Imaging-based In-Line Surface Defect Inspection for Bar Rolling

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ABSTRACT

We delivered advanced surface inspection systems to bar and rod mills based on imaging technology. Bar rolling has its unique requirements and poses certain challenges due to its geometry and rolling speeds. Three pilot systems have been installed; this paper reviews the systems' specifications and performance, and provides a comparison to eddy-current devices. Also discussed is the potential for using the data in process control. The goal is to help the bar mills to deliver a product free of surface defects.

1. INTRODUCTION

Hot rolling is a high temperature deformation process that provides the raw material for forging, cold drawing, and other various down-stream manufacturing processes. With the current state of global competition and high degree of automation, poor raw material quality is one of the most serious problems faced by these industries. As a result, customers will continue to demand that the steel suppliers provide a higher quality product. Among the quality problems associated with steel bars, the problem of surface defects is a crucial one, accounting for roughly 50% of steel rejects. Worse yet, surface defects, unlike metallurgical properties, tend to be sporadic. Therefore, sampling-based inspection is not an adequate method of measuring steel bar quality in terms of surface defects.

There are several technologies currently in use to detect surface defects on hot rolled bars. For instance, eddy current based devices are used in-line or off-line [1]. In-line eddy-current devices, sometimes called hot eddy, are among the most popular surface inspection systems in rod and bar mills. These devices detect surface conditions of a steel bar based on differential signals from the coils. Any impedance changes on the steel bar surface, such as those caused by surface defects, will change the degree of induced eddy current. However, hot eddy devices are not capable of detecting longitudinal defects, such as seams, in the mill environment. Detection of longitudinal defects requires a different design employing small probe coils that orbit about the bar instead of an encircling coil assembly [1, 2]. This kind of system is used primarily off-line, requiring additional processes and space, because it requires very precise control of the gap between the bar surface and the orbiting probes. The high orbiting speed, up to 20,000 RPM, adds additional complexity for the use of such systems. Attempts to migrate such orbiting devices to in-line applications have been reported, but have not yet matured.

Another approach is to use a traditional crack detection method, magnetic penetrant testing. The penetrating paste will seek its way into any surface indentations, such as a crack or a seam. Under UV illumination, the penetrant will become visible. A camera can be used to detect the penetrant residuals. While this is a feasible detection approach as an off-line solution, it cannot be used in-line because penetrant cannot be applied to a hot bar. Limited work has been done based on ultrasonic inspection methods [1, 3]. This includes the approach of using electromagnetic acoustic transducers and the approach of laser induced ultrasound. These methods, although offering the potential for improved on-line bar inspection, have not been actually used. Yet anther approach is to inspect the steel bars with infrared imaging. In this approach, room temperature steel bars, after exiting the de-scaling process, will be heated slightly with a surface-heating device, such as an induction heater. Because the induction heating effect is correlated to the local surface impedance, surfaces with defects tend to heat up faster than surfaces without defects. This transient effect is captured using an infrared camera and is used in determining whether there is a surface defect. This system could only be used as an off-line approach, and field test results have not been satisfactory.

Aside from the automatic detection approaches, a common practice in the industry is to have a manual review at the end of the hot rolling line. A small segment of the steel bar may be cut down for upset tests or manual magnetic penetrant examination. This practice is primarily a sampling test. It is not effective for surface defects due to their sporadic nature. An upset test performed on a 50 mm (2”) sample off a 3.2 Km (2 mile) long coil gives little indication about the surface quality of the coil.

To effectively cope with surface defects, one practice in the industry is to strip the surface of the steel bars off. This approach typically results in an 8% loss of material, increasing the costs of steel. In addition, deep surface defects, deeper than the peel off depth, cannot be addressed. Also, a deep seam might close near the steel surface and remain open deeper inside the bulk. One might find a seamless surface after removing a thin layer of material on the surface. However, the seam underneath is still there and will expose in the subsequent manufacturing process. An example of one of such seam is documented in this paper.

Automatic optical inspection has been used in strip mills with some success. These systems reported a detection accuracy of about 75% [4]. The inspected data has been used for process control and defect management. However, due to the differences between the strip mills and the bar mills, strip mill imaging systems are not applicable in bar mills. This paper reports an attempt to take the ever-advancing imaging technology into the rod and bar mills. The imaging based approach has the advantage of high speed, better forgiveness to environment noise and better data depth when compared with other automatic detection approaches.

2. IMAGING BASED SYSTEM

2.1 Challenges

Although hot rolling products have simple and constant geometry throughout the entire rolling line, the high throughput poses a big challenge. Rolling is a semi-continuous manufacturing process. Through a series of rollers, a billet can be shaped and reduced to the final bar. As the dimension of the bar reduces, the moving speed changes. At the exit of the first rolling stand, the speed can be as slow as 0.5 m/s. At the exit of the final rolling stand, the speed, in some instances, is faster than 100 m/s. The fastest wire rod mill reported a sustained rolling speed at 110 m/s, or 250 mph [5]. The critical dimension (CD) of the surface defects could be as small as 0.025 mm (0.001”). In order to conduct a 100% surface inspection at such speed and the CD, the imaging system must process at least 24 Giga Bytes of images per minute.

