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Development and qualification of the Eddy-Current testing techniques "EC" and "EC+" in combination with Leeb-Hardness-Measurements for detection and verification of hardness spots on heavy steel plates

Opracowanie i kwalifikacja technik badania wiroprądowego "EC" i "EC+" w połączeniu z pomiarami twardości Leeba do wykrywania i weryfikacji twardych plam na grubych blachach stalowych

ABSTRACT

Hardness Spots are local areas with increased hardness on the surface of semi-finished or end products in steel manufacturing. The cause of these hardness spots is attributed to effects in the casting or rolling process. As of stochastic nature, only a reliable non-destructive testing (NDT) technique, applied as a 100% surface examination can detect infected areas, of which, the individual hardness value is verified, by performing Leeb hardness measurements, in accordance with the given standard. The NDT-techniques developed by DILLINGER and Rohmann, to detect the hardness spots, are due to an Eddy Current (EC) procedure which in two consecutively developed variants came into application, named EC and EC+. Whereas the EC procedure is asking for shot-blasted surfaces, to remove the rolling skin (scale), avoiding larger scatter in the EC-impedance data, the EC+ procedure is applied without shot blasting. The contribution reports to the systems and the development of an Inspection and Testing Program (IPT) which was qualified, according the guidelines of the British Standards Institution PD CEN//TR 14748. Special emphasis is on the discussion of reliability.

Keywords: *NDT, Eddy Current application, hardness spots*

STRESZCZENIE

Twarde plamy są miejscami o zwiększonej twardości na powierzchni półproduktów lub produktów końcowych w produkcji stali. Przyczynami ich występowania są przemiany zachodzące w procesie odlewania lub walcowania. Ze względu na naturę stochastyczną, jedynie wiarygodna technika badań nieniszczących (NDT), stosowana w 100% badaniej powierzchni może wykryć zakażone obszary, z których weryfikowana jest indywidualna twardość w wyniku pomiaru twardości Leeb, zgodnie z odpowiednimi normami. Techniki NDT opracowane przez firmę DILLINGER i Rohmann, mające na celu wykrycie twardych plam, wynikają z zastosowania prądu wirowego (ang. Eddy Current), która w dwóch kolejno rozwiniętych wariantach została nazwana EC i EC+. W czasie gdy procedura EC wymaga śrutowania powierzchni, by usunąć zgorzelinę, w celu uniknięcia większego rozproszenia danych impedancji EC, procedura EC+ jest wykonywana bez śrutowania. Procedura jest rozwijana i dedykowana do systemu Programu Kontroli i Testów (IPT), który został zakwalifikowany, zgodnie z wytycznymi British Standards Institution PD CEN//TR 14748. Szczególny nacisk kładzie się na dyskusję na temat niezawodności.

Słowa kluczowe: *NDT, zastosowania prądu wirowego, twarde plamy*

1. Introduction

The common specification for quality inspection, as an essential part of a contract between a customer and Dillinger Hütte (DILLINGER) as producer of heavy steel plates, for example, as half-finished products, to further produce pipeline tubes, has its basis on long year successful experiences, paired with continuously performed R&D to enhance quality. This specification asks for batch-testing as statistical process-control methodology and cannot detect randomly occurring events, of which the quality features are not part of the continuously controlling. The random occurrence of hard spots as events, with extremely small occurrence rate during casting and rolling, but with a high impact on quality, therefore, has initiated in DILLINGER the development of a NDT-technique in co-operation with the equipment manufacturer Rohmann GmbH.

In the production of heavy steel plates by DILLINGER, the application of batch-testing for quality testing is based on taking samples, so-called coupons, from one plate, which has about 9 metric tons, per converter heat (about 185 tons). Therefore, DILLINGER's batch is defined by the selection of coupons from one plate in a total of about 20 plates. Different destructive tests, are performed in agreement to a customer specification, which is an essential part of the

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contract. Besides the performance of standard-tensile-tests, describing, for instance, strength values as usage properties, toughness characteristics are selected by performing Charpy tests and corrosion investigations can be a part of the quality tests, when the specification is asking for [1, 2, 3].

2. Hardness Testing

The mechanical hardness of a material per determination procedure, characterizes the ability of a material to resist plastic deformation performed by a standardized, well-defined indenter, using a well-defined indenting mechanical load. It is therefore a mechanical-technological value and not an intrinsic (physical) material property.

