Micromagnetic Testing for Rolled Steel

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Abstract. In forming of steel by hot and cold rolling a broad range of semi-finished and final products can be produced with very specific, custom-tailored technological properties. Here, the characteristics of mechanical-technological tests (tensile, hardness, creep, fatigue test) are often of central importance. Obviously the traditionally process orientated steel industry has a strong interest to replace time-consuming and expensive destructive mechanical tests by non-destructive (nd) methods, which can be applied in closed vicinity or even integrated within the production process.

Micro-magnetic testing, i.e. nd material characterization with electromagnetic methods is generally suited for this purpose, because the mechanical properties of a ferromagnetic material and its intrinsic magnetic properties are influenced by the same microstructure parameters. Furthermore the micro-magnetic measuring parameters are sensitive to load-induced and residual stresses. The so called 3MA technique (Multiparameter Micromagnetic Microstructure and stress Analyzer) is a combination of four micro-magnetic methods. After calibration it allows to predict mechanical properties like tensile, yield strength and hardness but also residual stresses in steels.

Recently, applications of this technique for different testing tasks in steel industry have been investigated in three research projects, funded by the former European Coal and Steel Community (ECSC). A first project was concerned in the improved non-destructive determination of mechanical properties of cold rolled and recrystallising annealed sheet steel. In this context a fully automated 3MA testing system for in-line determination of tensile and yield strength in moving steel strips was implemented in a hot dip galvanizing line. Task of a second project was the determination of mechanical properties in heavy plates. For this purpose a 3MA system was integrated in a remotely controllable testing trolley, which can be applied in a rolling conveyor. Finally in a third ECSC project it was analyzed, if the extension of 3MA by a Dynamic Magnetostriction module allows to precisely monitoring internal stresses in strip and plate.

1. Introduction

Steel industry is constantly addressing the challenge of meeting customers' demands for technologically ever more sophisticated materials, which results in a broad range of semi-finished and final products with very specific, custom-tailored technological properties. Over fifty percent of the steel industry's current product range has evolved just over the past ten years. Additionally the steel producer has to meet the ever-increasing quality requirements of its clients in order to maintain and to improve its competitiveness in a global market. Here, the characteristics of mechanical-technological tests (tensile, hardness, creep, fatigue test) are often of central importance.

State of the art in determining tensile and yield strength is to select standardized specimens at the end of the production process and destructively test them according to the definition in the inspection laboratory. Hardness measurements are performed by using standardized indentation techniques according to Brinell or Vickers. Obviously the traditionally process orientated steel industry has a strong interest to replace time-consuming and expensive destructive mechanical tests by non-destructive (nd) methods, which can be applied in closed vicinity or even integrated within the production process.

Micro-magnetic testing, i.e. nd material characterization with electromagnetic methods is generally suited for this purpose, because the mechanical properties of a ferromagnetic material and its intrinsic magnetic properties are influenced by the same microstructure parameters [1]. Furthermore the micro-magnetic measuring parameters are sensitive to load-induced and residual stresses [2]. Recently, the applications of micro-magnetic for different testing tasks in steel industry have been investigated in three research projects, funded by the former European Coal and Steel Community (ECSC).

2. Methods

2.1 Influence of Microstructure and Stresses on Magnetic Properties

Increasing the strength of a steel material, irrespective of whether purposeful or undesired is generally based on the fact, that dislocation movements - induced by static or dynamic loads - are impeded by 0, 1, 2, 3-dimensional defects in the metal lattice. The same lattice defects are able to hinder the movement of Bloch walls, which separate magnetic domains in ferromagnetic material [3]. Instead of a mechanical load, in the latter case the driving force is an external magnetic field and the reaction of the material is described by magnetic properties such as coercivity, permeability or remanence. This analogy between dislocations and magnetic walls appears in a series of comparable effects (e. g. Portevin-Le-Chatelier and Barkhausen effect). If mechanical and magnetic properties are influenced by the same microstructural parameters in ferromagnetic steels, it is not surprising to observe correlations between both [1].

Magnetic and magneto-elastic techniques for residual and structural stress determination are based on the fact that ferromagnetic materials change their domain structure under the influence of mechanical stress due to the increase of the elastic energy density [4]. The ferromagnetic solid reacts with a change in microstructure in order to keep this increase as small as possible. When a magnetostrictive positive material like iron is stressed the domains with magnetic orientations most nearly to a tensile stress direction tends to grow. The stress direction becomes a magnetic “easy” direction (stress induced magnetic anisotropy) with changed magnetic properties.