The rolling mill environment is not friendly, either. The surface temperature of hot rolled bars may be as hot as 1,100 °C. Along with the semi-continuous rolling process, the hot bar will emit significant amounts of heat radiation to the surrounding area and equipment. The bar can flutter significantly when traveling at a high speed. The magnitude of flutter can be even larger than the product diameter itself for small diameter wire rods. In addition, the bar rotates/twists as it is rolled. For high-speed mills, bars are well confined in a series of guides (to prevent the high speed, high temperature bars from cobbling), leaving little space for image acquisition equipment. Water and debris is another concern for the imaging systems along the rolling line. Figure 1 gives a view of a hot rolled bar in process.

FIGURE 1. HOT ROLLED BAR IN PROCESS.

In contrast to the strip mills, the non-flat surfaces of the bars pose a challenge in the optical design. A special optical train must be designed for this unique feature. It must also be noted that the bars are more likely to have superficial scratches on the surfaces because bars, particularly those high speed wire rods, are guided through stainless steel troughs. These superficial scratches are acceptable in the bar rolling operations. The free form contact between the bars and the troughs could mess up the surface. An example of such scratched surfaces is shown in Figure 2.

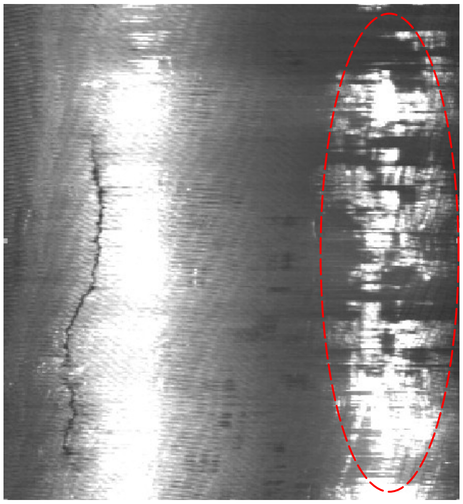


FIGURE 2. BAR SURFACE WITH SUPERFICIAL SCRATCHES.

In summary, the technical challenges in this application include the optical design, image acquisition functions, analysis algorithms, and protection mechanism design. The approach of implementing imaging technology in bar mills includes the use of very high-speed cameras and the proprietary HotEye™ technology. In order to process the vast amount of image data in real-time with confined system costs, an ad hoc parallel computing system is developed. Special optical design is adopted such that the images taken from the non-flat surfaces are in high quality.

2.2 Installations

With the interest and support from the steel industry combined with the support from the US federal government, an Alpha system and two Beta systems were delivered for rod and bar mills. The Alpha system, shown in Figure 3, was installed at Charter Steel (Saukville, WI) in June 2002. The system is limited in that it inspects less than one quarter of the bar surface, and requires frequent manual adjustments.

The Beta system for rod mills was installed at Inland Steel (East Chicago, IN) in December 2003, as shown in Figure 4. This is a full system. It is capable of inspecting the entire surface of a steel bar. The bar diameters can be from 9.525 mm (0.375") to 38.1 mm (1.5").

FIGURE 3. ALPHA HOTEYE™ SYSTEM.

FIGURE 4. BETA HOTEYE™ SYSTEM FOR ROD MILLS.

The Beta system for bar mills (Figure 5) was installed at Timken Steel (Canton, OH) in February 2004. This system will inspect bars with diameters ranging from 50 mm (2") to 150 mm (6").

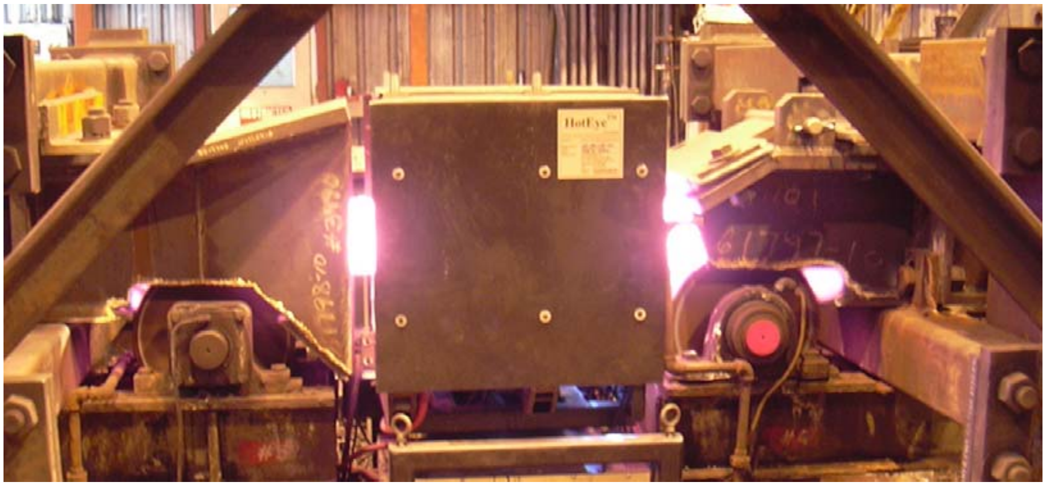


FIGURE 5. BETA HOTEYE™ SYSTEM FOR BAR MILLS.

