MECHANICAL PROPERTY DETERMINATION OF HEAVY STEEL PLATES AND COLD ROLLED STEEL SHEETS BY MICRO-MAGNETIC NDT

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Abstract: The presentation is to results recently obtained in collaborative research in the European steel programme performed by Fraunhofer-IZFP and co-operative steel industry producing rolling products. The objective was and is to characterize - i.e. to predict - mechanical properties like hardness, yield strength, tensile strength, deep drawing parameters r_m and Δr, etc., mainly online by use of contact-less NDT. The approach performed - developed a decade before - is by micro-magnetic NDT was optimized and especially adopted to sensitively classify a wider range of steel grades. The contribution reports to the technology development, the transducer optimization and the technology qualification.

Introduction: Mechanical properties are quality parameters characterizing the fitness for use of rolled products. State of the art to determine yield strength and tensile strength is the selection of standardized specimens at the end of the process and destructive testing according to the definition in the inspection laboratory using standard tensile testing machines. Hardness measurements are performed by using standardized indentation techniques according to Brinell or Vickers. Not satisfying for the producer is the fact that the material – per definition – is destroyed or locally damaged and that this kind of material examination can be performed only statistically and not continuously online.

There is therefore the tendency to develop non-destructive (ndt) techniques which – after a calibration by using the destructive techniques - can replace the destructive test. In the institute of the authors the topic is an objective and for years ndt-technology was developed and introduced into online process monitoring and control of production lines in the steel industry [1]. Besides ultrasonic techniques based on phase velocity measurements to characterize texture in cold rolled steel sheets and the vertical and planar anisotropy parameter (r_m and Δr) by using EMAT [2] mainly electromagnetic, respectively micro-magnetic techniques were applied [3] and introduced into practice under the acronym 3MA (Micro-magnetic, Multiparameter, Microstructure and Stress Analysis). Micro-magnetic techniques are especially suitable to determine mechanical properties because there are many similarities between the interaction with microstructure parameters and lattice defects and movement of dislocations under mechanical loads and the movement of Bloch-walls under magnetic loads. Figure 1 documents this fact.

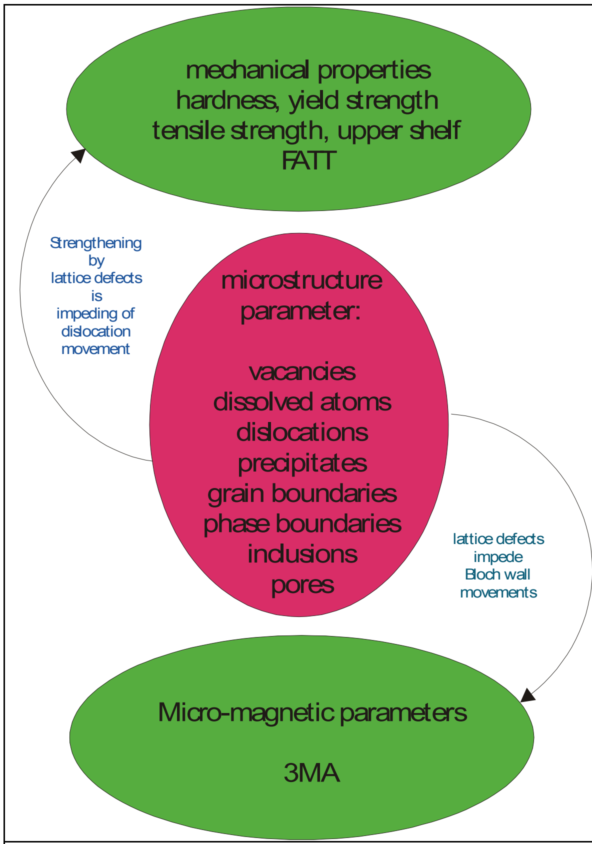

Figure 1: Micro-magnetic microstructure characterization, 3MA

Figure 2: 3MA inspection System

3MA is the combination of different micro-magnetic testing procedures: The measurement of the magnetic Barkhausen noise, the incremental permeability, the higher harmonic analysis of the tangential magnetic field and an eddy current impedance measurement. Over all, 22 different parameters are derived by the measurement and can be combined in a multiple regression model in order to determine the mechanical properties [3]. The special intelligence is designed into the transducer head, based on a u-shaped yoke magnet, which by time-multiplexing allows the allocation of all parameters. The 3MA-systen is shown in Figure 2. The magnetic field strength applied was up to 40A/cm.