A difficulty for deviating unambiguous stress values from magnetic measurements originates from non-linear magnetostrictive properties [5]. Polycrystalline iron has a positive longitudinal magnetostriction in the low magnetic field region ($H < 30$ A/cm). At higher field strengths, the magnetostriction becomes negative. One possibility in order to overcome this ambiguousness is to combine several electromagnetic parameters (see next section).

2.2 Micro-Magnetic Multiparameter Microstructure and Stress Analyzer (3MA)

If a specific target quantity - e. g. the yield strength or the residual stress level - should be determined from electromagnetic measuring parameters, it has to be kept in mind, that the latter are affected by a variety of internal and external influences. A possibility to separate these influences is to use several independent measuring parameters instead of only one. The combination of these parameters in a multiple regression or pattern recognition model allows to suppress the “unwanted” influences and to enforce the target quantities. 3MA is the methodical and instrumental combination of 4 different electromagnetic methods - Barkhausen noise, incremental permeability, harmonic magnetic field analysis and multifrequency eddy current [6]. Up to 41 electromagnetic measuring parameters can be allocated quasi-simultaneously. The 3MA-systen is shown in Figure 1.

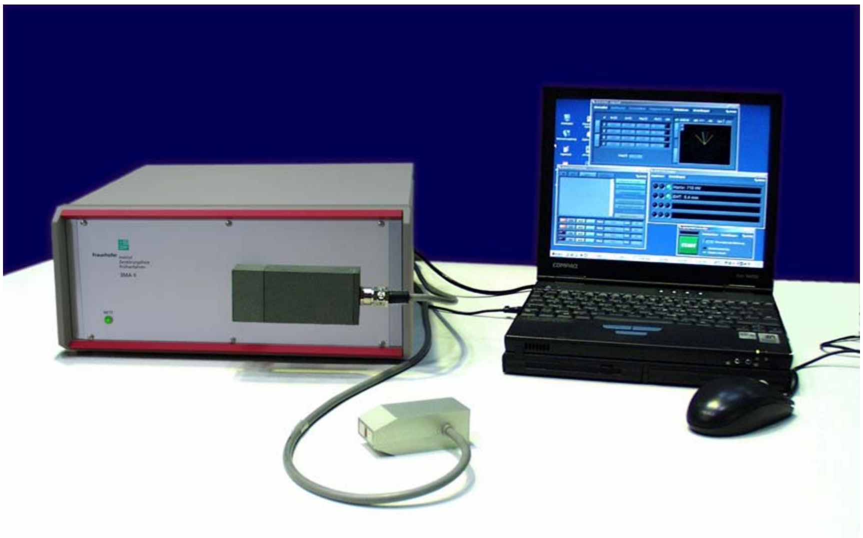

Figure 1. Basic 3MA manual test device

2.3 Dynamic Magnetostriction

Conventionally, the length variation due to longitudinal magnetostriction is measured by a strain gauge, adhesively fixed to the sample. This measuring procedure is time-consuming and has only limited usability as a non-destructive testing method. By using an EMAT for a magnetostrictive excitation of an ultrasonic (US) wave, the latter becomes stress sensitive acting at the position of the transmitter [7]. The efficiency of the magnetostrictive sound generation, i.e. the intensity of the generated US wave is proportional to the differential magnetostriction. If an alternating magnetizing field is applied, the differential magnetostriction and with it the US intensity periodically changes and an intensity profile as a function of the magnetizing field is observed. This intensity profile characteristically changes with tensile and compressive stress. Different measuring parameters can be derived from this intensity profile, which a very stress sensitive.

3. In-line Steel Sheet Inspection System

3.1 Motivation

Cold rolled and recrystallizing annealed sheet steel is a high-value product, used amongst others for automotive body shell parts. High customer's demands for physical dimensions and surface quality but also cold formability, which is described by mechanical parameters like yield strength, tensile strength, anisotropy value and hardening exponent must be met with sufficient accuracy. In a hot-dip galvanizing line individual sheets are welded one after another to an "infinite" strip which continuously passes through the annealing furnace and the galvanizing stage, ending up in a coil of several kilometres length.

