IN-LINE QUALITY CONTROL OF HOT WIRE STEEL

KAWALLA, R., GOLDBAHN, G. (1); PEREZ MELGUZIDO, C. (2), HARTMANN, K.; LLANOS, M. (3)

(1) TU Bergakademie Freiberg, Institute for Metal Forming, 09599 Freiberg, Bernhard-von-Cotta-Str. 4, Germany, rudolf.kawalla@imf.tu-freiberg.de
(2) Tecnatom S. A., Spain
(3) Sidenor Investigación y Desarrollo, S. A., Spain

Abstract

Within the frame of the EU RFCS (Research Fund for Coal and Steel) program an in-line control system for hot rods and wires was developed. The project named “INCOSTEEL” was realised in cooperation between Tecnatom S. A., Spain, TU Freiberg, Germany, University Kassel, Germany and Sidenor Investigacion y Desarrollo, S. A., Spain.

The main objective of the research was a new in-line hot steel inspection technique. Surface defects must be detected in extreme rolling conditions up to 120m/s rolling speed and temperatures between 850°C and 1200°C (non-ferrous behaviour about Curie temperature). So far Eddy Current (EC) techniques show important difficulties to detect and to characterise longitudinal as large surface defects in general.

The technology developed (EC sensors, EC electronics and excitation modes) was validated first at laboratory level by cold tests at Tecnatom (Spain) and University Kassel (Germany) and after that hot tests were realised on the continuous rod and wire pilot rolling mill of TU Freiberg (Germany), final tests took place in industrial conditions at Sidenor (Spain).

Successful results were achieved with the inspection prototypes developed.

Keywords: In-Line Control, Eddy Current Sensors, Rod Rolling, Wire Rolling, Defects, Quality Management,

1. OBJECTIVE

In industrial manufacturing, product inspection is an important step in the production process. Because product reliability is of great importance in most mass-production processes, hundred percent inspection of the whole finished product is often required. Steelmaking industry is one of these cases. In particular, steel rods and wire follow several quality control processes from the raw material to finished components, depending on the final usage or targeted industry.

Hot wire inspection is applied to detect “surface defects”. Electromagnetic techniques are the most suitable to identify these type of defects, especially eddy currents. Due to the high rolling speed and the temperature of the material under testing, non-contact techniques are needed. Inspection conditions are not the best ones, because of the rough surface (with some impurities, scale, etc.), that wire presents, the rolling speed (that produces some vibrations and require electronics with high acquisition rates), etc. Even in the most modern hot rolling mills, wire inspection presents some limitations that affect mainly to the detection and characterisation of longitudinal defects and especially for those that show very long dimensions and that require a completely different approach. So, the scientific objectives pursued in the project were:

1. To propose new in-line defect detection techniques and methods for characterising the surface defects produced in the rolling process, under the following operating conditions: 900 – 1200°C, 100 – 120m/s rolling speed.
New electromagnetic techniques based on the concept of array sensors and Electromagnetic-acoustic transducers (EMATs) were tested, focussed on the detection of longitudinal defects.

2. To improve also detectability, being the target defect depth 0.1 mm.

3. To reduce time and costs in the design and manufacture of the novel sensors: Electromagnetic and Ultrasonic Modelling activities were recommended to demonstrate if those techniques were feasible or not and to improve the characteristics and performance of the proposed sensors.

4. To reduce rejected material in further steelmaking processes. Parts of the material, which were preliminary acceptable after hot wire inspection, can present defects that could suppose the rejection of the whole steel coil or part of it later on. The project aimed to recover 50% of the present rejected material by reliably detecting smaller defects and longitudinal cracks and other type of flaws in the material.

   • To develop a methodology for easy application of a combination of electromagnetic and ultrasonic inspection techniques.
   • To develop data fusion techniques to combine the information coming from those techniques.
   • To design and implement functions for real-time decision making, applicable in in-line hot wire inspection.

5. To provide a tool for internal management of the production process and quality control associated: a database should be developed, to collect all the measurements carried out in each rod, including defect extraction, comparison with previous records, reports and statistics.