Application on heavy steel plates: In co-operation with the companies Dillinger Hütte AG, IRSID, Fabrique de Fer, Salzgitter AG and ThyssenKrupp-Stahl AG a research project was performed under the umbrella of the European Community of Coal and Steel. Table 1 documents the material selected by the companies of the different partners. Coupons were taken from the running production and destructively tested in the inspection laboratory of one partner. Each of the 88 coupons was measured at 8 different positions in order to have a better statistical approach. The values from position 1-4 were used for calibration and the values from position 5-8 for verification. The regression model applied here was based on 17 unknown coefficients and polynomials in the micro-magnetic parameters up to the 2nd order but also non-linear terms like mixed products and quotients. As target functions hardness, yield strength and tensile strength were selected. As function of the hardness a regression coefficient R with R^2= 0.97 can be found and a residual standard deviation ΔHardness=11.9 HB-units.

Table 1. Inspected material

Steel grade	Heat treatment	Thickness range in	Specimens

		mm	
S355	Normalized after (N) or during (NE) rolling	10-110	52
690 type	Quenched (Q) or quenched and annealed (QA)	15-80	36

In the case of the yield strength R^2=0.98 and $\Delta R_{p0.2}$=20.9MPa, the span length of the hardness was 147-522 HB-units and in the case of the yield strength 325-1010MPa. Figure 3 and Figure 4 document the comparison between non-destructively predicted yield strength and tensile strength values and the destructively determined findings.

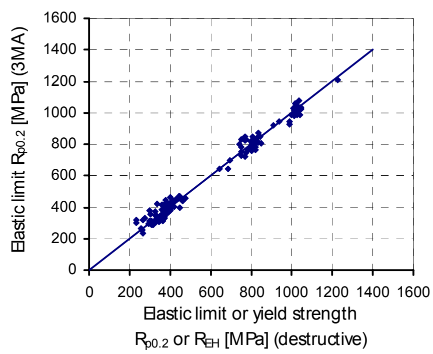

Figure 3: Verification of the yield strength on coupons

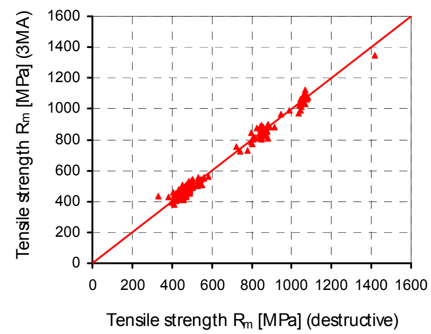

Figure 4: Verification of the tensile strength on coupons

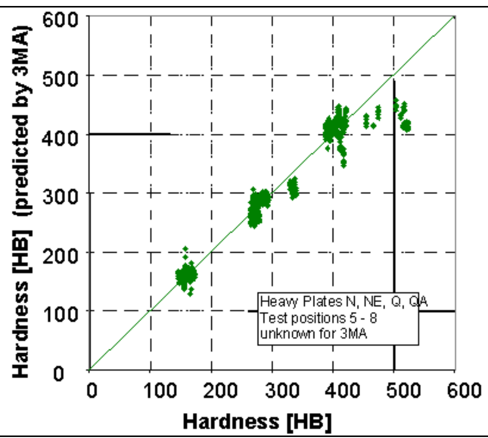

Figure 5: Verification of the hardness prediction, plates of the qualities N, NE, Q and QA

