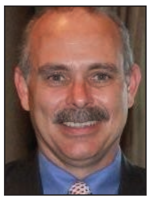
Process Control With a Focus on Surface Quality in Wire Rod Rolling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In promoting product quality for high-end automotive applications, an in-line surface inspection system was introduced into a 32-stand wire rod rolling train. Measured continuous improvement has been accomplished by way of a managerial plan, which includes the implementation of process control by adopting the data generated from the in-line surface inspection system, the best practices in rolling operations and the enforcement rules. This article documents the plan and its execution, as well as the results of surface quality–related technical and economical metrics over a period of three years.

The wire rod rolling operation is a state-of-the-art process in the hot rolling of long products. The ability to precisely shape a piece of red-hot metal at or above 100 m/second is no doubt technologically impressive. Modern high-speed wire rod rolling is an integration of mechanics, controls, metallurgy, energy, sensing and many other technical aspects in order to produce the finished hot-rolled products of excellent mechanical/metallurgical properties and perfect surface quality. Riding on the wave of digitization, the industry is trending for reduced energy consumption, increased automation, improved mill safety and defect-free finished product. One of the focal points in the rolling process is to keep the consistency and avoid uncertainties. These lead to the ever-stronger demand for in-line instruments that provide real-time information about the rolling process and product. This is especially true in achieving defect-free surface quality in wire rod rolling.

Conventional in-line wire rod inspection uses encircling eddy coils. The coil design pre-determines the detectable defects, as the defects that interrupt the wire rod surfaces have to be substantially perpendicular to, so that they can disrupt, the electrical or magnetic lines generated by the coils. Differential techniques were introduced to add phase information as well as avoid overwhelming variations. The data is limited and not visually intuitive.

Imaging technologies were introduced to bar and rod rolling as early as 2004 by Huang et al.[1] It is a combination of imaging sensors, optical design, digital processing and artificial intelligence. Thereafter, more efforts of imaging-based surface inspection on bars and rods were reported. In general, the technologies can be categorized into image morphology analysis,[1–4] image difference analysis,[5] and 3D scan contour analysis.[6,7]

The morphology analysis can vary significantly due to the use of different optical design and image processing algorithms. Strong capabilities and successful applications have been reported.[7] The image difference analysis is much like the arrangement of differential eddy coils. Instead of electrical coils, circular light rings of different colors, projected onto the bar or rod surface from two substantially different perspectives, are adopted to extract surface slope variations along the bar/rod moving axis. "Subtraction" of images of different colors taken at the same instance reveals the residue of "different slope" observed by different colors. The approach has the benefit of being quasi-3D, but is subject to a few considerations. First, "difference" is a process that is sensitive to noise because of the amplification effect. Second, wire rod vibrations pose an additional challenge as the vibrations introduce local slope changes. The 3D scan applications, while having the benefit of providing profile measurements at the same time and 3D visual views, are reported in use with hot-rolled products moving at a low speed, and the size of defects as reported is in the range of millimeters, despite various claims.

There is a trend to combine different inspection technologies. Disclosed as early as 2009 by Chang and Huang[8] and patented by Chang et al.,[9] the combination of imaging and eddy current has been an option offered to rolling mills. Chang et al.[7] reported 10 installations of imaging-eddy current combination. Such a combination can also be found in 2018 by Fuentes et al.[10] If affordable and the application conditions are adequate, it would be possible to combine 2D morphology and 3D scan.

With the improved availability and capability of surface inspection technologies for wire rod rolling, this article will document the process control for surface quality at a wire rod rolling mill, namely, the #3 Wire Rod Mill (#3WRM) of Zenith Special Steel, by way of a managerial plan that addresses not only the surface inspection technology, but also the use of surface quality data for continuous improvements in the rolling process, achieving measurable financial benefits for the business.