6. To reduce / avoid interruptions in the production process to validate the proposed technology. Validation tests require the use of industrial facilities (the end-user was Sidenor Investigacion y Desarrollo, S. A., Spain) or reproducing real operating conditions. The project strategy was based on testing everything in the pilot rolling mill available in TU-BA-Freiberg, Germany. This partner performed several modifications in those experimental facilities and allowed Tecnatom S. A., Spain, and University Kassel, Germany, to test their new sensors and techniques.

2. PROTOTYPES

Advanced EC techniques and sensors (a new encircling coil and array sensors) have been designed and some prototypes manufactured for validation. Different ways to generate a magnetic field within a sample have been studied, in particular for encircling coils (composed of four coils), the usage of inner excitation coils gave best results regarding sensor sensitivity. When ferrites were used to concentrate the magnetic flux, sensor sensitivity improved. So, the encircling coil with ferrite cores was the favourite sensor configuration for defect detection measurements. For surface probe sensors, several emission-reception schemes were proposed and tested. These sensors have a smaller sensitivity (hub) than encircling coil sensors. Their advantage is that they can detect even long longitudinal defects.

Unfortunately their sensitivity is strongly dependent on geometry. So many prototypes need to be modelled and manufactured to lead to an optimum geometry. The difference between encircling coils and surface unitary elements is that the second ones cover only a certain surface area of a specimen and must be arranged in array mode all around the wire (encircling coil provides global information (360°) in the area of application).
Considering that sensors operate with samples, which are 1000°C hot, a cooling system was needed to operate the ferrite sensor for a longer period of time. The material where the coil is wound (MARCOR), which is resistant up to 800°C; was easily machined and preserved sensor undamaged after rolling in real conditions (Sidenor).

The final inspection system was composed of the following elements:

Hybrid sensors: A combination EC encircling coil + EC array sensor based on surface coils was selected as the best option to detect any type of defect. The encircling coil detects the transversal defects and the array sensor is focussed on the longitudinal ones.

EC electronics and Software: The new hardware was used as data acquisition system, together with a Control Software. A multiplexer unit was designed and manufactured to simplify sensor connections and the identification of channels. Multi-purpose TEDDY Evaluation Software was used at the beginning to recognise the defects and to establish data processing algorithms to be used in in-line rolling processes. They were integrated into the control software. Some Software adaptations were made in TEDDY software to deal with array sensors and to combine this information with the typical encircling coil.

Inspection devices: They contain the sensor box, as well as the water cooling system and guiding cylinders.

3. COLD LABORATORY TESTS (TECNATOM AND UNIVERSITY KASSEL)

The EC prototypes (encircling coils and array sensors) were tested at ambient temperature on the calibration mock-ups. For this austenite steel was used. It contained three longitudinal defects (1, 0.5 and 0.1 mm) and a transversal defect. All defects were machined with grinding disks. Figure 1 shows the results on one of the calibration bars. Defects machined in this bar were, in this order: Longitudinal notch, 1 mm deep, longitudinal notch, 0.5 mm deep, longitudinal notch 3 mm deep. It is clear that the absolute channel can detect the longitudinal defects. So, it has been demonstrated that, in laboratory conditions, it is possible to detect the proposed longitudinal defects.

![Fig 1: Results with a 3-coils array sensor at room temperature, using a calibration bar](image.png)
4. TRIALS AT TECHNICAL UNIVERSITY BERGAKADEMIE FREIBERG

4.1 Three high mill

As preliminary trials for the continuous pilot mill and the industrial trials at Sidenor three different sensor types were tested on a three-high mill. Objective was, to investigate the sensor sustainability for daily use and to adjust the guides in front of the sensor precisely, that no destruction of the ceramics or electronics appeared. On the other hand should be seen, if the sensor and the ceramic are stable in the high temperatures, which appear at continuous rolling.

So, based on these results, the actions and improvements proposed to prepare the next trials at the continuous pilot rolling mill at Freiberg were the following:

- Improvements of guiding and centring systems: It was confirmed later than guiding was excellent in the continuous rolling mill. Additional centring cylinders near the sensor could help to protect the sensors and to reduce the lift-off effect.
- Research on data processing algorithms to correct the balance point observed in real operation compared with the calibrated one. Here again, it was expected that the continuous rolling process would provide longer materials, where the behaviour of the sensors could be assessed and corrected.
- Improvements of the actual sensors: Some minor modifications were proposed and validated by modelling by University Kassel.