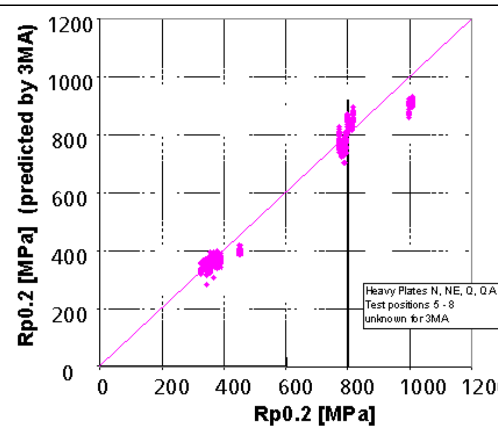

Figure 6: Verification of the yield strength prediction, plates of the qualities N, NE, Q and QA

The calibration was also tested on heavy steel plates of which the destructive values were determined after performing the 3MA-inspection. Figure 5 and Figure 6 represent the results and Table 2 documents the residual standard deviation as the differences ($\Delta R_{p0.2}$, ΔR_m, ΔHardness) between the values predicted by ndt and the values of the destructive test. If the calibration is limited to the material of only one producer then the model can be enhanced by reducing disturbing site effects.

Table 2: Results obtained by 3MA

Plate thickness [mm]	$\Delta R_{p0.2}$ [MPa]	ΔR_m [MPa]	ΔHardness [HB]
All steel producers mixed	36	34	13
Plates selected according to one producer	21	-	11

In order to perform the ndt on plates in the plant a remote controlled trolley was developed of which the 3MA transducer can half-automatically be moved along the surface of a heavy steel plate. A brushing device was integrated into the trolley in order to remove scale which otherwise is a strong disturbing influence parameter. Figure 5 shows the trolley in operation on a heavy plate on the roller table and Figure 6 shows the control desk for remote control of the trolley and the 3MA measurement.

Figure 7: Trolley in operation on a heavy plate

Figure 8: Control desk for remote control of the trolley and 3MA measurement

In addition to the 3MA-technique ultrasonic time of flight measurements were performed insonifiying in the plate thickness direction. A compression wave (t_{long}) and linearly polarized shear waves were applied polarized in the rolling (t_{shR}) and in the transverse direction (t_{shT}). In order to be independent of the plate thickness the relative time of flight ratios were discussed (t_{shR}/t_{long}, t_{shT}/t_{long}, $(t_{shR} - t_{shT})/t_{shT}$). Also here a correlation to the mechanical properties can be obtained. In table 3 the results are presented and compared with the 3MA results.

Table 3: The combination of UT data and 3MA

Technique	$\Delta R_{p0.2}$ [MPa]	ΔR_m [MPa]	ΔHardness [HB]
Regression with the 3 most significant 3MA parameters	36	20	10
Regression with the 3 most significant UT parameters	26	17	7
Regression with 17 3MA parameters	23	12	5
Regression with 17	11	10	4

Parameters combining 3MA + UT			

The combination between 3MA and ultrasonic data tremendously reduces the difference between the mechanical parameters predicted by ndt and the destructively determined values, which now are in the same range as the accuracy of the destructive tests.

Application on cold-rolled steel sheets: In a second project in the European Coal and Steel programme performed with ThyssenKrupp–Stahl AG, Salzgitter AG and a material research institute (IW) of the University Hannover, ndt technology was optimized in order to predict mechanical properties ($R_{p0.2}$, R_m) along the length of cold-rolled steel sheets. In 1995 a pilot online equipment was introduced into the FBA4-hot-dip galvanizing line [4] of ThyssenKrupp-Stahl which has - based on a magnetic incremental permeability measurement – predicted the yield strength. In addition - by using 2 EMAT-time-of-flight measurement devices in rolling and the transverse direction the vertical and planar anisotropy coefficients (r_m, Δr) were calculated. The old equipment was now replaced by an enhanced system basing only on a full 3MA-approach. Figure 9 shows a view on the roller table carrier which can be placed inline and Figure 10 is the detailed top view on the transducer which by a hydraulic can be positioned near the running sheet (speed 300m/minute) with a lift-off of 2±1mm.