3. FIELD TESTS

The imaging systems were tested with designed experiments as well as tracked naturally occurring defects. During the tests, both the in-line eddy-current device and the off-line rotating eddy-current coils were benchmarked for detection capabilities.

3.1 Detection Verification

The imaging systems detected many defective indications on the steel bars. To verify these detections, in several instances a coil was opened to track down the defective segment as reported by the imaging systems.

Roll Cracks

One such instance is the detection of roll cracks. Rolls used in the stands can crack, even break, during the rolling process. The imaging system demonstrated its capability of detecting the light imprints on the steel bar surface, induced by the very fine crack traces on the rolls. Figure 6 documents the HotEye™ images of different types of roll cracks.

The light trace marks are periodically repeating, indicating a problem of a cyclic element in the rolling line. Based on the pitch of the indications and the reduction rate at each stand, the root cause was identified and the cracked rolls were retrieved from the rolling line. Figures 7 shows the corresponding roll surfaces to those images in Figure 6. A segment of the hot rolled bar with roll crack mark is displayed in Figure 8.

(a)
(b)

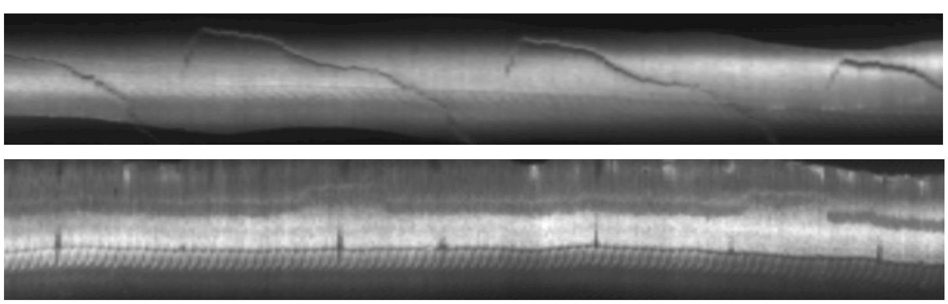


FIGURE 6. HOTEYE™ IMAGES OF ROLL CRACKS.

An in-line eddy-current device was in use at the time these roll cracks occurred. However, the eddy current device did not flag any indication of the problem. It is unrealistic to set an eddy-current device with a sensitivity to detect these roll crack marks, otherwise there would be a tremendous amount of false positives. An imaging system, on the other hand, could flag these preemptive failure signals, given the fact that the data carries an additional dimension and that images are available for visual review by human operators to render the final verdict as to what the indications truly are.

(a)

(b)

FIGURE 7. CRACKED ROLLS.

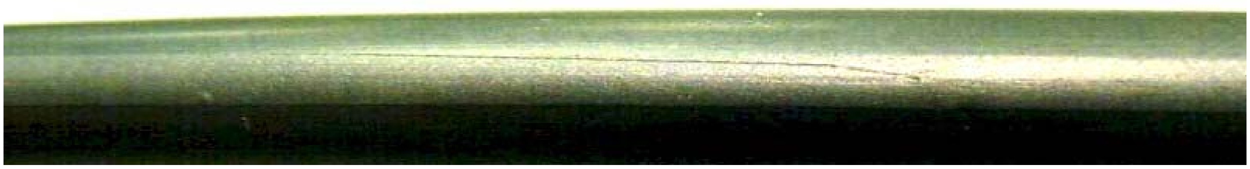


FIGURE 8. ROLL CRACK MARK ON STEEL BAR (CASE A).

Seams and Laps

The capability of detecting naturally formed seams and laps is also demonstrated. Figures 9 and 10 documents the detected defects. The defect pictures were obtained by tracking down the HotEye™ indications.

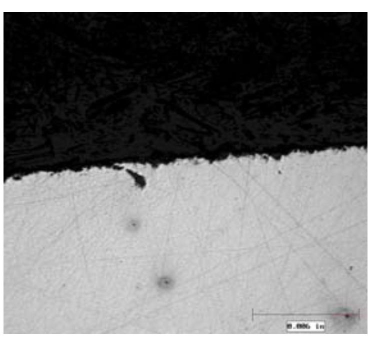


FIGURE 9. A DETECTED SEAM.

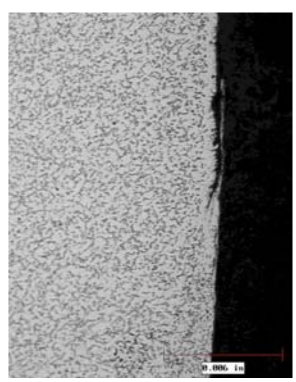


FIGURE 10. A DETECTED LAP.

Again, an in-line eddy-current device was in service while these defects were detected. There was no indication from the eddy-current device but the imaging system picked up these defects.

Shearing/Sliver

When rolling certain type of alloys such as those with high lead or sulfur content, it is known that the steel is subject to a higher degree of thermo-mechanical deformation. At times, a portion of steel will be peeled off from the bar surface, known as shearing. It's demonstrated that HotEye™ is capable of detecting shearing type, as shown in the following pictures. Note that there is a strong correlation between the HotEye™ and the in-line eddy indications for this type of defect. However, an imaging system provides real-time visual feedback for verification.

