Automatic Roll Mark Detector Improves Cold Rolling Mill Performance

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This paper introduces a new innovation, an automatic roll mark detector, designed to save cold rolling mills from costly roll mark defects. The solution is an on-line installation into the exits of cold mills to automatically inspect every coil for roll marks — even for non-visible roll marks, which require manual chalking. The system alarms the operators from the first affected coil. Operators can take corrective actions without delay with the help of the images the detector displays in the operator pulpit human-machine interface. Records from a full-sized industrial pilot show major savings in downgrading costs and more full-speed rolling time since detector hand-over in late 2015. Furthermore, better reassignment for the fewer affected coils, higher-scoring customer key performance indicators, and many more cost benefits are experienced thanks to keeping the rolling operation more process-focused.

Roll marks have been a constant issue for cold rolling mills since the beginning of cold rolling technology. Their greatest impact is on the most profitable products of the industry: the exposed products. The total cold-rolled production in Europe is roughly 45 million metric tons, with about 20% dedicated to exposed parts (~9 million metric tons).[2] The numbers are very similar in North America. In some plants, more than 5% of cold-rolled products can be affected by these defects. The non-quality costs associated with roll mark defects come from:

- Products sent to customers and leading to claim costs.
- Defective products detected before shipping to customer, with high reallocation costs.

The global cost estimate for Europe is greater than €225M/year.

Today's preventive measures and roll mark inspection practices have proven to be very costly. A common practice is to manually inspect one coil out of every four or five, when rolling exposed material. The short cycle time of the mill versus the 12- to 15-minute delay of the manual inspection result always leads to multiple coils being affected by a single roll mark. Human factors with missed marks increase this cost. In addition to this, rolling capacity is lost, hundreds of hours every year, because of only half-speed rolling while waiting for the results from the manual inspection.

Due to the nature of the rolling process, most roll marks have no contrast, making them very difficult to find in the exit of the cold mill. Coating can allow the marks to become more visible, but the harm to productivity has already been done. The real productivity improvement potential is to be able to block the affected coils at the exit of the cold mill and take immediate corrective actions to return the mill back to quality.

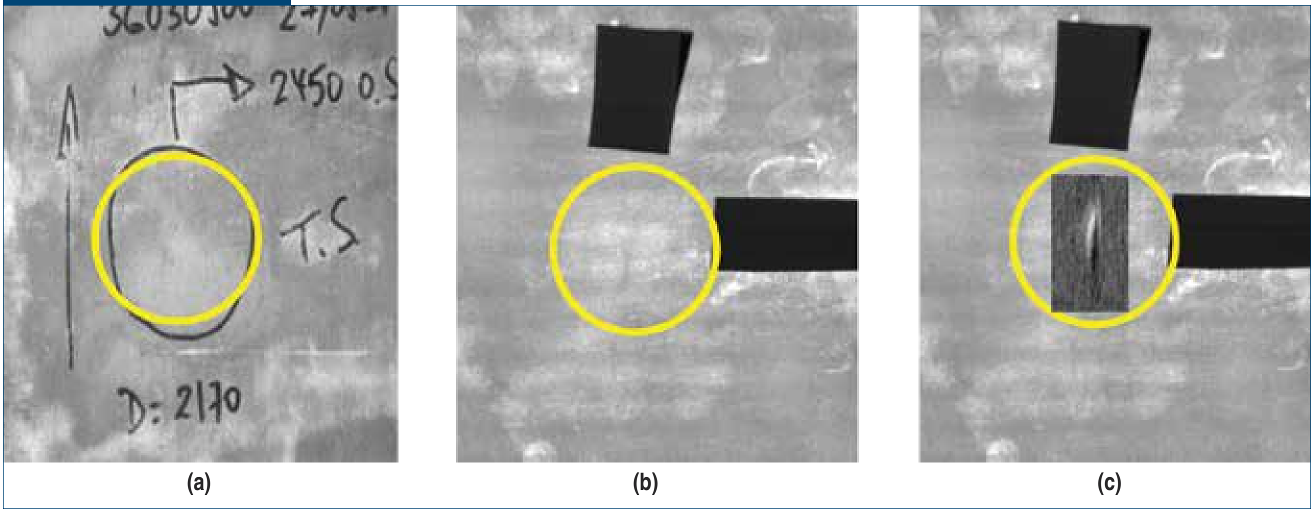
The Innovation

Despite numerous tests and trials with the classical automatic surface inspection systems, a satisfactory solution to detect roll marks on-line has not been found. A completely new approach was chosen in order to solve this challenge.