Hardness is mainly influenced by the micro- and macro-structure. At the very beginning of the metallurgical process there is the influence of the chemical composition of the steel iron alloy mixed crystal. The carbon content absolute, in this composition and its spatial distribution, in the product plays a decisive role in combination with time-dependent diffusion- and heat-treatment-processes by cooling-down after casting, reheating before rolling, as well as the thermo-mechanical controlled rolling followed by the cooling after rolling.

As the surface of the steel plate, during this last cooling in the process, on the so-called cooling bed, is directly in contact with the atmosphere, and the bulk stays on a higher temperature, cooling velocities of the surface and the bulk are different, and therefore the microstructures obtained at the surface of the plate and beneath the surface in the bulk material are not to 100% identical. There is a gradient from the surface in the bulk.

The surface microstructure in the condition as rolled and cooled down by nature is harder (bainite and self-annealed martensite) than the microstructure in the bulk (bainite). Therefore, hardness inspection – according to common specifications, is not tested immediately on the surface. Hardness analysis into depth begins not earlier than 1 mm beneath the surface edge of a selected sample (coupon).

Furthermore, during hot rolling, the so-called scale develops, which is a mixture of different iron oxides. The steel expert separates between loose (non-fixed) scale, which can be simply eliminated, for instance by brushing the surface, and the blue-black-colored, fixed, but brittle scale layer, also called rolling skin, influencing the surface hardness with higher hardness values.

Elimination of rolling skin then – if needed - is done mechanically by grinding or shot-blasting or chemically by etching in an acid bath, which is – to give an example - a standard procedure in so-called pickling-lines in case of hot-rolled thin steel sheets before cold rolling.

However, a common specification in heavy plate manufacturing (as an example), asks for a hardness with a maximum hardness requirement of around 201-220 HV10. By specifying this – the hardness measurement procedure (HV means hardness according to Vickers) is defined. This procedure – by nature and standard - is destructively performed on the above-mentioned coupons in the testing laboratory and, in no case, is delivering a hundred-% hardness information along the surface. Furthermore, the here selected sampling hardness test, per nature, in no case, can reliably detect local hardness changes, which can occur as mentioned above, as hardness spots and random events.

Without going in details, hardness testing is to separate generally into destructive and non-destructive procedures. The destructive tests follow given standards as there are: Vickers hardness testing [4], Rockwell hardness testing [5, 6] and Brinell hardness testing [7, 8]. The difference between them is the choice of the indenter geometry and the applied indenting load.

Non-destructive testing procedures to characterize hardness, based on physical property determination [9, 10], have been developed in the last 3 decades. The various test procedures, in common usage, are generally going back on many well-known physical phenomena which involve the phase velocity of ultrasonic waves (compressive wave and linearly-polarized shear waves) propagating in the thickness direction of the plate, as well as micromagnetic testing (Barkhausen noise, incremental permeability, magnetic field higher harmonic analysis) and electromagnetic testing (eddy current technique/eddy current impedance). When applied on heavy plates, the ultrasonic techniques average the information along the sound path length and – when propagating in thickness direction – they average the microstructure gradient. Micromagnetic and electromagnetic techniques – by nature of the restricted penetration depth, depending on the operating frequency – cover only surface-near areas, near the material surface. These techniques with their specific inspection data have allowed to develop good correlations with mechanical strength properties, such as yield strength and tensile strength, as well as with hardness. When the inspection data of the different (UT + ET + micro-magnetic) approaches are combined by data fusion algorithms like generic algorithms, multiple regression or pattern recognition algorithms, especially pronounced correlations with high regression coefficients and small residual standard deviations (prediction uncertainties) can be found compared to values determined experimentally using destructive techniques.

However, despite the high predictability, these various test procedures are always indirect measurements, rather than direct measurements of the required hardness property. Therefore, a correlation procedure is always required to calibrate the indirect non-destructive measurements with direct measurements, which must be determined destructively. Hence the absolute destructive measurements act as reference values for the non-destructive measurements, and therefore, the measurement uncertainty cannot be better than the values of the reference technique.

The various measurements for different approaches always must be validated/justified statistically with independently selected validation samples, which are not part of the calibration specimen set. To give an example, in comparison with the Brinell hardness (HBN) measurement as reference for calibration, nondestructively residual standard deviations, characterizing the uncertainty, of ± 4 HBN have been obtained [10].

Currently, no standards for non-destructive hardness measurement/testing, using ultrasonic, micromagnetic or ECT techniques exist. There is an ASTM standard for electromagnetic sorting, i.e. grading, of ferrous materials [11] and it would be possible to apply this methodology, after a recalibration in hardness units, although this is not yet an actual project of ASTM or other consensus standardization bodies.