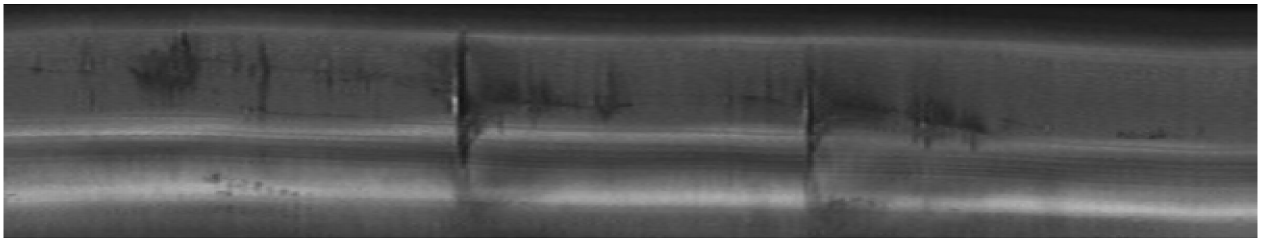


FIGURE 11. A HOTEYE™ IMAGE WITH SHEARING MARKS.

Top left: a series of severe shearing defects

Bottom left: a thick scab pulled back from the steel surface, but still attached to the base material.

Bottom right: a thin sliver peeled off from the steel surface and still attached to the base material

FIGURE 12. SHEARING AND SCAB MARKS DETECTED HOTEYE™.

Overfills

It is also demonstrated that HotEye™ is capable of detecting severe overfills. Two types of overfills are shown in the following pictures. The first is a continuous overfill caused by mill setup problems. The second one is a discontinuous overfill caused by periodically varying factors such as fluttering. In-line eddy device was not capable of detecting these defects.

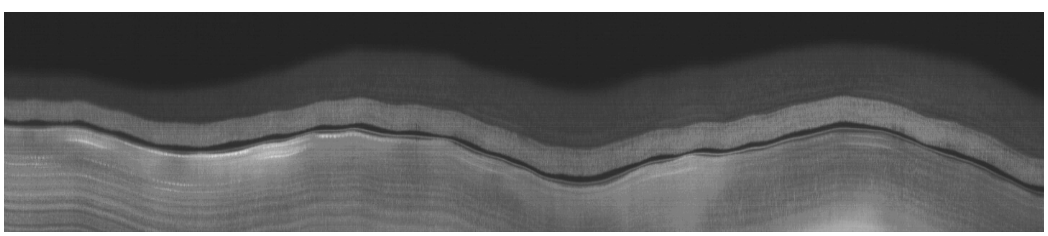


FIGURE 13. A SEVERE CONTINUOUS OVERFILL.

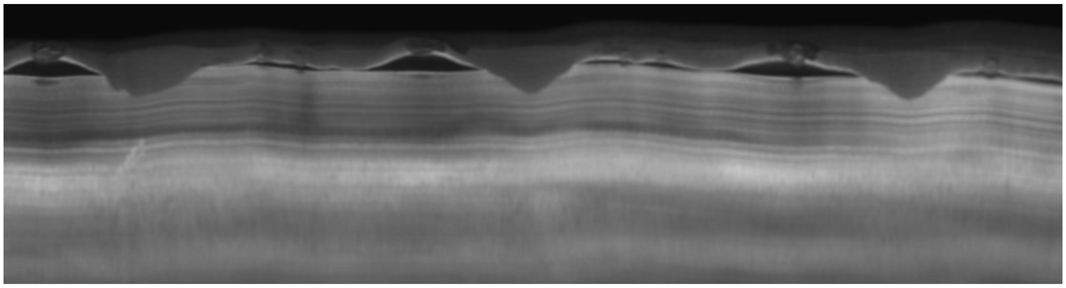


FIGURE 14. SEVERE PERIODICAL OVERFILL.

Roll Gap

The imaging systems detect "roll gap" signatures as well. Figure 14 is a record of a severe roll gap problem, overfill. In addition to overfill, several other patterns have been recorded. One of such patterns is shown in Figure 15. The roll gap has a pattern of periodical opens and closes. We suspect that this pattern is caused by flutter. This could be an un-wanted feature in a steel mill. It could make the cross section out of the specification, induce more force on the rolls to decrease their service lives, and increase the chance of cobbling.

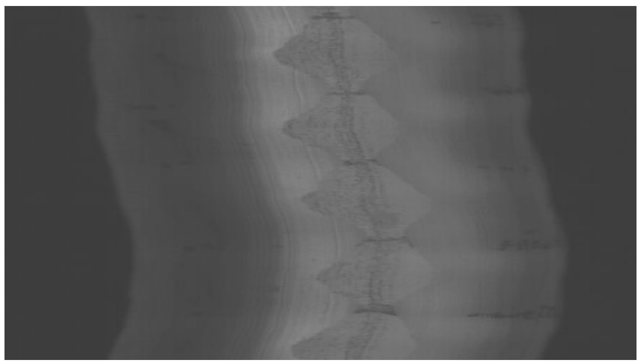


FIGURE 15. AN INSTANCE OF ROLL GAP.