Figure 9: Roller table carrier with integrated transducer

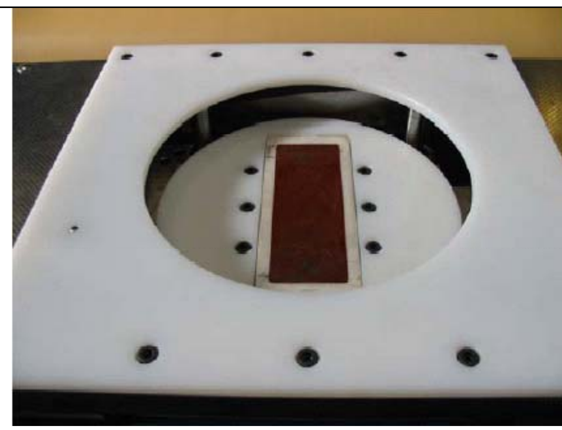

Figure 10: Top view of the 3MA transducer build in the roller table carrier

Figure 11: Experimental 3MA installation in a hot-dip galvanizing line

Figure 12: Electronic system

Online measurements in the project were performed in the cold rolling mills of both steel manufacturers. Figure 11 shows the flexible installation of the 3MA-transducer beneath the roller table and in Figure 12 the electronic system is shown.

Table 4 Results obtained by 3MA

Test conditions	Steel grades	$\Delta R_{p0.2}$ [MPa]	ΔR_m [MPa]
Laboratory	1 (Normal steel of producer 1)	9	7
Laboratory	2 (IF steel of producer 1)	6	9
Laboratory	1 + 2 (producer 1)	12	13
Online	1 (Construction steel of producer 2)	14	9
Online	2 (IF steel of producer 2)	9	6
Online	3 (Higher strength steel of producer 2)	18	14
Online	1 + 2 + 3 (producer 2)	22	16