The cornerstones of this system innovation are:

- Use of measuring instead of vision approach; use of sensor technology instead of camera technology.

Figure 1



An unacceptable roll mark on a sample (a) is often invisible at the tandem mill exit, and only barely visible after sanding (b), but very visible and detectable for the new roll mark detector (c). Defect image is captured in full tandem mill speed and placed on the photo to highlight the sensitivity of the system.

- Multi-reflectivity measurement to reach higher detection rate and detect all types of roll marks.
- Detecting the work roll roughness print from the strip surface.
- Fast data filters preserving the surface roughness information.
- Building of accumulated and residual images for the algorithms.
- A compact installation to fit in the mill exits and manage the environment.

The solution was developed from scratch. Industrial targets were defined by the industry, the future end users. To perform successfully, the detection rate requirement was set to be greater than 80%, the over detection rate to be below 10%, and the alarming time to less than the rolling time of one coil. Today all targets have been met and this innovation is the only system solution in the world with industrially proven performance for detecting roll marks.

New Technology

The system provides images similar to classical automatic surface inspection systems (ASIS), but the technology developed and used is significantly different. Instead of image acquisition cameras, the receivers are measuring technology: silicon photo diode arrays. This approach allows several necessary system features, required to meet the application requirements and ultimately to satisfy the user needs.

The roll mark system is a stand-alone, single-beam installation, utilizing an optical reflection method. It is delivered with standardized integration equipment for survivability and maintenance. The measuring system itself consists of three main components:

1. The detector beam incorporating:
   - An array of independent imaging detectors with onboard processing.
   - Three full-width LED light beams with necessary optics.
2. A control cabinet with three computers.
3. A user interface for the operators.

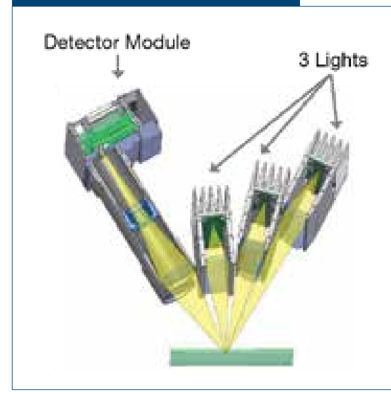
Three full-strip-width light beams are used to emit photons to the strip surface. A single detector array is used to pick up the reflecting photons from the strip surface.

The LEDs in the light beams are electrically modulated to operate in certain frequencies. Typical frequencies used are, for example, 60,000, 120,000 and 240,000 Hz, as no other light sources in the same environment with the system operate in these frequencies. By locking the detectors to be sensitive only in these frequencies which LEDs emit, several benefits are achieved. First of all, as all background light gets filtered from the measurement, the maximum possible signal-to-noise ratio is achieved in the measurement. Detectors can only collect light from the given three frequencies, and no other. Second, the modulation of the LEDs allows utilizing a so-called multi-reflectivity measurement method. All three illumination geometries (bright field, dark field and side light) are

Figure 2

Detector beam with an array of array of 20 detector units. Beam is in off-line (roll-out) position with covers open.

Figure 3



Multi-reflectivity measurement principle as used in the roll mark sensor.