3.2 "Seam" Test

A designed test was conducted in the alpha system in Charter Steel, to verify that the imaging system is capable of capturing the designated defect. In this test, a 1010 billet of 140 mm X 140 mm (5.5" X 5.5") with predrilled holes was re-heated and rolled into a coil at ϕ13.10 mm (ϕ33/64"). A bank of holes, ϕ6.35 mm (ϕ0.25") and about ↓12.7 mm (↓0.5"), were drilled at 915 mm (3 ft) from the nose end of the billet, as illustrated in Figure 16.

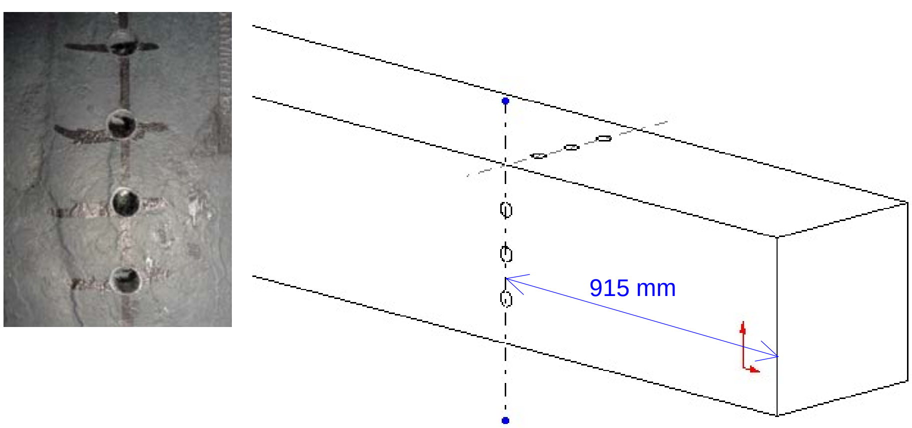


FIGURE 16. DESIGNED TEST TARGET.

This billet was rolled into a rod coil. In this rolling, both an in-line eddy-current device from Prueftechnik and a HotEye™ imaging system were in service such that the results could be bench marked. Figure 17 documents the test process.

Strictly based on the cross sections, this rolling involved a reduction of 145:1. The location and length of the expected surface defect could be predicted by assuming a perfect reduction. For instance, the “915 mm” distance from the billet nose end would become 132.7 m (435 ft) from the leading end of the coil. Less the typical in process front end trim, the induced defect was expected to be about 122 m (400 ft) from the leading end of the coil. The “ϕ6.35 mm” predrilled holes would be turned into 920 mm (36”) long traces. The real-time report from the eddy-current device did not give any indication at the expected location (+/- 100%). On the other hand, the imaging system indicated a detection of a 762 mm (30”) long surface defect, as shown in Figure 18. The reported location is 117 m (383 ft) from the leading end of the coil.

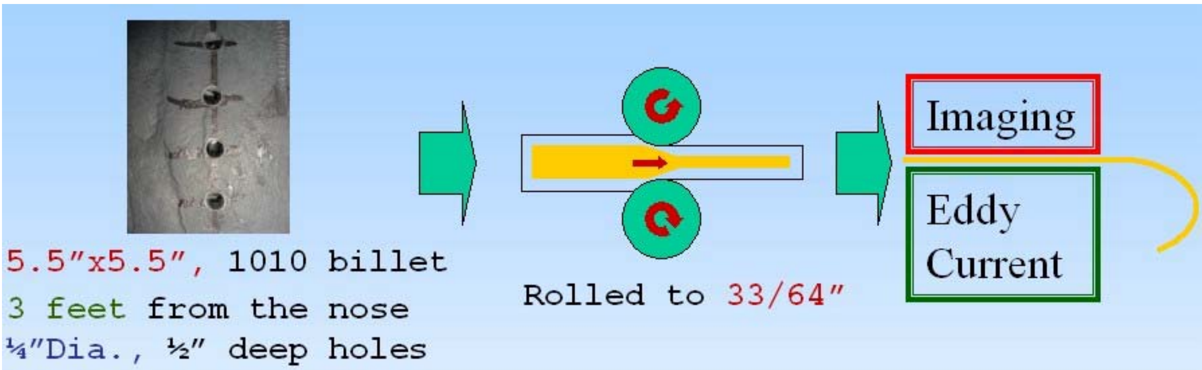


FIGURE 17. SEAM TEST PROCESS.

The designated defective segment was recovered from the coil, based on the reported location. The surface appearance and the cross-section of the defect are documented in Figure 19.

The defective segment was straightened and tested in an off-line eddy-current system with rotating sensor coils. The eddy current system was first calibrated with a calibration piece, on which a ~200 μm (0.008”) deep slit was EDMed in, as documented in Figure 20. Then, the defective segment was fed into the eddy current system, with either the vector mode or the phase mode. Figure 21 documents the results.

