# Development of an Eddy Current based Inspection Technique for the Detection of Hard Spots on Heavy Plates

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**Abstract.** Hard Spots are local areas with increased hardness on the surface of semi-finished or end products in steel manufacturing. The cause of these hard spots is attributed to effects in the casting or rolling process. In general the occurrence of hard spots cannot be avoided completely in production of heavy plates. Therefore, in various current line-pipe specifications the topic 'hard spots' is discussed.

As the incident rate of hard spots is extremely low, only a 100% inspection of production can ascertain their detection. For this reason Rohmann GmbH, together with Dillinger Hütte AG, as one of the world leading plate manufacturers, have jointly developed a new, eddy current based, inspection technique to ensure the detection of hard spots on heavy plates.

Basis for this inspection technique is the combination of an eddy current inspection with a pulsed magnetization. A phase-locked coupling in between the magnetization pulses and the eddy current excitation frequency allows a highly stable inspection for small hardness variations. The eddy current measurement is taken, while the material is going through its re-magnetization cycle, effected by a bi-polar magnetization pulse.

To be able to integrate this new method into the production process, the so called rolling skin or mill scale, a thin surface layer of different iron oxides with different material properties to the base material, should not influence the inspection results. The inhomogeneities of this rolling skin, especially in conductivity and permeability, normally render standard eddy current inspection impossible. The new technique using the re-magnetization overcomes this problem, which was comprehensively confirmed in long term on site tests, using inspection trolleys equipped with the new technology. Additionally test on pipes were conducted, which showed that even under quite thick coatings of several millimeters, hard spots (and cracks) could be easily detected.

The presented paper describes the method itself including the theoretical background as well as the calibration on artificial hard spots and the applied inspection procedure. Actual data and results gathered from in-production inspection runs gives an impression of the capabilities of the new technique. Finally, an outlook towards a 100% automatic inspection system, which will be placed in line in the production process, is given.

## 1. Inspection Task

In the production process of steel, it may occur in very rare cases that local hardening on the surface appears. This material science phenomenon (so called ‘hard spots’) is increasingly considered in the relevant specifications for line-pipe tubes, where a check for surface hardness is demanded. For example, it is specified in [1]: "Any hard spot larger than 50 mm in any direction, shall be classified as a defect if its hardness, based upon individual indentations, exceeds: 250 HV10 on the internal surface of the pipe, or 275 HV10 on the external surface of the pipe." From the requirements of the specifications, a new inspection task results, to find hard spots, respectively, to exclude the presence of hard spots.

In the production of steel, the hardness is usually measured on specimen samples using destructive measurement methods such as Vickers, Brinell or Rockwell. Non-Destructive measurements on heavy plates are acomplished using the Leeb rebound test with Equotip instruments. The measuring principle after Leeb is based on the dynamic rebound technique. An impact body (normally a metal ball) is thrown against the surface of the heavy plate. When the impactor strikes the test surface, the surface is deformed, which is resulting in a loss of kinetic energy of the impactor. This energy loss is determined by the difference of the balls speeds before and after impact. The measured difference is converted into a hardness value (ASTM A956 / E140 / A370, ISO EN 16859 (not yet published) and DIN 50156).

The classical hardness testing methods offer actually no real solution to the present test task, especially as the complete production should be inspected, which is hardly possible with a manual punctual method.

Theoretical analysis led to the approach to develop an NDT technique based on the eddy current technique for the detection of hard spots, as eddy current testing is a method, which can be easily automized and up scaled to the demanded extend.

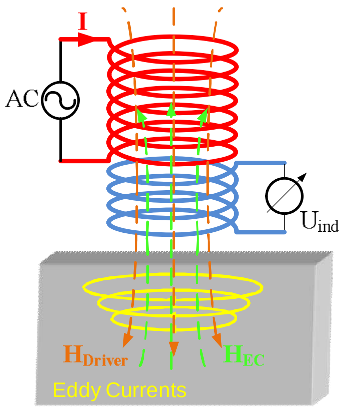


**Fig. 1**. Eddy Current Principle (schematic)

The eddy current testing is based on an alternating electro-magnetic field, which is generated by a driver coil and an injected alternating current. In case this alternating electro-magnetic field penetrates into a conductive material, it generates an induced potential, which due to the electrical conductivity results in currents which close around the induced field lines. Therefore these currents are called ‘eddy currents’ inspired by the usage of the word „eddy“ for a vortex.