4.2 Continuous pilot rolling mill

For the trials on the continuous pilot rolling mill in Freiberg, the sensors, including measuring system, were placed in the rolling line behind the water cooling line (see Figure 2). To avoid any destruction at higher finishing speeds the adjustment had to be very precise. Varying dimensions of top and end of the rod (so-called “fish tails”) could also destroy the equipment. For this reason, preliminary trials without sensors were realised.

![Fig. 2: Placement of the sensors in the rolling Line](image)

The sensors were installed on a ceramic part of MACOR (Figure 3) as close as possible to the rod surface. To protect the sensors from the high temperatures, the hot rod goes through a steel cylinder placed inside the ceramic part, and the space between this cylinder and the ceramic part can be water cooled. Finally, a metallic disk was inserted between both sensors, to isolate each sensor from the other one. The test bench was manufactured in brass (Figure 4), because of its resistance to high temperatures and heat conductivity.
The material (steel 16MnSiCr3) provided by Sidenor was prepared for testing:

- Bar machining (notches both longitudinal as transversal, holes),
- Manually measurement of artificial defect arrangement.
- Annealing (inductor to 1250°C, 5 minutes)
- Equalising (chamber furnace, 1250°C, 20 – 25 minutes)
- Roughing: (8 reversing passes). dead pass., speed up (driver 1),
- Finishing: (2 continuous passes).
- Slow down (slow down driver 2).
- Cooling of straight rods in air.
- Defect inspection and measuring (manually again).

The rolling speed was limited by 10m/s because straight rods were needed for a manual measurement of the defect arrangement after rolling. As finish dimension Ø12.0mm was used, the same as later in practice conditions at Sidenor.
Fig. 7: Teddy System, modular hardware and industrial prototype

The modular hardware and the prototype for in-line detection of defects in hot wire and rod rolling, developed by Sidenor can be seen in Fig. 7.

The artificial defects were selected according to defects appearing during rolling in practice: Longitudinal cracks, transversal cracks (flakes) and holes. Fig. 8 presents the defect arrangement on the rods before rolling. In Fig. 9 defects after rolling can be seen. The defect arrangement was measured manually and compared with sensor records (Fig. 10). This way it was possible, to compare the results of different sensor types and to select the best for practice inspections in the Sidenor rod and wire rolling mill.

Fig. 8: Schematic of artificial defects in a test bar at TU Berg-akademie Freiberg
Fig. 9: Artificial defects at TU Bergakademie Freiberg after finishing

Fig. 10: EC-record of longitudinal notches, drilled holes and transversal notches
5. VALIDATION TESTS AT SIDENOR

Two test campaigns were carried out in practical conditions at Sidenor rod and wire rolling mill. As before at TU Bergakademie Freiberg for the first tests at Sidenor, many longitudinal and transversal defects were mechanised in the test samples (see Figure 11). After that, samples were heated in a furnace to 1250°C and the sensor installed in the rolling line. Each rod had a square section of 150 x150 mm. Transversal defects were produced in two corners and the longitudinal ones on one side (Fig. 12). The bars had also two screws in the middle (one deeper than the other) that could disappear after heating or remain as a potential defect.

The rolling speed was 23,5m/s, the finish dimension Ø12,0mm, the measurement period was ca. 75s per rod.

Fig. 11: Schematic of artificial defects in a test bar at Sidenor

| a) Transversal notches | b) Longitudinal notch | c) Sensor in the rolling line |

Fig. 12: Artificial defects and sensor installation in the rolling line at Sidenor

Fig. 13 shows the complete measurement report of one bar rolled at Sidenor in practice conditions to a final dimension of Ø12,0mm, Fig. 14 potential longitudinal defects.

Table 1 summarises the results of sensor detection and manually inspected finish rods. It can be seen, that most of the artificial defects were found, in most cases simultaneously by several sensors. Advantageous was the installation of several sensors over the rod perimeter.