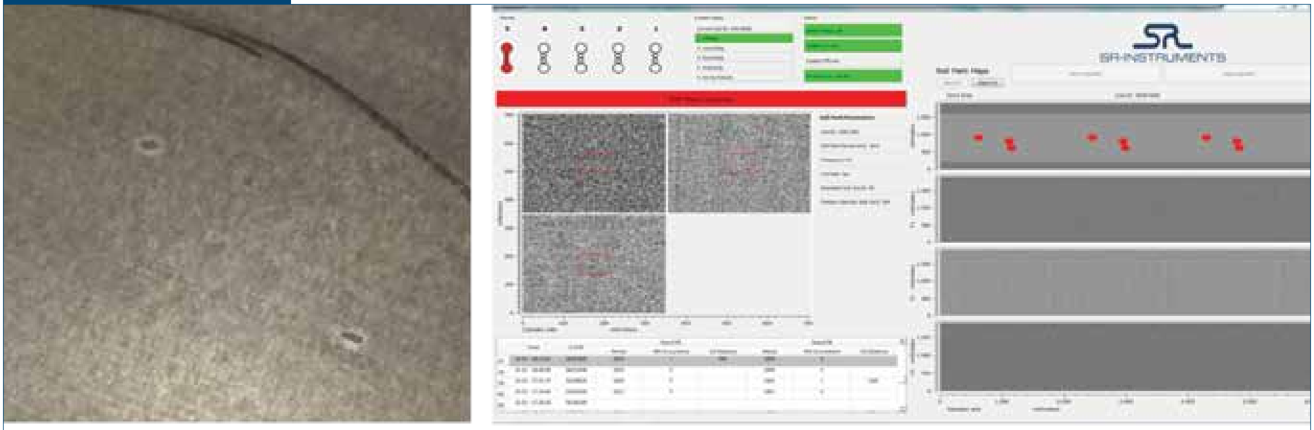
needed and used to achieve the required detection rate of more than 80% of all roll marks. The principle layout of this method with the three inspection geometries is shown in Fig. 3. In this method, three images are produced perfectly simultaneously without the strip moving in between the images: one image is produced in dark field configuration (DF), one in bright field configuration (BF), and one in side light configuration (SL). Every pixel gets three values — a value from each optical geometry. A higher detection rate will result as various roll marks diffuse photons differently and are only visible when viewed in certain optical geometry. We humans are looking for the same capacity when rotating a roll mark sample in our hand in order to see the mark better. The third advantage from the modulation is that the system can be kept very compact. All three light geometries can be read out with a single sensor array.

The measuring of the photons reflecting from the strip surface is performed with independent but identical detector modules spanning over the full strip width. Each detector views 100 mm of strip (in width), overlapping with the neighboring detectors to provide 100% inspection coverage for the system. The technology inside the receivers, silicon photo diode arrays, is more typical for highly sensitive optical laboratory instruments not previously found to perform measurements in imaging resolution. In high-speed applications like the roll mark application, the new imaging sensor outputs a signal-to-noise ratio 20 times higher than the classical surface inspection camera technology with CCD or CMOS cameras. The raw data produced for the detection algorithms to operate on is 14-bit data. This sensitivity is needed to detect the roughness maps that the work rolls produce on the strip surface. By being able to read and detect these periods, the algorithms can work very efficiently. Another unique feature is that the total sensor surface, the active light collecting surface of the silicon sensors, is very large. The silicon photo diodes cover 66% of the strip width, giving the system superior ability to collect light compared to the classical CCD elements in the ASIS system. This comes into benefit especially in high speeds when there is less time to collect photons into the pixel array, before the strip moves again and a new set of photons is needed to produce the data into the next array of pixels. Also, this sensor technology allows for continuous measurement to be performed. Sensors are not speed-dependent in the same way as the classical CCD or CMOS cameras used in surface inspection systems. In the roll mark detector, the detectors perform constant measuring and the image is produced with the tachometer input continuously delivered to every 100-mm detector module. The modular 100-mm detector design also allows the inspection geometries to be kept the same over the entire strip width.

All data processing takes place inside the 100-mm detector units. So where the data is produced, it gets locally processed. Each detector unit includes a 6-core digital signal processing unit and 2 Gb of memory to host the algorithms and system management software. With this type of distributed data processing, the data transfer rates are kept minimum as well as the amount of processing hardware inside the PC and control cabinet. The cabinet contains only three normal computers.

Dedicated filtering algorithms make use of the periodicity of the defects to enhance strongly their contrast prior to the detection stage, revealing objects that are almost invisible in both the raw data and strip samples without stone brushing. The algorithm, using only the images as inputs, is able to filter out emulsion patterns, to adapt to period fluctuations coming from reduction rate variations and slipping of the strip, and to identify without ambiguities which roll is responsible for the mark.

Figure 4



(a) (b)

A defective work roll (a) and the corresponding screenshot from the user interface with detection results (b).