However, EC Testing is one individual methodological part of micro-magnetic testing and the German Engineering Societies VDE/VDI [12] have compiled guidelines, called 2616, under the acronym QEM - Quantitative Electro-Magnetic Testing (non-standardized methods) which have a pre-normative character. These guidelines are the basis on which the German Iron & Steel Institute (VDEh – Verein Deutscher Eisenhüttenleute) compiles regulations for the delivery of flat products; this includes then eddy current applications too.

The only existing standardized, non-destructive hardness testing procedure is the Leeb test [13], a dynamic test, which measures hardness indirectly as the loss of energy of an indenter, which is accelerated on to the surface of a given test object. The mass of the indenter is accelerated to the surface of the test object and impinges on that surface at defined speed [14], i.e. kinetic energy. The impact creates a plastic deformation of the surface, i.e. an indentation, because of the impact body loses part of its original speed – or energy. It will lose more speed by creating a bigger indentation, which will be the case with soft material. The softer the material, the bigger the indentation, the more loss of kinetic energy. In technical terms, the measurement is implemented by means of an impact body which has a spherical tungsten carbide tip and which is impelled onto the test surface by spring force. Contactless measurements are taken of the speed before and after the impact. This is done by a small permanent magnet embedded into the impact body, which generates an induced voltage by passing an induction coil. The induced voltage is proportional to the speed.

The Leeb hardness, HL, is then calculated, by the ratio of the impact speed to the rebound speed. As the measurement principle is influenced by the elastic properties of the individual material too, and not only by plastic deformation influences, an absolute and generalized conversion to other hardness scales can't be calculated. Instead, conversion from Leeb hardness to other hardness measurements must be performed, for different material classes by experimentation, for instance on well-defined calibration specimens, so-called hardness plates. The paper cited here [14] refers to this methodology and the standard [15] set out the details. However, as the instrument makers are especially interested in a reliable compatibility in calculating one hardness value in another, a lot of R&D work was initiated to develop conversion tables and to integrate them into modern equipment software. These tables – on a first glance – are covering certain material classes. Proceq as developer and distributor of Equotip hard- and software [16], applied by DILLINGER, has performed especially high-valued R&D-work to find reliable conversion functions also for the steel grades of DILLINGER. In these investigations ([14] is only one example) it was shown, that grinding and polishing procedures before performing Equotip measurements, have stronger influences on the measurement uncertainties, than the above-mentioned elastic property influences.

3. The EC- and the EC+- Procedure

Eddy Current Testing (ECT) is a well-established technique, based on detecting changes in the impedance of a so-called search-coil as sensor. The impedance of that coil is nothing else than its electrical resistance, if the coil is excited (flowed through) by an alternating (time-dependent, sinusoidal, typical 60 kHz frequency) electric current (current flow). The resistance is the ratio between the alternating voltage at the coil pins and the alternating current driving the coil, based on a generator as a source of the current.

The coil with its current flow in its windings, produces an alternating magnetic field, perpendicular to the coil plane (see Fig. 1), the so-called primary field.

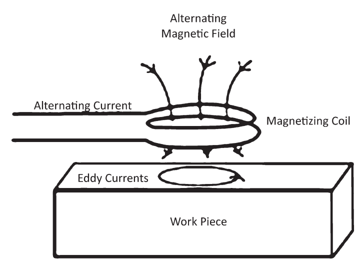

Fig. 1. The ECT phenomenon
Rys. 1. Zjawisko ECT

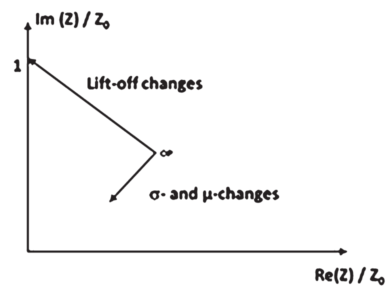

Fig. 2. The normalized impedance plane
Rys. 2. Znormalizowana płaszczyzna impedancji

If the coil is in direct touch, i. e., stand-off distance = 0 (called in the terminology lift-off) with, or near of an electrical conductive material , so-called eddy currents (eddy – because the currents are closed loops) are induced. The higher the electrical conductivity σ, the higher the density of the eddy currents, the more energy is dissipated by heating the material, so-called Ohm's losses. If the material is ferromagnetic steel, then the product of (σ×μ) is relevant for the energy dissipation and it is much larger, than in case of only conductive materials, as the value of μ is large; beside the electrical losses, in addition, magnetic-ones are to observe.

The eddy currents are coupled with a so-called secondary field (named secondary, because it is a consequence of the primary field due to induction) which is, because of the energy law, in the opposite direction to the primary field.