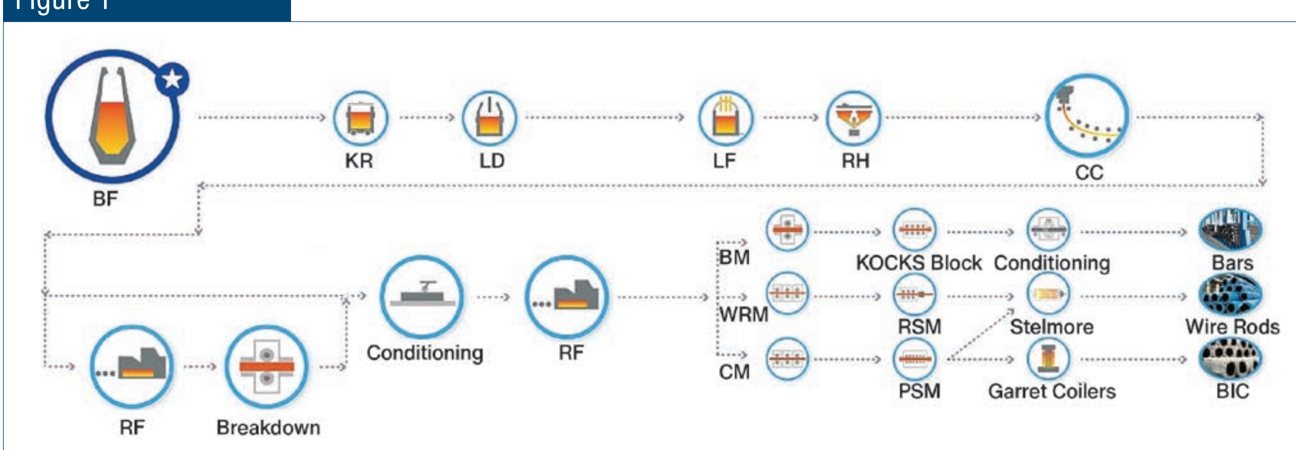
Discussion

Mill Description – Zenith Steel Group ("Zenith") was founded in 2001. To date, the group has more than 15,000 employees and an annual steel production capacity of 11.8 million tons and operates eight long product rolling lines. Three dedicated rolling lines focusing on special bar quality (SBQ) products, i.e., #3WRM (wire rod mill), #6BM (bar mill), and the newly commissioned #8CM (coil mill), along with designated steelmaking facilities, form the Zenith Special Steel Co. Ltd. (ZSS). This article specifically focuses on the experience of surface quality promotion carried out at the #3WRM.

The ZSS production process is schematically illustrated in Fig. 1. State-of-the-art steelmaking and rolling equipment have been installed to serve the SBQ marketplace. The #3WRM has a rolling train comprised of 32 stands, including a 6-stand roughing mill, an 8-stand intermediate mill, a 4-stand pre-finishing mill, a 10-stand no-twist mill, and a 4-stand reducing and sizing mill. The rolling line produces high-quality SBQ wire rods for applications in sectors of automotive, petrochemical, aerospace, electronics, etc. Specifically, products of the ZSS #3WRM are used in tire cords, bearing rollers, suspension, valve springs and fasteners.

In order to meet the demanding needs of the SBQ market in mechanical/metallurgical properties and surface quality, the #3WRM has to continuously pursue perfection of its process, in both equipment and process control on all fronts. For instance, efforts in the reheat furnace control allow the mill to avoid decarbonization and segregation. Enhanced water box control contributes to better in-line cooling, resulting in more uniform metallurgical properties. Thermomechanical rolling is practiced to achieve finer grains and higher strength. One of the important items to address in the pursuit is surface quality, which is handled with the adoption of billet conditioning, tailored guiding and in-line surface inspection.

Figure 1



Schematic of Zenith Special Steel (ZSS) process (schematic, excerpt from Zenith webpage).

Figure 2

ZSS #3WRM (wire rod mill) (excerpt from Zenith webpage).

The project for the development of the cold heading quality (CHQ) products at the #3WRM exemplifies this effort. The project was planned and implemented in a multiple-stage approach, starting from low-carbon steel (e.g., ML08A1, SWRCH6A-45A) with the strength grade range of Class 3.6–8.8, and moving toward higher-strength grades such as the range of Class 6.8–10.9 (e.g., ML20MnTiB, 10B21) and Class 8.8–12.9 (e.g., ML40Cr, SCM435). The effort is to aim even higher, with the strength grade of Class 12.9 and above in sight. Such a development effort is a pursuit of purer steel grade composition, superior structure performance and perfect surface quality.

A key factor in achieving the development goal was the installation of an imaging-based in-line surface inspection system, known as HotEye® (Fig. 3). The installation occurred at the #3WRM in second half of 2018 as part of the tools to address the demanding surface quality issue.

Figure 3

The in-line surface inspection equipment installed at ZSS #3WRM.

Surface Quality — Quality is a result of making, not inspecting. Good surface quality comes from keeping the rolling process in control. An inspection system, regardless how powerful it is, may not result in better quality by itself. On the other hand, holding a hot rolling operation for quality, particularly surface quality, is challenging. There are many sources of variability to be contained by the operation. To reduce the influence of human factors and uphold the tight process control for product quality, modern steel mills are built with hundreds or thousands of sensors and instruments from steelmaking to rolling and processing. Wherever possible, actuating devices are added for automatic action based on sensing data and information. Surface quality, among other quality indicators, is no exception.