The mechanical parameters of this coil are affected by hot- and cold rolling followed by recrystallization annealing. Typically, the mechanical properties are ascertained by taking samples from the beginning and end of the rolled strip. These samples undergo extensive and time-consuming tensile tests, after which the coil is released. If the samples do not fulfil customer's requirements, the entire strip must be reworked, downgraded or even scrapped. The time delay between sample collection and testing can reach up to several hours. During this time the finished coil can not be shipped and has to be temporarily stored in the coil yard. A quick detection and reaction on deviations in the production process is not possible.

Higher strength steel grades are produced with rather high cooling rates during hot rolling. The faster cooling at the strip ends can provoke smaller grain sizes in comparison to the microstructure of the accurately cooled mid section of the strip. This leads to a deterioration of mechanical parameters at the ends, which is transferred to the cold rolled and galvanized strip and can not be repaired during continuous annealing. In this case there is a risk to underestimate the quality of the entire strip by testing samples only from the strip ends (see figure 2). On the other side, it is not guaranteed, that the quality of the entire strip is lying within the tolerance range, if the strip end's samples do.

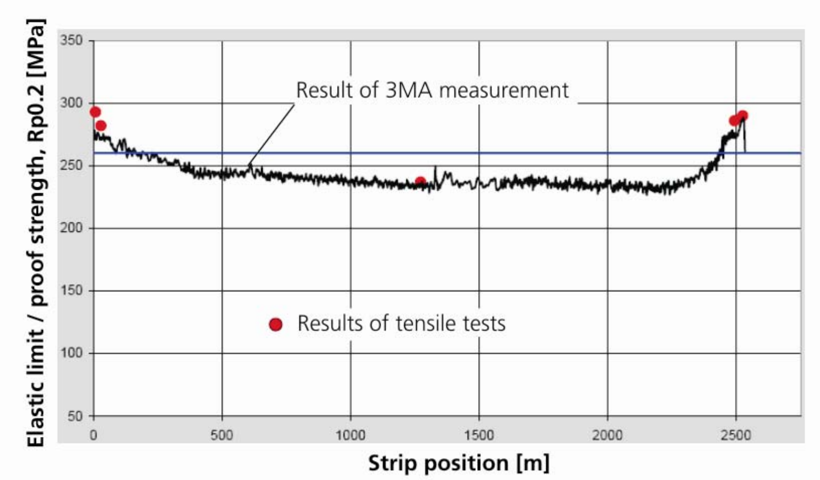

Figure 2. Continuous Rp0.2 measurement with 3MA on a steel strip with increased strength at the ends

In order to overcome these limitations, the development of new concepts for on-line determination of mechanical parameters in the entire steel strip has been promoted in the recent years. A first approach is to use physical models, describing the evolution of the steel's microstructure during hot and cold rolling in order to predict the mechanical properties of the finished product [8, 9]. Alternatively or complementary non-destructive testing (ndt) sensors have been developed, which allow to monitor the mechanical parameters of the entire length of the strip [10, 11, 12]. In the author's institute this topic is an objective for years and ndt technology was developed and introduced into online process monitoring and control systems in the steel industry [13]. This work has culminated in a fully automated in-line steel sheet inspection system, which was developed within the scope of an ECSC project, as described in the next section.

3.2 Project Description

Based on the 3MA technique, a online test system was constructed, which allows continuous contact-less determination of tensile (Rm) and yield strength / elastic limit (Rp0.2), but also other mechanical-technological characteristics in the running strip (up to 300 m/min.). During spring 2003 this system was installed into the hot-dip galvanizing line 4 (HDGL 4) of ThyssenKrupp-Steel in Duisburg. The 3MA probe was fitted into a movable, rotatable holder (see figure 3, left). This allows the positioning of the probe from the bottom side to the strip with 2 ± 1 mm lift-off. The single-sided access of the probe is favourable in case of a strip rupture. The orientation between the main magnetic field and the feed direction of strip can be adjusted to 0°, 45°and 90°. The probe holder again is mounted within a hydraulically lowerable table carrier, equipped with distance rolls (see figure 3, right). A fast lowering of the entire construction in case of an escape warning is necessary to avoid damaging of the probe due to weld seams or zinc deposits on the strip. One of the distance rolls is covered with a hard-chromium layer ensuring electrical contact between the steel strip and the probe, which is necessary to achieve disturbance e free signals from Barkhausen noise method.