The superposition of the two fields (primary + secondary) change the impedance of the coil. Every effect, which disturbs the eddy currents in their flow (amplitude and/or direction of flow) changes the coil impedance. The measurement quantity normally is not the impedance, but the voltage at the coil pins, which is directly proportional to the impedance, so far, the current is impressed .

ECT has a wide spread application in defect detection of crack-like surface-breaking defects, for instance in aerospace industries, if their direction disturbs the current flow. However, one class of application is in non-destructive materials characterization, which is based on detecting changes in σ and/or in μ. These principles can be applied to detect variations in surface hardness of metallic materials. Changes in lift-off and shape of the surface (including roughness) produce also measuring effects, as well as coatings, like scale, seen here as disturbing influences, called disturbing noise.

The testing of flat objects uses pick-up inductive coils as absolute coil inspection transducers. As the coil – because of wear protection – must always be, at a certain lift-off from the surface, this actual lift-off, and its changes, when the coil scans the surface, influences the interaction of the primary field with the material. It is trivial, the larger the lift-off, the smaller is the interaction.

If there is an increase in hardness, due to a local harder microstructure, e.g., due to a martensite or bainite microstructure development, as it can be the case of hardness spots on heavy plates, then from the physical basics, it is known: The harder the material is, the lower is the magnetic permeability. Furthermore, the electrical conductivity is reduced since the local harder microstructure has a higher dislocation density and the dislocations are the main scattering centers for the conductive electrons in the eddy current flow field.

The reduction of (σ, μ), provides an indirect, but accurate possibility, to measure the material hardness influences. Eddy current phenomena are normally discussed in the so-called normalized impedance plane as shown in Fig.2. The impedance Z of the inspection coil is normalized on the value of the impedance Z0 which is measured when the coil is not influenced by material, i.e. in the case of a very large lift-off. For a fixed operating frequency and coil design, the impedance has a fixed operation point in this diagram (called here OP). By changing the lift-off, the impedance change is along the lift-off curve in the direction of the value 1 on the imaginary axis. If the σ- and μ-values change, the impedance will change along a direction perpendicular to the lift-off curve. To make the understanding simpler, these curves are shown as exact straight lines. However, there are small deviations from linearity, depending on the coil geometry. The effect, shown in Fig. 2, allows to reduce lift-off variations produced by scanning fluctuations, by the so-called Phase-Selection principle. This is no more than a transformation of the coordinate system by translation of the origin into the operating point OP and rotating of the real axis into the lift-off direction. The σ- and μ-value changes are now indicated along the transformed, new imaginary axis. Large imaginary values indicate mechanically soft material while smaller values indicate harder material. By calibrating against well-defined reference specimens with known hardness, the system can predict hardness and detect hardness changes; however, this is not yet standardized.

As mentioned before, as the impedance curves of lift-off- and the (σ, μ)-changes are not exactly along straight lines, the Phase Selection procedure does not eliminate to 100% the lift-off variations, it only reduces them to a residual noise which influence the measurement uncertainty, i.e. the scatter in the data.

A simple calibration for hardness characterization. i.e. hardness spot detection – following the Phase Selection - is by introducing two threshold values. The first threshold is set at a calibration point on a specially designed calibration plate (chapter 4) where the hardness by reference is 220 HV (as an example), characterizing acceptable, i.e., the specified material surface hardness. Here, the so-called Zero-Compensation is performed, i.e. the coil impedance – due to an electronic circuit - is set exactly in the middle of the equipment screen (Zero-point). The second threshold is set at a reference point on the calibration plate where the hardness by reference is 250 HV (as an example). By tuning an amplifier and selecting a phase rotator the impedance belonging to this calibration point is set downwards from the Zero-point on the imaginary axis on the 50% screen height level.

A technology, to reliably produce calibration test pieces with the special selected reference HV hardness values, was developed by DILLINGER, performing series of ECT-tests together with Rohmann GmbH at heavy plates and coupons. Based on these results, the development of a Test-Equipment by Rohmann was initiated (Fig. 3).

The experiments also revealed, that the ECT-procedure requires, the rolling skin of the test material to be removed by shot-blasting. Fixed scale, influences permeability and conductivity and, unless removed, results in a higher false alarm rate (false-positive indications).