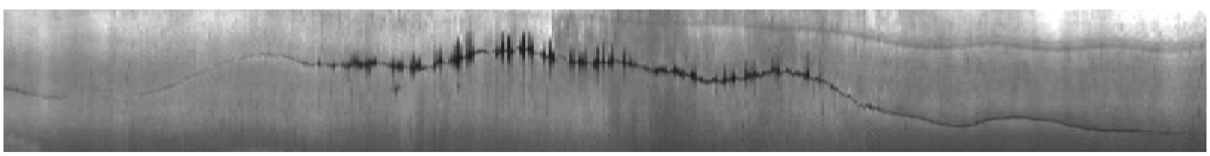
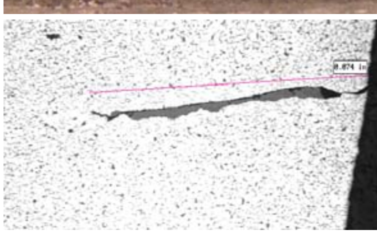


FIGURE 18. DETECTION FROM THE IMAGING SYSTEM.



TOP: Picture of the recovered bar segment.

LEFT: Cross section of the defective segment. Acutal defect depth is about 190 μm (0.076”).

FIGURE 19. DEFECT ON THE ROD.

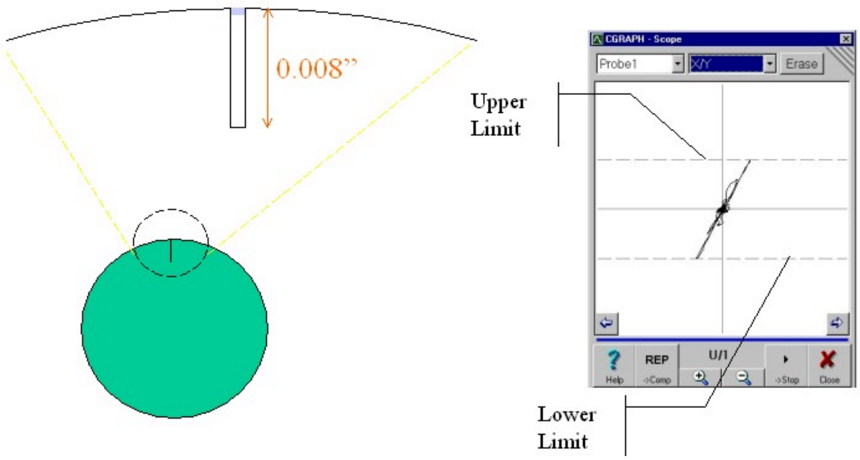
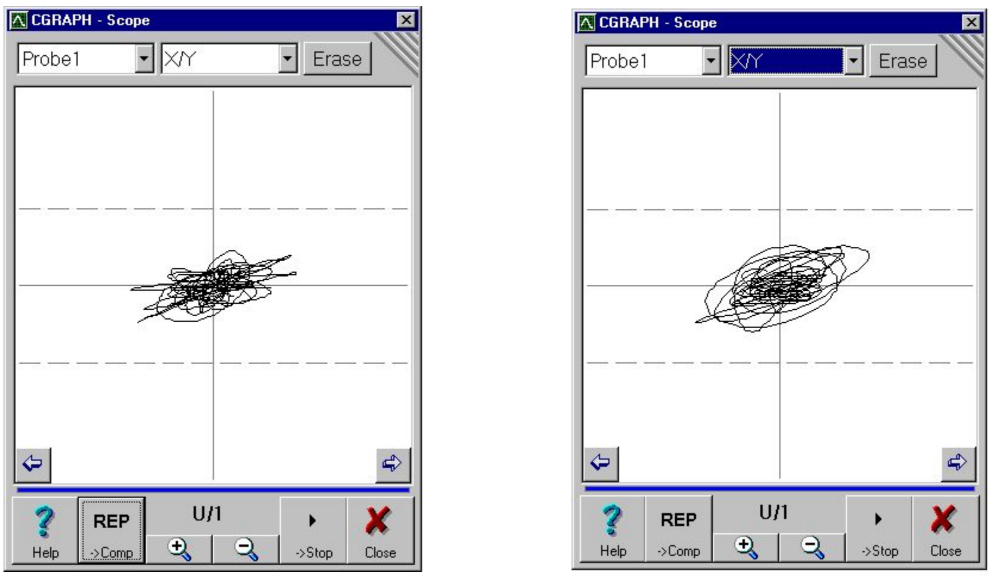


FIGURE 20. CALIBRATION OF THE EDDY CURRENT SYSTEM.



(a) Phase Mode (b) Vector Mode

FIGURE 21. EDDY CURRENT TEST RESULTS OF THE DESIGNATED DEFECTIVE SEGMENT (SAMPE SNAPSHOOTS).

Based on the data, while the imaging system detected the designated defect, the in-line eddy current system did not detect the designated defect. The off-line rotary eddy current system did not indicate an explicit detection.

The imaging system indication matches the prediction of the designated defect in both defect location and defect length. The recovered defective segment further verified that the detected indication is indeed the designated defect based on the fact that most of the pre-drilled holes could be identified.