Those eddy currents themselves generate an alternating magnetic field. Both fields the injected driver field as well as the eddy current field overlay to form a resulting field, which can be measured in amplitude and phase angle outside the test specimen using a simple coil and measuring the induced voltage. All this can be calculated based on

Maxwell's equations, which describe in general the electro-magnetic field and its interactions.

As it can be quite easily seen, the eddy current testing yields information on the electrical conductivity **σ** and magnetic permeability **μ** of the test specimen in the interaction volume under the probe.

Normally different hardness or grain structures of a material also show at least minimal differences in conductivity and/or permeability. Therefore the eddy current inspection should be able to detect those local inhomogeneities of the material properties.

## 2. Test Specimens with Artificial Hard Spots

In order to develop and validate an appropriate test method heavy plates are needed with superficial hard spots. To have suitable test specimens available, during the last year Dillinger Hütte AG has developed a method for producing local, artificial hardness increases.

The artificial hard spots can be produced in different sizes, have the same thermo-mechanical history as the rest of the sheet, the almost same chemical composition and are largely invisible.

To produce those artificial hard spots a carbon substrate (for example carburizing powder) is applied onto the slabs and the dimensions and position of the regions of the applications are documented. The base slabs have the same chemical composition of the steel grade which has to be examined later for hard spots.

During the subsequent slab heating, there is superficial carburizing in the areas with applied substrate by carbon diffusion from the substrate into the slab. The slabs are then rolled using the same production pass schedules as for the production plates. Finally the verification of the "hardening" in the carburized areas is carried out with Equotip hardness measurement units on the surface. It was thus possible to produce areas with increased hardness of 250-300 HV relative to the base plate material, with around 200 HV.

## 3. Inspection Method

### 3.1 Development

On test specimens with the artificial hardness increases, the first tests were executed and it could be proven that the hardness increases could be detected using the eddy current technique. For those tests a standard off the shelf eddy current instrument Elotest PL500 was used together with a standard surface probe PLA-62.

The calibration of the test system was setup on a test block with artificial hardness increased areas and a sensor spacing of around 0.4 mm to the surface. As test frequency 60 kHz was chosen.

The system was 'nulled' on an area with a hardness of 229 HV, were the signal point was set to 100% screen height (2 V). Then the probe was moved to an area with 250 HV and the amplification was adjusted to a amplitude of now 50% screen height (1V), which was also set as threshold for the later evaluation. If the amplitude falls below the 50% threshold this was indicated to the operator by a signal light.

Based on this, a first 8-channel industrial test carriage for field trials on heavy plates in the rolling mill of Dillinger Hütte AG was built.

First, plates with artificial hardness increases were measured and all of them could be detected easily. In addition, first customer orders have been processed and first plates were identified with natural hardness increases, which were made available for later enhancements and verifications.

Unfortunately the tests also show a strong influence of the so called rolling skin or mill scale, a thin surface layer of different iron oxides with different and very inhomogeneous material properties to the base material. Therefore the standard eddy current technique could only be applied to plates with blasted surface, where the rolling skin was removed.

To overcome this problem Rohmann developed new approach (patent pending). It is based on a probe combining a standard eddy current absolute surface probe with a magnetizing yoke. The yoke is driven by bipolar current pulses, which drive the material under test through its hysteresis curve. The absolute eddy current probe then measures the change in the local permeability relative to the hysteresis curve. To accomplish this, the eddy current frequency is phase locked to the magnetization pulses.

To reach the required inspection speed, magnetizing pulse rates of up to 200 Hz are used, while the eddy current test frequency is adjusted around 80 – 100 kHz.