Therefore, a further development of the ECT was asked for. The optimized technique works, by superimposing the normal eddy current flow field, produced by the absolute mode pick-up-coil (60 kHz), discussed before, an additional magnetic yoke magnetization, with magnetizing direction in the rolling (inspection) direction. In contrast to other available systems on the equipment manufacturer market, this magnetic yoke magnetization is not due to a sinusoidal alternating current flow in the magnetizing coils of the yoke. It is a pulse magnetization, utilizing a bipolar rectangular voltage pulse with Vi = 24 V [17] in the magnetizing coils of the yoke. The magnetic field is excited in the coils and the yoke, made by a high permeable material is the magnetic circuit, to feed-in the magnetic field flow in the material under inspection (Fig. 4).

The pulse repetition rate as a parameter, can be free selected between 100 – 200 pulses/s (100 – 200 Hz), which allows an inspection speed, in any case, of about 1m/s in walking direction. Due to the pulse excitation, the material under inspection is dynamically and periodically magnetized in a hysteresis loop. The superposition of the magnetic field of the pick-up eddy current coil, placed exactly symmetrically between the pole shoes of the yoke, is continuously performed, exciting so-called small inner loops inside the hysteresis loop. The eddy current impedance measurement of the pick-up coil then, is triggered at a certain, free selectable, delay time after the moment of the pulse excitation, i.e., at a fixed operating moment during the hysteresis cycle. As the ECT coil is driven by a current source, producing a constant but small incremental magnetic field, influencing the magnetic properties only linearly, the impedance of the pick-up coil is proportional to the inclination of the inner loop, excited by the EC coil at the operation moment, which – according to physics - is the incremental permeability value of the material at this excitation moment. In contrast to the ECT technique, described before and named EC or Eddy, the new method was named EC+ or Eddy+.

Fig. 3. Inspection Trolley
Rys. 3. Wózek inspekcyjny

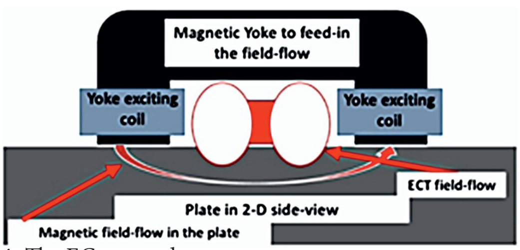

Fig. 4. The EC+ transducer
Rys. 4. Przetwornik EC+

The advantage of the EC+ (Eddy+) technique is its insensitivity against local permeability changes due to the rolling skin. In practical terms, this means, that plates can be inspected, on an industrial scale, without the need to remove the rolling skin, i.e., without the need for prior shot-blasting. In all other respects, the testing procedure is the same as in EC (Eddy) testing.

The Inspection system (Fig. 3) has its base on a linear array of 8 absolute-coil transducers for the EC-procedure which in a time-multiplexing mode are switched to one impedance measurement channel. In the case of the EC+ procedure, the 8 absolute coils are replaced by transducers as shown in Fig. 4. A standard-eddy current equipment, available by Rohmann [18] was used for the system integration into an inspection trolley, movable by wheels, of which the design was according to DILLINGER design ideas.

4. The Calibration Coupon

By use of carbon powder, locally distributed on the surface of a slab, and reheating the slab at 1200°C, the carbon can diffuse in surface near zones. After rolling the slab in a standard procedure, in the surface, hard spots – based on martensitic microstructure - can be detected after shot-blasting, due to the Eddy-technique (as an example). The plate can be sectioned into coupons, of which the surface after grinding and polishing can be analyzed and described in the test laboratory according to Vickers and Leeb hardness testing

By following this procedure, the calibration coupon for the equipment manufacturer was produced and analyzed, which is shown in Fig. 5. The two calibration points with hardness 200 HV (threshold 1, soft microstructure for Zero compensation) and with hardness 250 HV (threshold 2, hard spot microstructure) clearly are indicated by red circles.

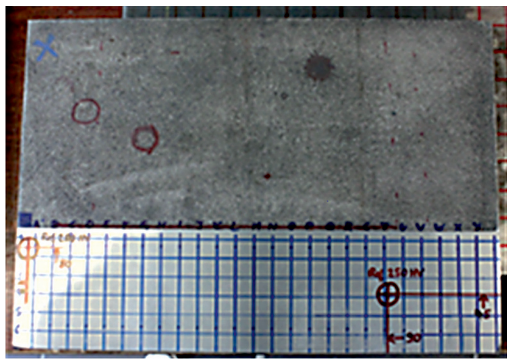

Fig. 5. Calibration Coupon
Rys. 5. Odcinek kalibracyjny

Fig. 6. Control Test Plate No. 8-18314 /3
Rys. 6. Płyta kontrolna nr 8-18314/3

Rohmann has used the Coupon to calibrate each channel of the ECT system, respectively the EC+ systems in the laboratory.