The Measurement Cycle — The system runs a repeating measurement cycle to inspect every coil. To start a measurement cycle, the roll mark system checks the value of two signals, strip tension signal and mill ready signal. Only when both signals are equal to 1 will the system start the measurement cycle. On the other hand, if the value of either of these signals changes (from 1 to 0) before the end of the completion of the measurement, the measurement, and thus the cycle, is aborted and the system is protected from any abnormal situations. The guard window is opened by the system's own logic and the sensors start to collect data. Data is collected from 70 m of strip length (out of a total coil length of 2,000–3,000 m) and over the full strip width. This is sufficient for the system to perform its analysis, and the guard window is closed. The system is exposed to the strip for less than 5 seconds per coil. This supports the maximum availability, as in keeping the system clean and well protected 95% of the time. After closing the protective guard window, the system shifts into a calculation mode. Obviously, the delivered result corresponds to the 70 m from where the data was collected. If the roll mark appears later in the coil, it can only be revealed by the next measurement, the next coil.

A roll mark being a mechanical and periodic defect, it is not necessary to monitor the entire strip length to detect it, because it does not disappear on its own. In the situation with stops, the system could make several measurements on the same coil.

In principle, this first measurement should always be performed from the beginning of the coil. There is no constraint on the strip speed during the measurement: the strip speed can be constant or variable. A tachometer provides the speed signal to the roll mark system. Measurements can be performed up to 1,650 m/minute with good image quality.

The data processing is started in each detector module. The steps are: normalization, filtering, calculation of first period (length of the last stand's work roll circumference), corresponding accumulated and residual images, and roll mark detection; then the same sequence is conducted for the second period (the second last stand's work roll circumference). The data and the results are also sent from each detection module to the so-called RTM, real-time computer, which collects and synchronizes them. The RTM integrates the strip edge positions and generates the detection result images for the database and the user interface. Then all detection results (image and data) are transferred to the master computer, also located inside the electronics cabinet, to be stored and sent to the client computer's for their display. After that, the system is ready to start a new measurement cycle as soon as the conditions are met, strip is on the coiler and the mill is ready.

System Integration — The system was designed from the beginning to operate in cold rolling mill exits. Its features, functionalities and diagnostics support this. Standardized equipment is used to integrate the installation into the line. Integration equipment consists of structures with certain functionalities such as the rollout between on-line and off-line positions, and the guard with an opening and closing protective window.

The detector beam is fed with fan air to produce a positive pressure inside the detector beam. This prevents the pollution from entering the system and provides the necessary cooling to assure maximum component lifetime. Other integration requirements

Figure 5

Roll mark detector integrated in the exit of a 5-stand tandem mill, inspecting all coils to the second coiler (on the left side).

are a few PLC signals, a tachometer input and a level 2 connection for TCP/IP communication.

A full-sized pilot was installed on a continuous 1.9-million-ton, 5-stand tandem cold mill exit (shown in Fig. 5) in 2012. After completing the software and algorithm development, the system was handed over for operator use in September 2015. Industrial approval was received in December 2015. Finally, the calculation speed was upgraded with a detector swap in January 2018 to increase the system capacity to inspect every coil. The system is integrated with level 1 and level 2 connections and fully follows the mill operation. Abnormal situations are handled by the system automatically. During rolling, a coil database is collected on all coils, and an alarm sound is implemented to focus the attention of the operators whenever a roll mark is suspected on the coil rolled at that particular moment.

In case of an alarm, the mill operators use the user interface and roll mark image(s) to judge if the rolling can be continued or should not. The decisions depend on many criteria, like the material and customer, but the system has allowed the team to step on a learning curve to keep the operations process-focused. The system was learned in a matter of minutes, because ultimately it is just an alarm system, showing the reasons for the alarms. In the simplest operating mode, the system could block all suspected coils automatically. The management at the pilot mill reported it took some 6 months for their operators to build trust and get a feeling of which marks are acceptable and which marks require immediate corrective actions.

For example, during the integration to the operations, the sensor regularly detected marks that were not possible to confirm by chalking (stone brushing) operations, but were effectively revealed after finishing operations. Nowadays the instructions are to use the sensor information and to change the rolls, even if the mark is not detected during the stone brushing operation. The proportion of roll marks detected directly at the exit of the tandem mill instead of the exit of the galvanizing line has increased by 20%, which represents a significant decrease in non-quality costs.