There are some questions about whether the off-line rotary eddy current system detected the designated defect. Based on the explicit indication, the strength of the signal is not strong enough to indicate a 2 mm (0.08”) deep seam. The phase diagrams in Figure 21 did not show any indication of 10 X stronger than the calibrated 0.2 mm (0.008”) limits. However, experienced eddy current experts pointed out that the degree of mess carried in the signal, as shown in Figure 21, implies defects.

Another similar “seam” test was carried on the Beta system, which have a full coverage on bar surfaces, at Inland Steel. The Beta imaging system successfully detected “seam-like” defects caused by the drilled holes. The “seam” segments were recovered. We found that the distances between two adjacent defects can be very accurately predicted based on the area reduction ratio (from billet to rod). However, the seam lengths are all 10% to 20% longer than expected.

4. DISCUSSION

This section summarizes the comparison between the imaging approach and eddy-current systems. The impact of a successful in-line surface defect detection system to the downstream industry is also included.

4.1 Comparison to Eddy-Current Devices

Both the imaging system and the eddy-current system can be used in-line, accommodating the high speed of the rolling process and providing real-time inspection reports. Both are capable of detecting transverse defects such as scabs and shearing. However, the in-line eddy-current system to date is incapable of detecting longitudinal defects such as seams. The test results as documented in Section 3 are in accord with the industrial experience, as reported in [1].

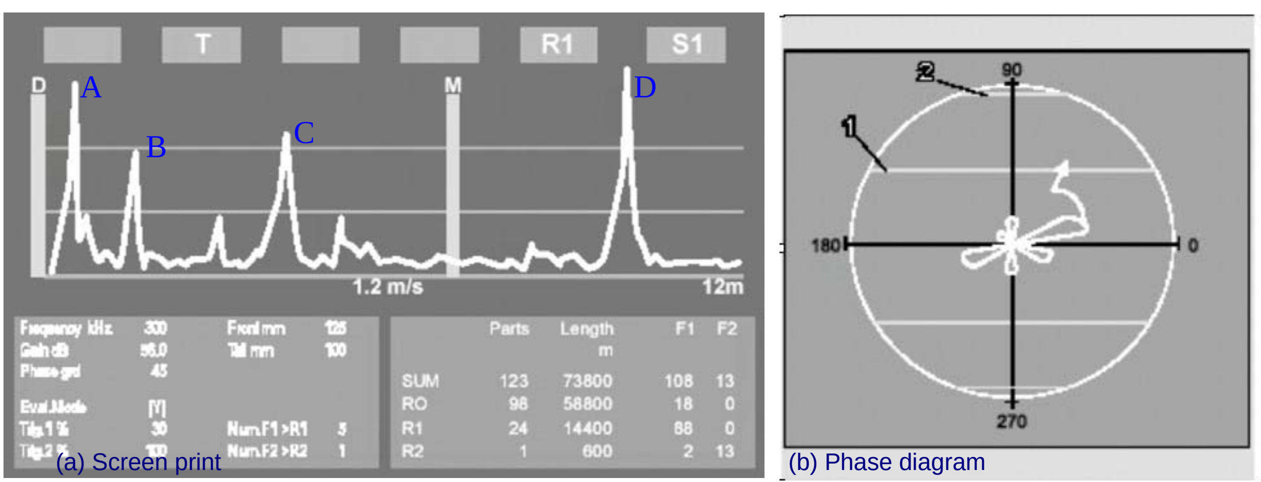
Aside from its detecting capabilities, the imaging system has shown to be more forgiving than the eddy-current system with respect to the working distance between the sensor tip to steel bar surface and sensitivity to bar vibration. The eddy-current probes need to be in a close proximity of the steel bar surface, typically 3 mm (0.125”) or closer. On the other hand, the imaging system has a working distance, from the tip of the imaging lens to the bar surface, greater than 100 mm (4”). Greater working distance is desirable because it decreases the chances of damage to the sensors and allows a less stringent guiding requirement.

Greater working distance also contributes to the forgiveness to vibrations. The same vibrating amplitude, say, 0.5 mm (0.02”), represents a much smaller impact to the imaging system, say, 0.5% (0.5 mm over 100 mm), than to the eddy-current system, say, 16.6% (0.5 mm over 3 mm).

The in-line eddy-current system is also sensitive to the bar temperature. The steel bars must be at a temperature that is above the Currie temperature, a temperature point at which the permeability of the steel changes significantly. A locally cooled spot caused by, for instance, a water drop could fire an indication from the eddy-current system. The HotEye™-based imaging system is not influenced by the bar temperature. The glowing effect is removed by the HotEye™ technology.

The rotary eddy-current system has demonstrated the capability of catching longitudinal defects, although the system is still greatly affected by the surface conductivity. However, the issues of tight working distance and high sensitivity to vibrations remain unresolved. The rotary system to date can only be used off-line, on bars at room temperature. This practice increases production costs because it is an additional process that does not perform any value-added work to the products. Due to the high rotating speed (~20,000 RPM) and close clearance, the bars must be tightly guided and run at a slow speed. The feed rate is less than 10 m/s (2,000 ft/min.).