5. The Inspection Testing Program (IPT)

DILLINGER, in co-operation with Rohmann developed a non-destructive Inspection and Testing Program, which is capable of testing 100% of the plate production based on a combination of Eddy Current and Leeb testing on an industrial scale. EC or EC+ can applied to identify infected areas of the plate surface where the hardness exceeds a defined threshold. These areas are then tested for Leeb hardness to obtain an absolute hardness value which, following detailed reference calibration experiments, can be converted to Vickers hardness values, to determine, whether the contractual specification is met or not. The advantage of this combined procedure is, that a sensitive detection technique, based on a calibrated Eddy Current Testing is used to set a sensitivity threshold, but the actual evaluation and decision of the given contractual conformity or not (acceptance criteria), is only based on an objective, standardized Leeb hardness measurement, which itself does not therefore require any special qualification procedure.

However, the combination needs a qualification (chapter 7) according European qualification rules [11]. Where, the Eddy Current tests show indications of a transition from a soft microstructure to a hardened-one, the orange lamp alarm is initiated (the lamp light will change from green to orange).

- When the lamp shows orange light, according to the test specification and his training, the inspector is asked to reconfirm the indicated microstructure transition from soft-to-hard by going-back with the inspection system in the soft microstructure region (the green lamp again is indicated). By slowly move the system forward, to reach again the hardened region (the orange lamp switches-on).
- The inspector marks, as accurate as possible, by chalk on the surface, the transition position.
- The test then is further performed in the forward direction; the hardened microstructure is confirmed up to a position, where now the transition is from hard to soft.
- The procedure to mark this position, is the same as before.

The so identified and locally marked, potentially infected area – after having performed the full first side plate inspection – is now tested by Equotip for Leeb hardness determination. By doing this, a further verification/justification of the NDT inspection result - in any case, and independently - is given.

If after local grinding and smoothing (polishing) the Equotip test gives readings larger/equal the threshold agreed with the customer, e. g., 250 HV10 equivalent (as an example), further grinding (by emery paper, 300 μm grinding depth) is performed at the affected zone up to the specified thickness but not exceeding the negative thickness tolerance. Wall thickness is checked using standard ultrasound testing with longitudinal waves and vertical incidence. After grinding and polishing, Leeb hardness is measured again, to verify a new hardness value. If the hardness is within specification and the wall thickness is also within the specified tolerance, the procedure is stopped and the plate is accepted. If the hardness is still too high, further grinding, followed by Equotip measurement is performed. If the minimum wall thickness is reached, but the hardness remains outside specification, the procedure is stopped and the plate is rejected.

6. Control-Testplate for System Performance Check

So far, a heavy plate, is artificially infected, according to the procedure described in the previous chapter, the plate (Fig. 6) can be inspected by the EC or EC+ procedure. The infected hard spot is localized in its lateral dimension (area) by ECT- and verified by Leeb hardness-measurements as described. So, on plate No. 8-18314 / 3 two patches (size 380 × 90 mm2) have been identified and selected, to be representative for performance-checking of the linear sensor array. The patches are chosen in size exactly such, that the inspector can drive with the trolley to their position and can adjust the linear sensor array lengthwise on the patch. Patch S1 is for confirming the soft microstructure (all green lamps are illuminated) and the patch S2 describes hardness values in the hard spot microstructure (all orange lamps are illuminated). According the QM-rules, the System Performance check is asked for, at each beginning and each finishing of inspection of a plate, to confirm the 100% system performance.

7. Inspection reliability and System Qualification

The most important question describing the system reliability is to find a characterization of the false positive and false negative rate in the detection procedure of hardness spots, using EC and EC+. Both, are probability values, and according to the methodology of Bayes [19] one defines:

- The false positive rate, as the probability to find in a very large number of inspection trials the rate of inspection events, where the inspection system indicates a positive infection diagnosis (hardness spot detected) – but – the verification by the Leeb measurement, reveals a so-called "false alarm".
- The false negative rate, as the probability to find in the same large number of inspection trials the rate of inspection events, where the inspection system has indicated a negative infection diagnosis (the plate shows not any hardness spot) – but a destructive test as reference – e.g., sectioning of many plates into small coupons, of which each is carefully hardness tested – reveals, there are a certain distinct number of plates, which have been infected. As the infection rate of hardness spots, as mentioned before in general, is extremely low, it is obvious: experimental investigations, like the here described, are extremely cost intensive, to identify the representative number of plates to be destroyed for verification.

Therefore, another methodology was chosen, to determine the statistical distributions of the EC impedance values in the sound as well as in the infected material surfaces and to describe statistically the ability to separate both as an intrinsic feature of the testing procedure.