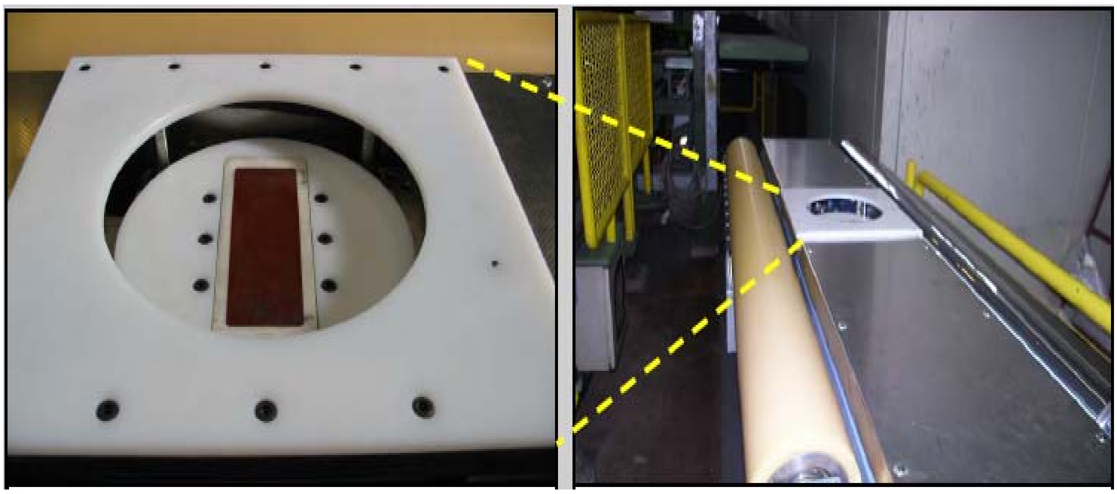

Figure 3. 3MA probehaed holder and table carrier of the in-line steel sheet inspection system

The measuring procedure is controlled by the external electronic equipment integrated in the measuring cabin, located in the exit section of HDGL 4. The electronic equipment mainly consists of the 3MA measuring module, the electro-pneumatic device control, interfaces to supporting signals like weld seam recognition, meter pulse or strip velocity signals and interfaces to the plant process control (PCS) and data management (DMS) systems of HDGL 4.

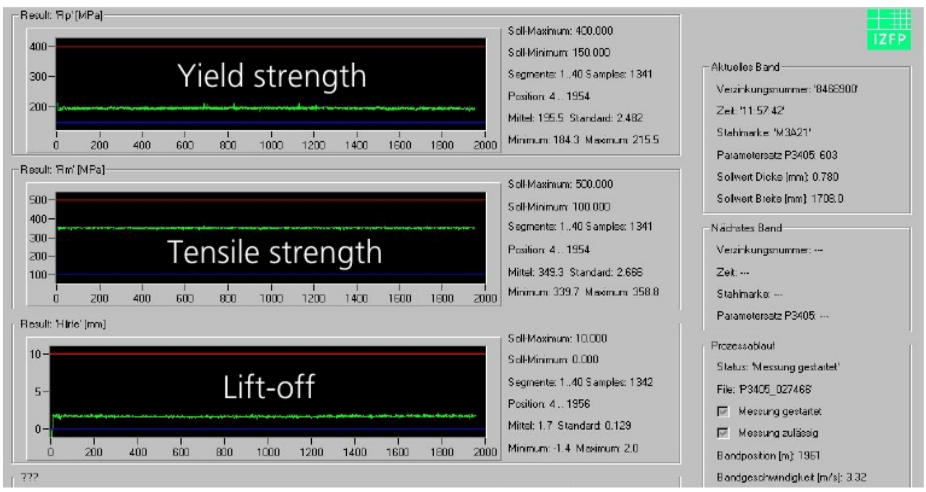

Figure 4. Online visualization of yield and tensile strength of a running strip

Before a new strip is tested, it is announced by a data telegram from the PCS signal, which includes strip identification data and other process parameter data (grade, thickness, skin pass degree, etc.). The test system automatically loads the measuring procedure, i.e.

calibration function and parameter set-up consistent with the announced steel grade. The weld seam recognition signal initiates the start of the test procedure. The detection of meter pulses allows the test results to be assigned to the strip position. The electromagnetic 3MA parameters are continuously measured and transferred into Rm and Rp0.2 values based on the grade specific calibrations functions, which are stored in an internal database. The test results - Rm and Rp0.2 as a function of strip position - are visualized in real-time on an arbitrary monitor, which is connected with the HDGL 4 network (see figure 4). Finally all test results from a strip are statistically analyzed, and stored / filed in monthly directories and transferred to the PCS on request.