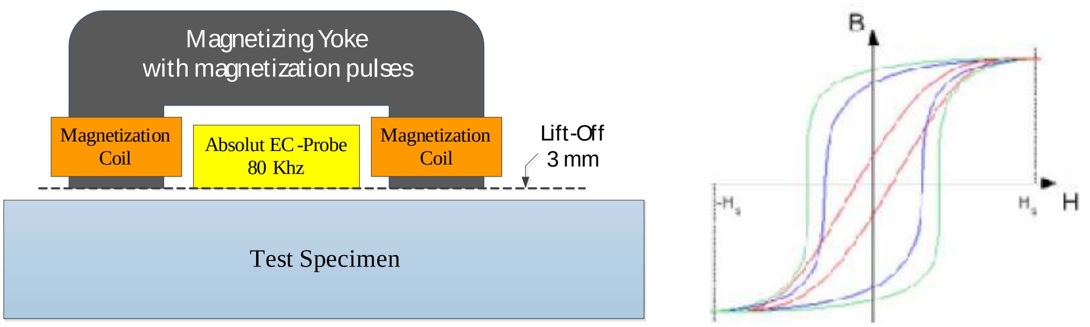


**Fig. 2**. Eddy+ principle

For magnetic soft material, the hysteresis curve is quite narrow while magnetic hard material show a wide hysteresis curve. This magnetic behavior correlates with the mechanical hardness and therefore the hardness variation can be detected quite reliably with the new approach, independent of an existing fresh rolling skin. Soft areas show a high signal amplitude, while harder areas show significant amplitude reductions. Also lift-off of the probe show significant amplitude reduction and therefore no hard spot can be missed due to improper guiding of the test system. As soon as a suspect area is detected, a crosscheck with Equotip is recommended.

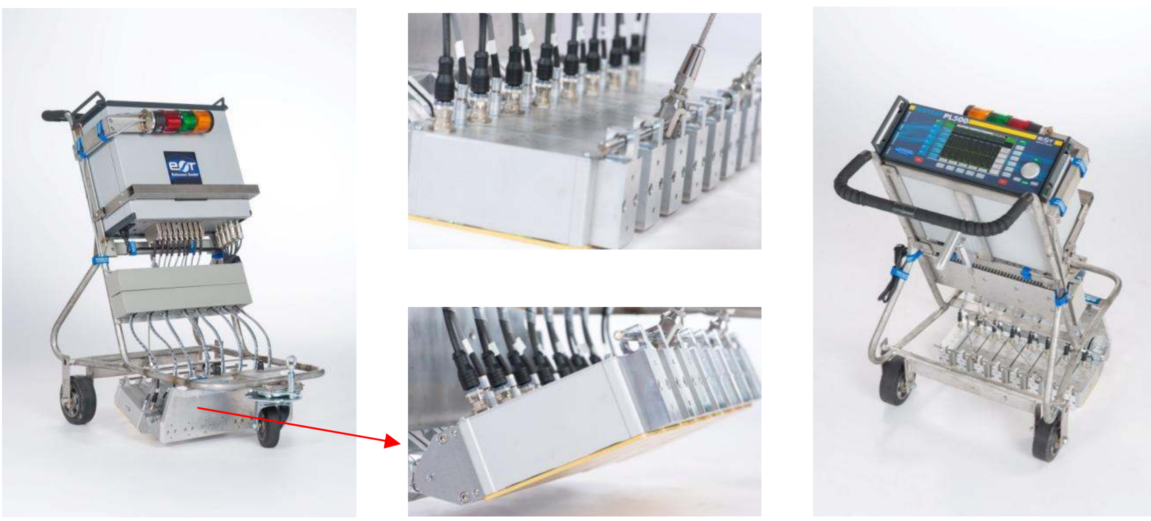

**Fig. 3.** Eddy+ industrial test carriage

After the basic test capability of the new approach was verified on heavy plates with artificial and natural hard spots, another industrial test carriage with ELOTEST PL500 and eight side by side sensors (type PLA-61 H-1974) was designed.