The most significant difference between an imaging system and an eddy-current system is in data depth. The imaging system provides an additional dimension in data, allowing a better detection accuracy and improving the utility of the data in effective process control. A screen print of an eddy current report is shown in Figure 22. Although the intensity of the signal is supposed to indicate defects, there is no intuitive interpretation as to what these indications represent. There is no answer as to whether they (peaks A and B, for example) are similar defects or not, or even whether they are true defects or not. The phase diagram does extend the data space beyond one-dimensional, and therefore, intuitive answers are not readily available from the diagram either. The bottom line is, there is no additional information to verify and evaluate the eddy current output.



(a) Screen print (b) Phase diagram

FIGURE 22. EDDY CURRENT REPORT.

The imaging system, while providing a similar indication summary with labeled defect severity scores and locations, retains the original data, the images of the potential defective sites, throughout the inspection process. The original data is part of the data report. For each defect indication in the imaging system, an image is available. This additional dimension of data depth contributes to the improved detection accuracy and data utility. Because the original data is retained, the original data can be reviewed multiple times with different algorithms to improve the detection accuracy. On an exception basis, a human reviewer can make the final decision if necessary.

The availability of images is important in field practice. It is vital to verify and map the indications of defects with real-world objects. However, reviewing a defect on a hot steel bar, particularly a hot steel coil, is very difficult, if not impossible. The imaging system provides a very intuitive basis for review. The users can look at the pictures before opening up a coil. Pictures can also reveal when repeating defects occur, which implies that the problem was mill-induced. Furthermore, data with high confidence contributes to effective process controls because the conclusions arrived at by linking the defect data to the process variables are more trustworthy.

4.2 Potential Impact to the Industry

An effective and efficient in-line surface detection system will benefit the steel rolling industry in various aspects. Currently surface defects represent more than half of the customer claims and rejects to a typical bar mill. However, due to the lack of a reliable sensor system, the exact causes of these defects are still unknown. To address this issue, two approaches are typically in practice. First, an inspection method, such as cold rotary eddy current device, is utilized as a gatekeeper to prevent defective products from being shipped to customers. The other approach is to improve the process in order to prevent defects from happening in the first place. A reliable imaging system can help the bar industry in both directions.

The potential of the imaging system has been demonstrated by the pilot installations. In several instances coils have been scrapped or trimmed based on reports from the imaging systems. Seeing real images of surface defects has given the quality engineers who use the system greater confidence in making ship/no-ship decisions. In terms of process control, the imaging systems demonstrated their value by preemptively detecting roll failures (roll cracks) and potential mill setup problems (fluctuating roll gap patterns). Using real time defect tracking feedback, it is possible to further enhance root cause analysis capabilities, a direction we are currently pursuing.

Better surface quality will also benefit downstream industries such as the forging industry. If surface quality of steel bars is in control, the forging industry can reduce its over stocking, which is typically used to handle uncertainties such as surface defects in the raw material. Furthermore, improved surface quality of the steel bars enhances the possibility of net-shape or near-net-shape forming. Knowing defect locations on the coil is certainly better than not knowing them, if the coil can’t be 100% defect free. The downstream processors can either remove the defective segments, or perform targeted sorting on parts made from the defective segments. Either approach will reduce the operational costs in the downstream industries.

4.3 Next Step

Unless the data is used in improving the production process and the product quality, inspection adds no value. The next step is to use the data in two perspectives. First, the data will be used in improving the steel making and rolling processes through advanced process controls. The goal is to minimize the number of bars having surface defects and minimize the number of defects per bar. A predictive process control system is being developed for the SBQ industry based on the imaging surface inspection systems.

While the quantity of surface defects is expected to be greatly reduced with effective process controls, defect free steel bars could still be years away for the downstream processors. A 0.5 m (20”) long seam in a 3,200 m (2 miles) long coil must still be dealt with. If the defective segments can be accurately marked, they can be removed during the downstream shearing process. A protocol that will enable accurate defect marking and tracking throughout the rolling and shearing process is being studied.

5. CONCLUSION

Imaging based surface defect detection is being developed and implemented. Pilot installations have demonstrated the capability of detecting critical defects such as seams, laps, and shearing. The imaging approach provides greater benefits, such as higher detection accuracy and greater data depth, over other approaches such as eddy-current systems. Additionally, the system provides more complete and intuitive information about potential problems in the steel making and rolling processes. A reliable surface defect detection system could also potentially benefit the downstream industry by enhancing production capability, efficiency, cost, and quality. In order to deliver these benefits to the bar industry and its customers, additional research and development has begun based on the imaging surface defect detection technology.

6. ACKNOWLEDGEMENTS

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7. REFERENCE

(1) T. W. Judd, "On-line Detection of Longitudinal Surface Defects," *Detection, Classification, and Elimination of Rod and Bar Surface Defects*, American Institute of Steel and Iron, pp. 17-20 (1996).

(2) "CIRCOGRAPH: Eddy-current Testing with Rotating Sensors," Foerster Instruments Incorporated, http://www.foerstergroup.com/NDT/circograph.html.

(3) *"Laser Ultrasonic System"*, the Timken Company (2000).

(4) Interview given by China Steel Corporation (2003).

(5) Interview given by Morgan Construction about the Wire rod mill at Baoshang Steel Corporation, Shanghai, China (2004).