3.3 Results

For calibration about 11,000 strips from 12 different steel grades have been used. It was observed, that these 12 grades could be combined into only 4 calibration classes, because the material properties within one class were comparable (see table 1). Besides standard steel qualities (normal steel and construction steel) interstitial-free (IF) steel and high strength material were investigated. For each strip the 3MA parameters have averaged over a certain length (e.g. 20 m) at the beginning and at the end of strip. These data have been associated to the destructively determined Rm- and Rp0.2-data in order to determine the calibration functions for the 4 classes. Table 1 shows the result of this calibration in terms of the residual scatter 1σ of the correlation between 3MA data and destructive data.

Table 1: Residual scatter calibration

Steel class	**ΔRm (1σ) [MPa]**	**ΔRm (1σ) [%]**	**ΔRp0.2 (1σ) [MPa]**	**ΔRp0.2 (1σ) [%]**	**No. of strips**
IF	5.4	1.7	8.2	4.9	2667
IF, high strength	11.3	3.1	12.3	5.4	7764
Bakehardening	5.8	1.5	8.8	2.9	1294
Structural	7.9	2.5	10.1	5.1	164

In order to validate the correct function of the calibrated test system, the nd determined Rm and Rp0.2 measuring data have been compared with the data from destructive tensile tests with 2,700 strips more. Again the result is described by the residual scatter (table 2). The residual scatter in case of the IF-material is much smaller compared with the other steel grades and reflects the higher homogeneity of the IF-steels. In general, the measuring inaccuracy is not far away from the destructive reference method.

Table 2: Residual scatter validation

Steel class	**ΔRm (1σ) [MPa]**	**ΔRm (1σ) [%]**	**ΔRp0.2 (1σ) [MPa]**	**ΔRp0.2 (1σ) [%]**	**No. of strips**
IF	5.3	1.7	7.4	4.5	1895
IF, high strength	6.8	1.8	9.3	4.0	688
Bakehardening	11.2	3.6	15.6	7.7	55
Structural	7.5	1.9	12.4	4.1	34

4. Quality characteristics of heavy plate

4.1 Motivation

Not only thin sheet but also heavy plate with a slab thickness up to 400 mm is produced in nearly all non-alloyed and alloyed steel grades today. The diverse range of properties - e.g. yield strengths from 200 to more than 1100 N/mm^2 - ensures the precise suitability for use in bridges, high rise buildings, offshore platforms, ship building, line pipes, pressure vessels, heavy-duty machines, and much more. In order to reduce the constructive thicknesses and with it the self-weight of a construction, higher-strength steel grades are increasingly requested, whereas the weldability and the cold toughness still have to be acceptable. For production of such steel grades modern manufacturing processes, like water/air quenching and tempering, accelerated cooling, normalizing and thermo-mechanical rolling come into operation.

The customer asks for geometrical and mechanical properties, which are uniform across product length and width, especially for these high-value grades. Consequently, high demands on determination and documentation of product quality are made. Comprehensive dimensional, shape and surface inspections already take place within production flow directly on the plate. In the same way, the 100% defect detection based on integrated or a mobile US system is state of the art [14, 15]. On the other hand it is still necessary to extract tests coupons from the boarders of the un-trimmed plate in order to determine the mechanical properties. Tensile and toughness tests are performed according to codes and delivery from highly qualified and certified personnel and cannot be integrated into online closed loop control with direct feedback. For hardness tests the surface must be carefully prepared by removing scale and decarburized surface layers and relieving residual stresses. The coupon extraction and testing is very time and cost extensive. Costs in the range of several thousands Euro per year arise in a middle-sized heavy plate plant only from coupon scrap. For these reasons, heavy plate producers have an itch to replace the mechanical testing of coupons by an nd technology, allowing transferring these tests from the laboratories of quality assurance to the shop floor.

4.2 Project Description

In co-operation with the different European steel producers a research project was performed, in which a nd device based on the 3MA technique should be constructed and analyzed, which is able to provide a real-time, nearly 100% information on the actual state of surface hardness, tensile and yield strength. The nd device should be applicable for fast testing on random sampled coupons in the test laboratory as well as for the inspection of complete mother plates during manufacturing, i.e. in the roller conveyor or on inspection bed prior the final trimming of individual plates.