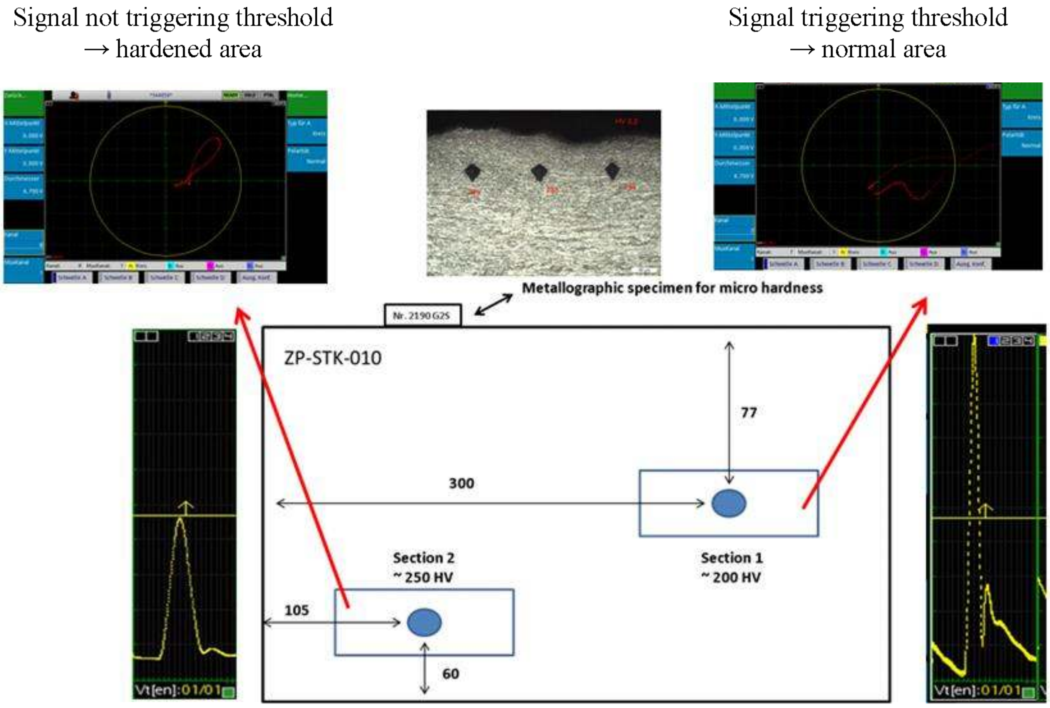


**Fig. 4.** Eddy+ Adjustment

All test sensors were previously adjusted in the laboratory on a dedicated test block ZP-STK-010 (surface-rolled with real hardening) (see Figure 4).

The adjustment takes place first at the section 1 with 200 HV. Here, the signal amplitude is set to full screen height (100%). The amplification and detection threshold is then adjusted at the section 2 with 250 HV. Here, a signal drop must be achieved to 50% screen height.

The resulting signal is shown on the left side of figure 3. The adjustment is stored in the system and is automatically uploaded when the device is restarted.

The operator later on is not able to change the initial calibration parameters. Changes can only be carried out by specially trained and authorized personnel.

To facilitate the operation of the system it carries three indicator lights. A green light indicates that the system is active. A red light indicates system faults. The detection of hard spots is indicated by an orange light.

### 3.2 Industrial Application

The industrial tests were performed similar to the proven and reliable implementation of manual ultrasonic testing with US carriages by suitably trained and certified (ET - Level 1-qualified) personnel (Figure 5). Both sides of the heavy plates were 100% tested. Areas with suspect indications (i.e. threshold indications) were cross checked with Equotip hardness measurement and are geometrically delimited and marked on the surface as well as on a report sheet.

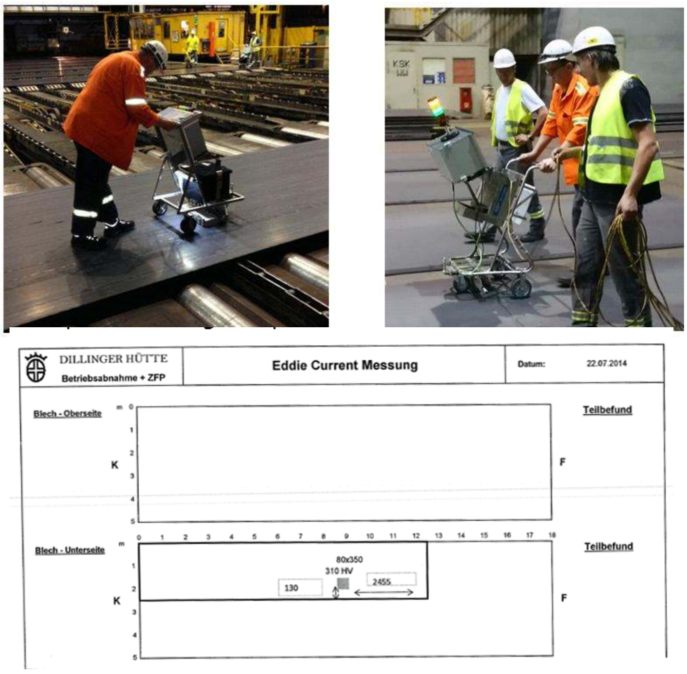


**Fig. 5.** Testing on plates with at example for the documentation of the test results

After a predefined period (for example, every ten plates) the functionality of the test system is verified on a specially prepared test plate with defined and marked areas of "normal" hardness and” increased” hardness (hard spot).

