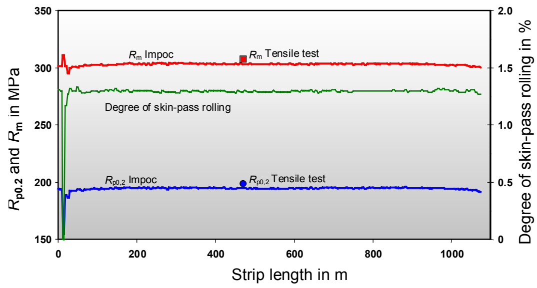

Fig. 5 Example of an Impoc measured curve with values obtained by subsequent destructive testing

Using the measured data and the models of Eko Stahl GmbH, the steel grades were classified into various material classes and then analysed using regression. The proven multiple linear regression accounts for the measured Impoc value, the sheet thickness, and the total deformation (yield and degree of skin-pass rolling). Linear functions of the following type were calculated:

$$R_x = k_1 + k_2 \cdot H_I + k_3 \cdot d + k_4 \cdot V_{ges}$$

where

- R_x : mechanical parameter $R_{p0.2}$, R_{eL}, R_{eH} or R_m
- k_i : regression coefficients
- H_I : measured Impoc value
- d : sheet thickness
- V_{ges}: total deformation

The objective was to generate as few material classes as possible.

Taking the example of soft IF steels (grades DX53D+Z and DX54D+Z), the result of the regression calculation is represented for yield point and tensile strength, see **figure 4**. Furthermore, the 5 % limits with respect to the deviation from the value obtained in destructive testing are shown. The graphics show that, with reference to the yield point, over 81 % of all values differ by less than 5 % from the absolute value of the related tensile test. With respect to tensile strength, almost 100 % of all measured values are within the 5% window.

Basic steels, construction steels, high-strength steels and hot-rolled strip were gathered in further groups with similar results. The stability indices for these regressions are currently between 75 and 85 % with standard defaults of approx. 10 to 15 MPa. Experience has shown that it is reasonable to treat hot-rolled and cold-rolled strip of the same steel grade separately, an exception being hot rolled IF steels which can well be grouped with cold-rolled strip.

It has also become apparent that the measurement of more complex steels, e.g. multiphase steels, requires special care in terms of calibration. Some influences on magnetic behaviour are still unclear and require e.g. the analysis of so-called “outliers” from the regression models. The present co-operation with material scientists is useful and essential in this context.

Results. Using the regression models, the measured results are immediately converted into mechanical parameters in the measuring PC and then displayed and stored.

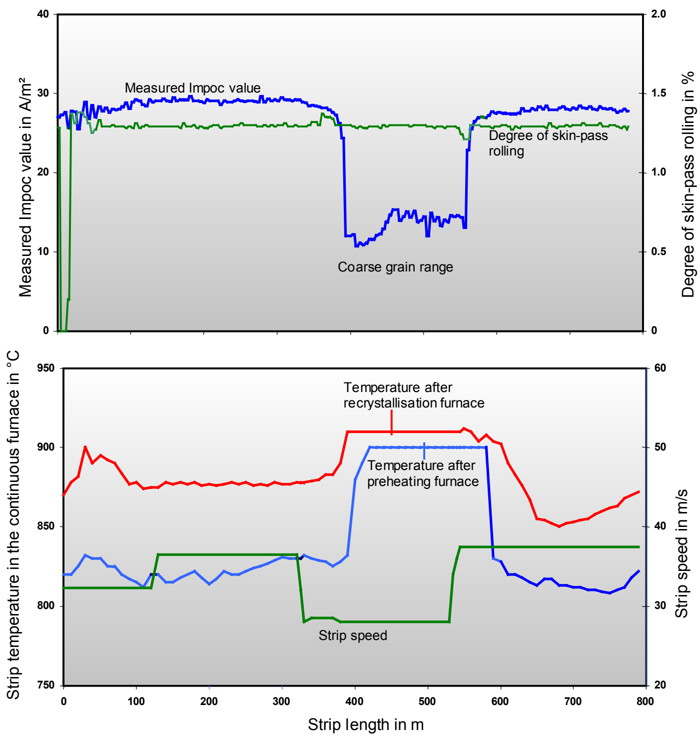

Fig. 6 Impoc measurement and process data of a galvanized IF steel strip displaying coarse grain as a result of temporary line faults.

An example of a measured curve can be seen in **figure 5**. Furthermore, the results of later tensile tests are shown. There is a good correlation. Of course, throughout the long measuring campaign, system failures occurred from time to time and occasionally inhomogeneous material was detected. While only random samples are checked when common testing is carried out using strip end samples, on-line measurement allows for full evaluation. This is the strength of the on-line system. An extreme example is shown in **figure 6**. During recrystallization annealing, as in the case of hot-dip galvanizing in continuous furnaces, some steel grades react sensitively to excessive temperatures. The structure clearly becomes coarser, and an undesirable deterioration in mechanical properties occurs. In the example in **figure 6**, the plant was operated approx. 20 % slower than usual for a short time due to line fault. As a result, the strip temperature rose above the critical limit, and coarse grain was partially produced. In this area, the Impoc measurement shows a clear drop in measured values. The result of such a failure is shown in **figure 7** using laboratory measurements carried out on ZE thin sheet. On inspection the annealed and galvanized material showed an undesirable surface in some areas which is due to coarse grain resulting from hot rolling. The results of visual inspection of the blocked strip was confirmed by Impoc measurement and metallographic examination.

Outlook

On-line measurement methods for mechanical parameters make a positive contribution to closing a gap in total quality control of continuous strip plants. The Impoc measurement process has stood the test in on-line use. Above all, the results for homogeneous steels such as IF steel agree very well with those obtained by destructive testing.

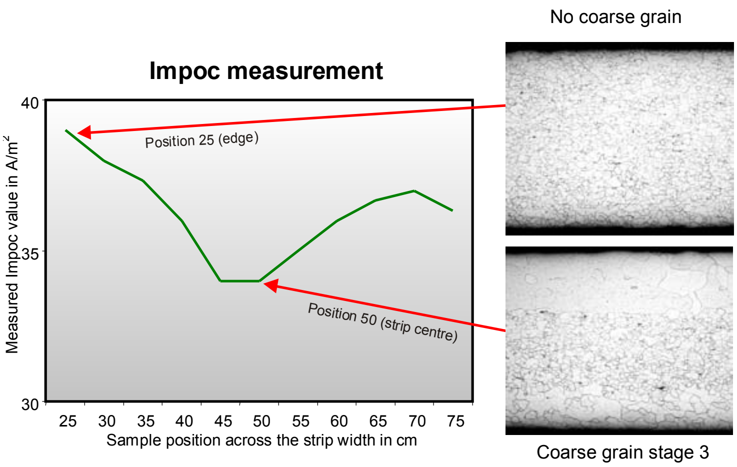

Fig. 7 Impoc measurement of sheets with coarse grain and micrographs from selected samples

Nevertheless further experience has to be gained in terms of measurements of special steels. For this purpose, measuring equipment was recently installed in the new hot-dip galvanizing plant 8 of ThyssenKrupp Stahl AG, which is mainly used to produce thin galvanized sheet for demanding applications in the automotive sector. Here the measuring equipment will be further developed, and the regression models will be refined.

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