Due to a total elongation of $\lambda = 156$ after finishing the defects were tiny. It was hard to find these by optical inspections. For this reason metallographical methods were used, to decide, if the defect was recorded precisely or not. Fig. 15 and 16 present some characteristic defects after finishing. These correspond to defects created during the rolling and cooling process in a mill.
<table>
<thead>
<tr>
<th>Encircling Coil Position [m]</th>
<th>Peak-to-peak voltage</th>
<th>Array sensor [°]</th>
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<tbody>
<tr>
<td>47.7</td>
<td>19.00</td>
<td>45°, 90° and 135°</td>
</tr>
<tr>
<td>47.8</td>
<td>38.00</td>
<td>45°, 90° and 135°</td>
</tr>
<tr>
<td>225.0</td>
<td>5.70</td>
<td>Not detected</td>
</tr>
<tr>
<td>261.9</td>
<td>122.00</td>
<td>315°, 0°, 45°, 90°, 135° and 180°</td>
</tr>
<tr>
<td>262.2</td>
<td>5.79</td>
<td>270° and 315°</td>
</tr>
<tr>
<td>296.9</td>
<td>9.93</td>
<td>135° and 180°</td>
</tr>
<tr>
<td>332.5</td>
<td>3.32</td>
<td>Not detected</td>
</tr>
<tr>
<td>394.1</td>
<td>28.63</td>
<td>315°, 0° and 45°</td>
</tr>
<tr>
<td>399.3</td>
<td>6.97</td>
<td>0° and 45°</td>
</tr>
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<td>399.6</td>
<td>13.67</td>
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<td>631.0</td>
<td>59.27</td>
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<td>812.5</td>
<td>25.93</td>
<td>135°, 180° and 225°</td>
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<td>816.5</td>
<td>4.47</td>
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<td>816.6</td>
<td>104.45</td>
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<td>816.8</td>
<td>3.68</td>
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<td>132.97</td>
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<td>817.0</td>
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<td>837.4</td>
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<td>837.5</td>
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<td>Longitudinal defect</td>
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<td>838.4</td>
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<tr>
<td>1490.8</td>
<td>81.42</td>
<td>90°, 135°, 180°, 225° and 270°</td>
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</table>

**Tab. 1:** Detection results of a rod rolled in industrial conditions at Sidenor (low carbon steel)

**Fig. 13:** Complete record of a rod rolled in industrial conditions at Sidenor (low carbon steel)
Fig. 14: Potential longitudinal defect

Fig. 15: Double longitudinal lap detected by EC
6. CONCLUSIONS

Several designs of EC array sensors were validated in hot rolling tests in laboratory and industrial practice. These showed good performance for detecting surface defects produced during hot rolling. Some difficulties remain to detect long longitudinal defects for depths < 0.6 mm.

Based on a combination of EC sensors, all defects can be detected. In the calibration (where surface material shows optimum conditions for testing), the proposed techniques were able to detect up to 0.5 mm defects (depth). Sensor-to-wire distance reduces sensor sensitivity remarkably.

In laboratory rolling trials, where sensor can be closer to the wire because of a better guiding of the rolled material, 0.1 mm deep defects could also be detected.

For best defect detection, the sensors should be operated within their working points. Calibration in laboratory conditions and using calibration bars (stainless steel) is the only method to identify inspection parameters.

Because of the harsh environment, the sensor’s working point needs to be controlled during operation and, if needed, to adapted. This can be done either by means of electronic circuits or controlled by software within a PC. If working points are not controlled as suggested, defect detection is still possible but defects indicating signals are smaller in amplitude, making much more difficult defect detection and characterisation.

Numerical modelling of different sensors was carried out; performance analysis has been done based on simulations as well as in experimental measurements. Optimization of all the developed sensors has been performed by modelling. So, the number of prototypes to be manufactured for validation could be reduced. Other aspects like the influence of rolling speed in the electromagnetic induction were also analysed by simulation. Models were quite accurate compared with real sensor performance.

The pilot rolling mill in Freiberg allowed a deeper knowledge of continuous hot rolling process, rod and wire quality (natural types of surface defects, surface finishing, etc.), making possible the improvement of EC techniques and sensors.

Validation tests carried out in this mill reduced considerably assessment tests. The main aspects (sensor resistance at high temperatures, sensor capabilities to detect surface optimising sensors and techniques, final validation tests) were performed in Sidenor. Sensitivity remained unaltered and sensors did not suffer any physical damage. The cooling system for longer duration tests worked properly.
REFERENCES