In this context a wide range of steel grades used as heavy plate material - structural steel, high strength steel, wear resistant steel and pipe steel - have been investigated. Several calibration strategies have been analyzed in order to achieve most precise and robust predictions of the mechanical properties. It was claimed, that the calibrated nd device should be insusceptible to perturbations, like plate temperature, lift-off effects, caused by bad flatness or scale, residual stresses, decarburisation and residual magnetism, which are typically deteriorate the accuracy of measurements with electromagnetic methods.

In order to perform nd testing (ndt) on plates in the plant a remote controlled trolley was developed, allowing the 3MA transducer is half-automatically moved along the surface of the plate. A brushing device was integrated into the trolley in order to remove scale which otherwise is a strong disturbing influence parameter. The left picture in figure 5 shows the trolley in operation on a heavy plate on the roller conveyor and the right picture shows the control desk for remote control of the trolley and the 3MA measurement.

Figure 5. 3MA inspection trolley (left picture) and remote control desk (right picture)

4.3 Results

Coupons were taken from the running production and destructively tested by one project partner. It showed up, that best results could be achieved, if individual calibration functions were used for each steel producer, each steel grade and each plate thickness. In this case the residual scatter was in the range of 4 HB units for hardness determination (ΔH) and 10 MPa respectively 20 MPa for Rm respectively Rp0.2 determination. Acceptable results could also be observed, if different steel grades of only one producer have been combined. For that case, figure 6 documents the comparison between the non-destructively predicted yield strength and tensile strength values and the destructively determined findings. Nevertheless, combining several steel grades and thicknesses from different producers resulted in a pronounced degradation of the results. In terms of residual scatter, this means ΔH = 13 HB, ΔRm = 36 MPa and ΔRp0.2 = 34 MPa. This inconsistency shows that especially for heavy plate the same mechanical properties can be achieved by highly different microstructural characteristics, affecting the electromagnetic properties unequally.

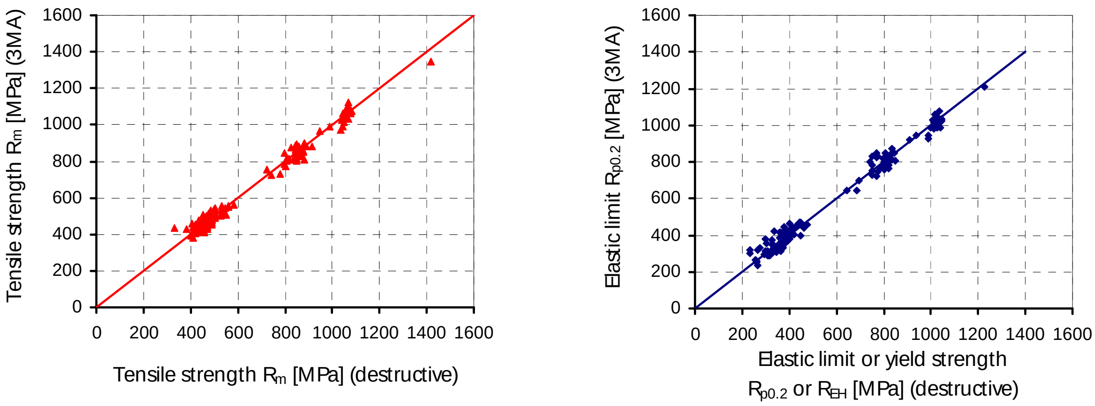

Figure 6. Non-destructively predicted tensile and yield strengths as a function of the destructively determined results

In addition to 3MA, also the time of flight measurements of US waves propagating in the plate thickness direction were performed. 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} – ts_{hT})/t_{shT}). Also here a correlation to the mechanical properties can be obtained. The combination between 3MA and ultrasonic data tremendously reduces the difference between the mechanical parameters predicted by ndt and the destructive methods.

5. Residual stress determination in strip and plate

5.1 Motivation

A number of initiatives have been progressed by steel mills to effect improvements in plate and strip flatness, while at the same time ensuring that internal stresses are reduced. This is being done in order to minimize distortion of the product during subsequent cutting for fabrication. Many complaints for hot rolled, pickled and oiled strip coils are for shape and distortion defects. For the ability to machining in fast and precise production processes (i.e. punching techniques or production of cans or screen masks) there is a great demand for cold rolled strip with extreme flatness and an extremely low level of internal stresses. Here increasing standards of post-cutting condition have to be attained. This is also true for high strength steels, because their application in deep drawing is connected with an increase of spring back, which is a criterion for shape stability. On the other hand residual stress is also influencing the spring back behaviours.