To do this, the trolley system was additionally equipped by the Rohmann company with a position encoder at the rolls. Using this facility, an amplitude versus the scanning coordinate image can be build-up by software. Each of the 8 measuring channels is writing a Line-Scan; the 8 parallel Line-Scans are combined in the PC to an area-image visualizing the amplitude variation in a color-coded scale (C-Scan).

It is interesting to discuss the results obtained at a plate with an artificially produced hard spot. The full C-Scan of a test-run is shown in Fig.7, right-hand-side. In addition, the impedance variation in one channel is documented on the left-hand-side and the Line-Scans of the imaginary part (Y-value) and real part (X-value) are to see in the lower part of Fig.7.

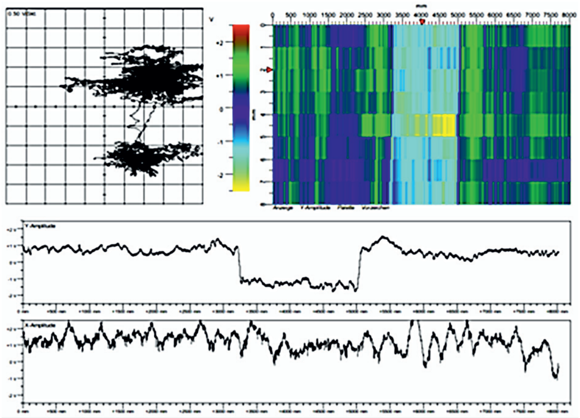

Fig. 7. Scans of a plate with an artificially produced hard spot; on upper right side, full C-Scan, on upper left side, impedance plane, lower part Line-Scans of the imaginary and real impedance parts
Rys. 7. Skany blachy z sztucznie wygenerowanymi twardymi plamami; pełen C-Scan (na górze po prawej) oraz płaszczyzna impedancji (na górze po lewej), dolna część odpowiada części rzeczywistej i urojonej impedancji otrzymanej podczas liniowych skanów

Obviously, the hard spot is clearly indicated, in all three of these individual figures:

- In the full C-Scan a light-blue strip but with a local yellow (very hard) maximum can be found.
- In the impedance plane, significantly two individual point clouds are detected. The upper-one, documents the sound, soft microstructure and its variability. The lower-one, shows the variability of the impedance in the hardness spot area.
- The two-transition path's (soft/hard and hard/soft), which connect both clouds, are to identify.
- The sound, soft microstructure is indicated always with values in the upper half plane. The mean value position of the impedance variations (center of gravity) is to find at (+ 1.5 V, + 0.73 V).
- The variation of the hard spot impedance values is always in the negative half plane. The mean value position (center of gravity) is to find at (+ 1.25 V, - 1.33 V).
- The distance between the two center of gravity has a value of 2.07 V, i.e. ≈ 2. V.

Without a loss in generality two-dimensional Gauss distributions can be assumed in the data statistics of the impedance plane and the standard deviation of the soft microstructure variation is σ_{soft} = 0.31 V, in the hardness spot the value is σ_{hard} = 0.18 V.

In the Line Scan of the imaginary part (Y-value) of one probe channel (as an example) clearly the hardness transition can be detected. In the real part (X-value) the residual noise after lift-off-reduction is indicated.

Discussing the separation between the two centers of gravity (2. V) of the distribution functions and the two standard deviations (0.31 V, respectively 0.18 V), it is to conclude that the separation of the gravity centers is:6.7 times σ_{soft} and 11.5 times σ_{hard}.

Fig. 8 visualizes the relationships as top view on the distributions in the impedance plane. The two centers of gravity, surrounded by each 3σ-bounded, respectively, 6σ-bounded environments are shown. According to statistic laws within the 3σ boundary 99.7 % of the distribution values are to find inside and only 0.3% outside. The 6σ boundary separates 99.9997 % inside from a negligible rest of 0.00034 % outside, or spoken in numbers of one million of registered impedance values, a part of only 3.4 values is to find outside.