3.3 Qualification

The eddy current based method Eddy+ and the hardness test following Leeb are used for the detection of hardened areas on the surface of heavy plates outside the existing standards and regulations. Therefore, the detection of "hard spot areas" had been qualified in accordance with the procedure described below. The qualification was carried out by blind trials according to DIN technical report CEN / TR 14748. This qualification should prove that the described procedure ensures finding hard spots on the sheets. During the qualification program eleven inspectors with ET 1 (ISO 9712) qualification have tested the same reference plate which carried 2 hard spots with different geometrical extend. All eleven results of the blind tests were compared with the results of Master test.

Result of the qualification tests: all inspectors have found both hard spot areas and the maximum mean deviation of the position of the hard spot areas of the heading plate edge was only 5.5 mm.

The qualification was conducted by the final acceptance and NDT department of Dillinger Hütte AG and it was supervised by Prof. Dr. Dobmann as an independent NDT expert and appraiser.

## 4. Operating Results

Up to now more than 100,000 t of heavy plates were tested on both sides for hard spots with the process described above. The test system gave very stable results. In the 2,000 verifications of the test performance, there was not a single miss. In the third quarter 2015, a first major customer order was 100% inspected with Eddy + for hard spots. This contract was a line pipe contract for longitudinally welded large-diameter pipes with a wall thickness > 30 mm. Over 4,600 plates were inspected from both sides. As from the contract the mean material hardness was about 200 HV on the surface, the hardness threshold for a hard spot was set at 250 HV.

The internal inspection showed only a few sheets (<0.5%) with increased hardness areas. In most cases, the hardened areas could be removed by slight grinding (removal 0.1 to 0.3 mm).

In a next step in the operational application, sheets with detected hard spots were specifically formed into for pipes, to verify the detectability of the hardness increases with the eddy current technique. The proof was obtained with "standard" eddy current at blasted pipes, both from the internal and external surface. As instrument the ELOTEST M3 was used. Even through the 4 - 5 mm thick outer coating, the hardness increases could be clearly demonstrated on the tube outside surface.

The first standard tests have - as described above - shown that a local hardening occurs with an extremely low probability, so that only a 100% inspection can avoid the appearance of hardening on the products.

## 5. Implementation of an Inline Test System

To adapt the above described inspection technology to an inline system, different parameters have to be taken into account such as: plate dimensions, testing speed and inspection grid.

In general plate width is up to 4.800 mm, testing speed is at maximum 1m/s and an inspection grid of 10 mm² seems reasonable. Based on these parameters and taking the steel mill environment into account, a high speed scanning device with only a few probes seemed not suitable. A close look to the established inline ultrasonic inspection system showed, that the inline system had to be based on a huge quantity of probes which simply ride on the plate surface.

Therefore Rohmann GmbH has involved an experienced mechanical partner Woll Maschinenbau GmbH to design a suitable mechanical solution.

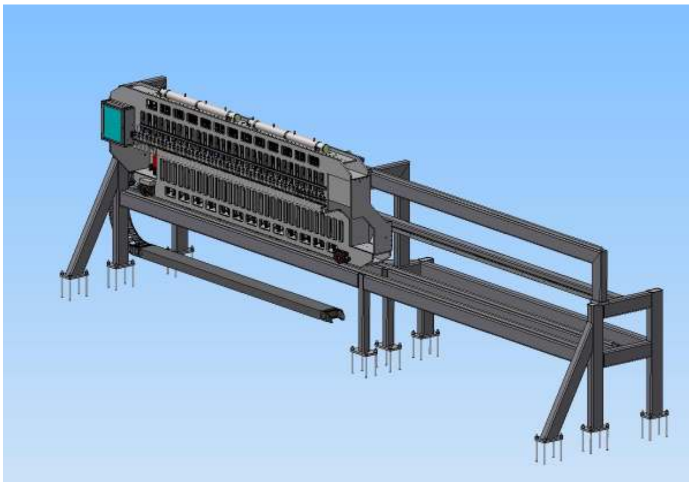

**Fig. 6.** First design of a test mechanics

Finally the current state of planning is a test system based on 2x 60 probe heads, each carrying 8 probes. Each probe head is individually applied to the plate surface, depending on the plate width and edge geometry.