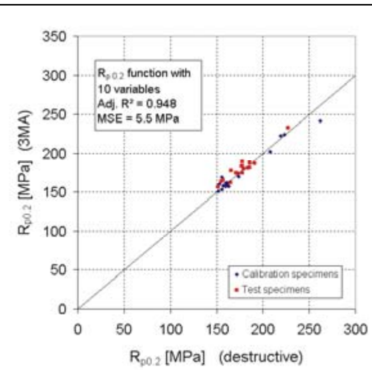

Figure 13: IF-steel of producer 1, laboratory verification

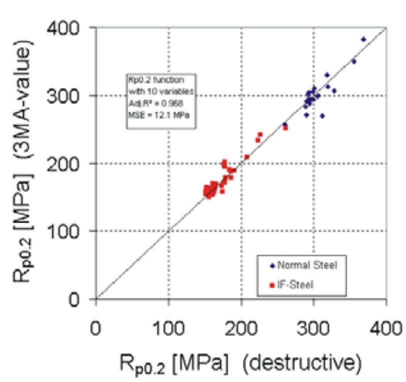

Figure 14: Normal + IF-steel of producer 1, laboratory verification

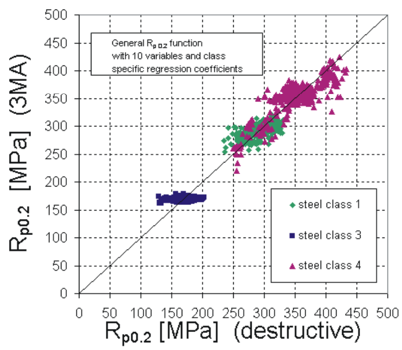

Figure 15: 2, Steel class 1+2+3 of producer online verification

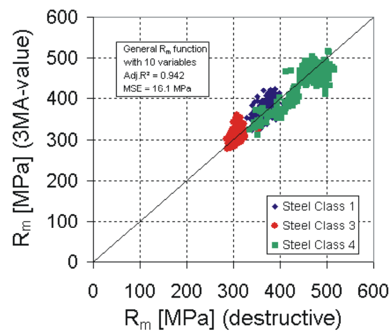

Figure 16: 2, Steel class 1+2+3 of producer online verification

The results obtained in the laboratory as well as online are documented in Table 4. The residual standard deviations as differences (Δ-values) between the mechanical properties predicted by ndt and the destructively determined values are presented. Besides standard steel qualities (normal steel and construction steel) interstitial-free (IF) steel and high strength material was investigated. The residual standard deviation in the case of the IF-material is much smaller compared with the other steel grades and reflects the higher homogeneity of the IF-material.
So far the calibration is tailored to the steel grade the regression model fit the reality much better and when a regression is performed taking into account all classes of steel together (1+2, 1+2+3), then the residual standard deviation becomes larger.

The yield strength and tensile strength values are predicted online from the magnetic measurements and monitored along the length of the coil on a CRT-screen. This presentation gives the user a best overview about the homogeneity of the properties in the coil and can directly used as a 1:1-quality document. Figure 17 and Figure 18 show such presentations collected in the steel mill of producer 2.

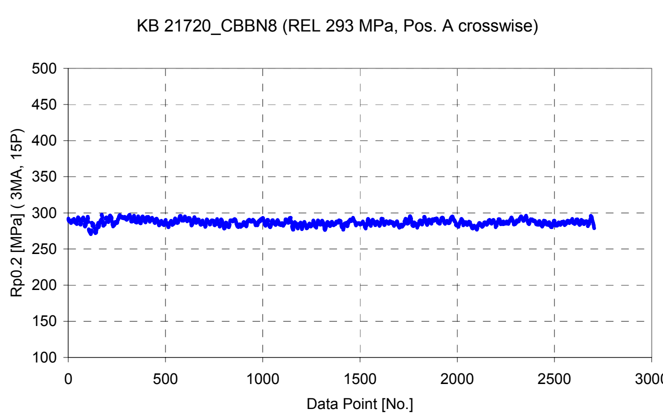

Figure:17: Yield strength along the coil length, online documentation

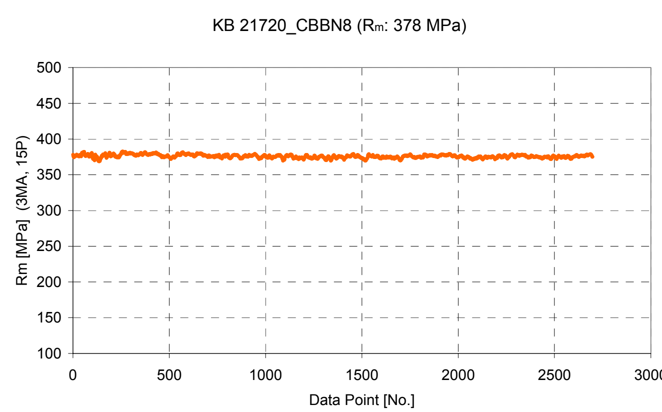

Figure 18: Tensile strength along the coil length, online documentation

Conclusions: The 3MA technology is matured to be integrated into the production process of steel manufacturers and mechanical properties can be predicted with high accuracy online. The

processing speed can be up to 300m/minute in the case of steel sheets and a hot-dip galvanizing line.
Also in the case of heavy plates 3MA can be applied with high reliability. However, the prediction model can tremendously be enhanced if acoustic properties are additionally implemented into the regression model. The resulting residual standard deviations are then in the range of the accuracy of the destructive tests.
A further enhancement of the technology therefore should have in its focus the combination of micro-magnetic and acoustic properties.

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