It should be noted that, at the pilot mill, the operator team is very experienced and is allowed to take decisions on roll marks. User experience and learning allows for improved operating practices for different situations. Ultimately it is mill-specific, depending on operator experience and the decision-making hierarchy.

A 5-year track record in on-line conditions has proved the system requires only limited maintenance operations. Its maintenance follows the normal maintenance program. Main periodical work includes the wiping of the protective glass window from outside every 6 weeks. The fan unit should be checked every 6 months and the air filters inside changed once a year.

Improved Mill Performance

The roll mark system will obviously not prevent roll marks from happening, but it offers a means to improve the mill performance without any parallel investment needs. Considerable savings and capacity increases are achievable when the installation is backed up with certain improvements into the operating practices and corresponding training. From the installation, it will follow that the operators are delivered valuable information in near-real time, giving them the missing tool to keep the operations process-focused. Quality-focused activities, such as dealing and processing defective coils, are reduced on all downstream processes.

By inspecting every coil, the detector will help to detect the roll marks faster, leading to fewer affected coils. Detecting them earlier at the exit of the tandem mill instead of the finishing lines allows better reassignment possibilities for the affected coils. For a mill with roll marks, the payback comes from decreasing reallocation costs, avoiding large series of coils being affected by roll marks, and better service to the customer thanks to an improved lead time.

- Faster detection will come from an improved detection rate. Every coil is inspected if the system is located before the shearing machine. Every other coil is inspected if the system is located between the two coilers.
- Earlier detection: In the case where roll marks are missed by the chalking (stone brushing) inspection, the defect is most commonly detected at the exit of the finishing lines, resulting in a very high reallocation cost. An average figure is to detect 50% of the coils affected by roll marks at the exit of the finishing lines. For earlier detection, the roll mark detector has proved to be able to detect roll marks that have not been detected by stone brushing, but revealed at the exit of the finishing line (or even at customers' facilities). The value creation linked to the use of the sensor is clear in that case, since reallocation costs are much lower when it is done at the exit of the tandem mill.

For a mill with fewer marks, the payback comes from increased rolling capacity and reduced need for reprocessing suspected coils. By inspecting every coil, the rolling may be continued at full speed even while waiting for the manual inspection result. On an annual basis, typical waiting times and low-speed rolling accumulates to 400–1,000 hours, depending on mill type.

As an example from the pilot plant, an improved operating practice is to change the work rolls after two consecutive detections by the system, even if the mark is not confirmed by chalking (stone brushing). This practice was only applied for a part of 2016, but the proportion of defective coils detected at the exit of the tandem mill raised from 50% to 70%. It is also known that 50% less roll marks were produced within 2016 compared to the previous year. All these figures, leading to significant value creation, are expected to further improve during 2018 with the improved computing capacity now also available in the pilot system.

Stone brushing operations will of course not be stopped after the installation of the system, since the last upgrades into the system were done only recently. Also, the fact that the pilot installation is inspecting the secondary side instead of the guaranteed side, the detection rate is expected to stay at about 90%, since approximately 10% of marks will not be duplicated to be detectable from both sides. The system will complement the stone brushing operations and, in addition, it also transforms many times a "detection" stone brushing into a "verification" stone brushing. In that case, the operator need only verify the relevancy of the sensor detection, leading to less steel surface to stone brush and less inspection time. But with that high level of performance, the sensor is a very valuable tool continuing to help the mill to improve their overall performance. Results have been noted.

Summary

This paper introduced a new, industrially approved roll mark detector. The detector already has a proven track record of a few years on detection performance and achievable returns. Use of the detector has significantly improved the performance of a 2-million-ton cold mill. Downgrading costs are reduced when roll marks are detected faster. Faster detection allows more responsive and timely corrective actions, and saves the following coils from being affected by the same mark. With the detector, affected coils are also identified earlier than before. Reassigning after the tandem mill, instead of after the finishing lines, results in considerable savings in reallocation costs. Inspection of every coil at the exit of the mill allows the cost of the precautionary measures to be reduced, such as slowing down the mill while waiting for the results from manual roll mark inspection.

References

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