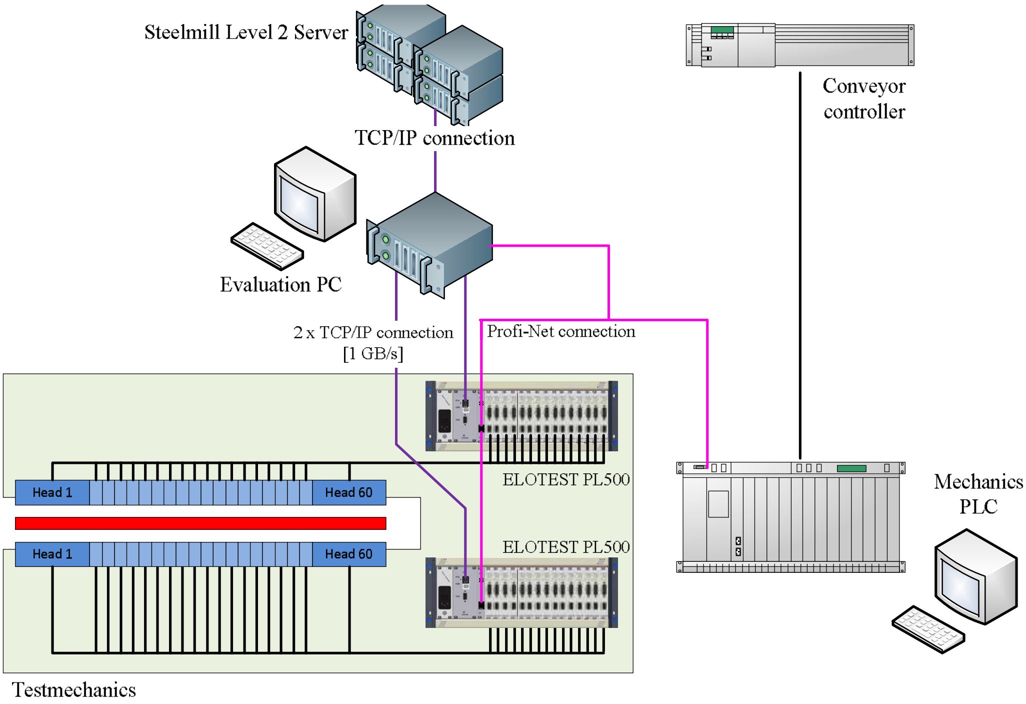


**Fig. 6.** Block diagram test system

In total this sums up to 960 probes which are operated using just 2 Elotest PL500 instruments. Both instruments are connected via a 1Gb/s Ethernet port to an evaluation computer, which will acquire all the data and generate a C-Scan image of both sides of the heavy plates.

## 6. Summary and Outlook

- Dillinger Hütte AG has together with Rohmann GmbH developed a system based on the eddy current technique to prove the compliance with the current specifications for heavy plates to avoid local surface hardening (hard spots).
- This is the world's first industrial testing system for the detection of hard spots on heavy plates.
- For this purpose, first a dedicated process had to be established, to industrially produce hard spots, to get known calibration plates. These calibration plates were the basis to validate the test system performance.
- Blind tests were carried out for the qualification of the non-standard procedure which is not contained in any regulations or procedures.
- Large-scale industrial test series now provide sufficient experimental data to clarify the mechanisms leading to the formation of hard spots.
- First statements could be made about statistical appearance rate of hard spots.
- The method can also be applied to pipes with and without coating.
- Currently there is an inline system for 100% inspection of the production for Dillinger Hütte AG in commission.

## References:

[1] Offshore Standard DNV-OS-F101–Submarine Pipeline Systems, October 2013, page 134, §109