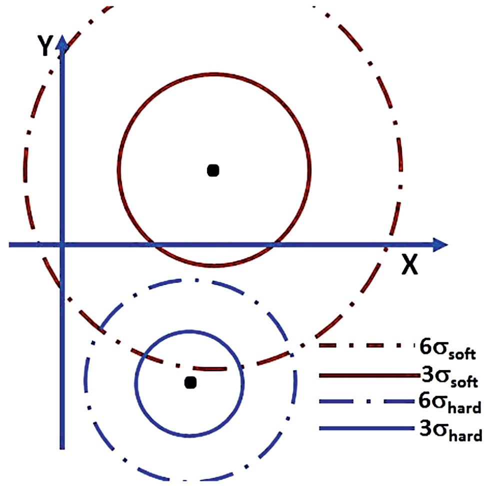

Fig. 8. Separability of the impedance values distributions - hardness spot (blue) versus sound/soft microstructure (red)
Rys. 8. Obszary występowania wartości impedancji - twardych plam (niebieskie) kontra zmiękczona mikrostruktura (czerwony)

Obviously, there is some overlapping and exact predictions of the false alarm rate and the false negative rate can only be determined by mathematical numerical integration. However, the center of gravity of the hardness spot is outside the $6\sigma_{soft}$ – environment and most of its $3\sigma_{hard}$ environment too. Therefore, the probability to evaluate a sound (soft) microstructure as hard (false positive event, false alarm), according to statistical laws, can be characterized as in the 3.4×10-6 range, and the probability to evaluate a hard spot as soft (false negative event) is negligible, vanishing small.

As the testing procedure described in the TIP is not yet standardized, qualification of the combination technology was carried out by DILLINGER under the supervision of an independent NDT expert for both, the EC and the EC+ Procedures. It was carried out in accordance with DIN CEN/TR 14748 [20], which is identical to the document of the British Standards Institution PD CEN//TR 14748:2004 [21]. The performance demonstration as blind tests, which is asked for by the EC Procedure was organized, using 15 inspectors. In the case of the EC+ Procedure, 13 inspectors were involved. Four different plates were selected for testing: (i) shot-blasted plate for system performance-check (EC), (ii) shot-blasted test plate (EC), (iii) plate with rolling skin for system performance-check (EC+), (iv) test plate with rolling skin (EC+).

The results obtained by the individual inspectors were anonymized and compared with master test results obtained from tests carried out axially in the rolling direction (length detection) and indicated by the 8-channel EC-test-system position, and, laterally, perpendicular to the rolling direction (width detection), from the Equotip-hardness measurements. This allowed both, the inspection reliability of the combination techniques to be determined, and additionally, considered the variability of any human factor influences, as many inspectors have been involved, allowing a statistical evaluation (mean value and standard deviation). The results are documented in Qualification Reports, which are integrated in the QM-handbook. The result reflects – on one hand – the influence of the human beings by discussing the maximal obtained standard deviation σ_{max} in detecting the hardness spot boundaries and the maximal deviation of their mean values Δ_{max}mean from the master values. These master values were carefully and independently measured in an open trial by two supervisor inspectors (4 eyes principle). Table 1 summarizes the result for EC and EC+ and Leeb testing:

Tab. 1. Qualification result in hardness spot detection of length and width according to the TIP, EC, EC+ and Leeb in blind tests
Tab. 1. Kwalifikacja wyników detekcji twardości na długości i szerokości zgodnie z testami TIP, EC, EC+ i Leeba

EC length σ_{max}	EC+ length σ_{max}	EC length Δ_{max}mean	EC+ length Δ_{max}mean	Leeb width σ_{max}	Leeb width Δ_{max}mean
156.1 mm	34.4 mm	36.4 mm	13.6 mm	70.2 mm	12.7 mm

It is to assume, that the differences in the result to EC and EC+ are not due to the different techniques, but to the different selected individual inspectors' actual fitness, which all had EC Level 1 and Level 2 qualification.

Reproducibility investigation were performed in the same manner, but with 2 inspectors in an open trial, repeating the test 10 times with the EC+ technique in combination with Leeb testing. The σ_{max} value in EC+ length detection was with 34.2 mm comparable to the value in Table 1, the maximal difference to the master value in hardness spot width detection was with 4.3 mm much smaller.

8. Conclusion

DILLINGER in co-operation with Rohmann has developed a new combination NDT technique, which connect a not yet standardized EC+ procedure, basing on incremental permeability measurements, with the standardized Leeb hardness measurement. The combination technique was evaluated in detail and embedded as well defined and quality-assured procedure with Technical Inspection Plan (TIP) in the standard procedure for customer negotiations and specifications. Based on the TIP, the heavy steel production can be quality tested for the detection of hardness spots on an industrial scale. The technology was qualified according European qualification rules and with this qualification DILLINGER is the 1st heavy plate producer in the world with the ability to deliver quality according to this specification.

9. Future Trends

DILLINGER is strictly performing the next steps to innovative quality procedures. In the second half of 2017 a fully-automated EC+-test system will be installed; parallel DILLINGER has initiated with the DIN standardization body a consensus standardization project.

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