Recording residual stress distributions offline and online and determining the influences of preceding production steps like cooling, heating, skin passing and levelling on these distributions could help to find the optimum process parameters in order to produce plate and strip that is flat, distortion free following shape correction and will remain flat during subsequent customer processes.

5.2 Project Description

The scope of a third ECSC project was the development of an nd test system based on the measurement of electromagnetic and magnetostrictive parameters in order to monitor internal stresses in rolled steel. This nd technique should be designed for fast post process as well as for process integrated application. As described in section 2.2, the 3MA-technique combines 4 different micro-magnetic methods in a single instrumental approach. In case of the Dynamic Magnetostriction (DM) method, quasi-static and alternating magnetic fields are superimposed, in order to generate mechanical vibrations, i.e. US signals. Amplitude and phase of the US signal are strongly influenced by strain (stress). A main objective of the project was to retrieve, if the DM could be a useful addition as a fifth measuring module for the 3MA technique, especially in order to increase the sensitivity towards residual stress.

The hardware of the 3MA system was re-designed in form of a modular front-end concept (3MAII). Based on this front-end architecture an electronic hardware unit was constructed, which allows in-plant applications of the 3MA and the DM method simultaneously (see figure 7, left picture). In order to use the DM method for in-plant applications, a special rugged design of the probes was developed. Receiver and transmitter are embedded in a holding frame serving for a fixed distance. This probe unit is supplied with rollers, allowing the movement on a strip (see figure 7, right picture).

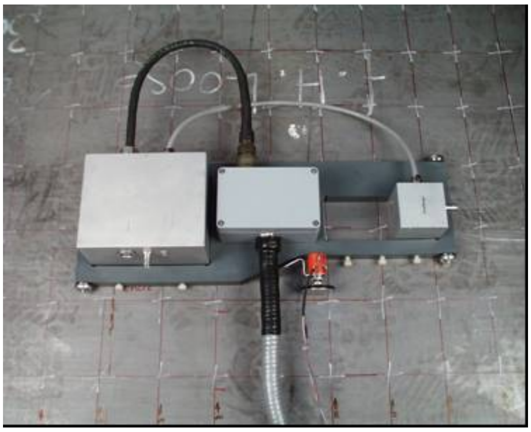

Figure 7. Combined 3MA+DM hardware unit (left), DM probe with transmitter and receiver(right)

5.3 Results

As described in section 2.1, micro-magnetic parameters usually do not show a distinct linear correlation to stress, even if many of 3MA measuring parameters vary clearly, if stress is altered. On the other side, it was observed, that some measuring parameters derived from the DM intensity profile (see section 2.3) show up the preferred linear correlation to stress. The use of DM amplitude values originating from the part of the intensity profile with low magnetic field excitation seems to be advantageous in terms of sensitivity and stability. By using theses parameters, it was possible to determine tensile stresses with a resolution less than 5 MPa, at least on the laboratory level.

DM measurements have also been performed in case of a relative motion between steel strip and probe. Besides a small enhancement of the noise level, a further influence could not be observed. To investigate the influence of stress orientation and texture on the DM and 3MA results, pole figure measurements have been recorded on a steel plate at three different positions across the plate width (left, right edge and in the middle). By comparing these results with US group velocity pole figures, it showed up, that DM pole figure seems to be only slightly influenced by the crystallographic orientation distribution and predominately reflects the stress orientation distribution.

It should be noted, that for the measurement of US group velocity (texture) the same equipment was used, which originally was developed for the DM measurements. Therefore this equipment allows characterizing residual stress and crystallographic texture at the same time.

6. Conclusions

Micro-magnetic techniques, like 3MA have reached a sophistication level of industrial standard and are ready to be integrated into the production process of steel manufacturers. Mechanical properties, like tensile, yield strength and hardness as well as the residual or structural stress level can be predicted with high accuracy. Meanwhile, different test systems are available, which allows the continuous online inspection of thin sheet strip, but also the conveyor integrated testing of heavy plate. However, in case of strongly textured heavy plate the prediction of mechanical properties can tremendously be enhanced if acoustic properties are additionally implemented into the regression model. In a similar way the Dynamic Magnetostriction (DM) method should be a suitable extension for the 3MA technique, if residual stress should be measured with high accuracy with less liability towards disturbing influences (thickness, steel grade variations).

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