However, surface quality is somewhat unique. First of all, the formation mechanisms of surface defects can be complicated. It may be a result of metallurgical, chemical, thermal or mechanical variations in the hot rolling process, or any combination of the aforementioned mechanisms. While some, such as roll marks, may be systematic and directly linked to the root causes, many could be sporadic and difficult to trace back. Secondly, the technology for non-destructive testing is quite limited, bounded by basic physics: the detecting waves, either mechanical or electromagnetic, must be interfered by anomalies. Such interference depends on various conditions such as the wavelength, thus frequency, of the detecting beam and whether the detecting beam projects a fixed orientation, as well as whether the conditions of the object are adequate to receive and propagate the detecting waves. As hot rolling is a less precisely handled and continuously evolving process, the selection of inspection technology is difficult. However, the key to holding product quality is process control, in which "feedback" is indispensable.

In fact, immediate feedback would be much preferred in process control. It is a critical mission of the mill management to identify and implement a practice for surface quality on hot-rolled wire rods.

Surface Quality Improvement Plan — To be poised for success, the Zenith #3WRM management developed and implemented a surface quality improvement plan (SQIP) with the goal of setting up a closed-loop process to monitor and control the surface quality of wire rod products rolled at the #3WRM. The SQIP plan included selecting an in-line surface inspection system, assembling a team with knowledge of all aspects of the rolling process and equipment, and establishing the enforcement rules.

1. Inspection System: After collecting information about different in-line wire rod inspection technologies, the #3WRM, with the assistance of experts from Zenith Tech Center, selected HotEye, an imaging-based system for in-line inspection. The reasons for the selection are as follows:

- It has ability to inspect for all kinds of surface defects, including longitudinal defects such as seams/laps and scratches, transverse defects such as slivers and necking, or slant defects as the wire rod may twist due to the laying head motion. Detection of surface defects of 0.050 mm or finer, along with an array of common wire rod defects, is reliably demonstrated and documented.
- The ability to automatically discern and set off alarms on defect patterns, such as repetitiveness (in coil or cross coils) and aggregation of same or similar defects, is superb.
- The imaging technology is immune from surface temperature effects; it is able to service in thermomechanical rolling for high-strength quality wire rod products.
- Intuitive and timely visibility with images of the surface defects as the wire rod being rolled enables quick verification and the implementation of corrective actions at the control pulpit. Additionally, the images also allow the extraction of the information and data on the surface defect length, width, estimated depth, shape and other attributes.
- It provides 100% inspection coverage of the rolled surfaces even for the Ø5.5-mm wire rods hot rolled at over 100 m/second.
- The maturity and reliability of the equipment is proven and documented, based on its number of global installations and its demonstrated ability to deliver results under a variety of managerial and operational paradigms.

However, the inspection system is a tool, and only part of the equation to address the surface quality need.

2. Team: A team was selected to take advantage of the newly available wire rod surface data from HotEye. The purpose of the team was to analyze the surface defect data for the underlining information, integrate the results of the analysis and apply the information into the rolling process control with their knowledge about the rolling process and/or equipment status.

The team at Zenith #3WRM consisted of multifunctional personnel from maintenance, operation, process and quality departments. Each team member has a clear responsibility in the SQIP. The maintenance crew is involved in not only keeping the new surface inspection system in good standing, but also connecting their knowledge of the mill equipment status to the wire rod surface quality data. The mill operators are tasked with retrieving the real-time surface quality information and reacting accordingly in equipment monitoring, adjustment and control. Quality is involved for aligning the #3WRM quality standard to the data of automatic surface inspection. Process engineers are the lead team members that coordinate the activities among maintenance/equipment, operation and quality. The team is supervised and administered by the mill management.

For participation in the SQIP, the approximate time allocated for the team members is outlined in Table 1.

Table 1

Time Allocation of the Team Members for the Surface Improvement Plan

Team member	Time allocation	Tasks
Maintenance	1–2 hours per week	Primary maintain the HotEye® for normal operation.
Operation	1–4 hours per week	Responding to the surface quality data in equipment/process adjustment.
Quality	4–6 hours per week	Responding to the surface quality data for inspection adjustment and product judgment.
Process	1–4 hours per week	Supporting the operation of HotEye in terms of data analytics and inspection settings. Establishing the links between surface quality data and the equipment/process status.

3. Enforcement Rules: Enforcement rules were developed by mill management to incentivize and govern the team, and to ensure that team members are held accountable to the faithful implementation of the SQIP. The rules cover the following aspects:

1. The procedure, frequency and standard of maintenance to be performed on the automatic surface inspection system.
2. The procedure to respond to a surface quality data alarm.
3. The procedure to refine the inspection settings.
4. The targets of surface quality improvement, along with the incentive and penalty schedule.

Specifically, the procedures are focused on quality and operation.

For quality, the initial focus was to align the HotEye inspection settings to the quality standards of the #3WRM. This is an ongoing process since the quality standards evolve dynamically due to changes in product mix and customer requirements. In addition to the initial efforts, periodic reviews are necessary. Furthermore, a procedure was developed and implemented for assessing the coil quality based on the defect data, and validating the detected defect when a further physical inspection is necessary.

For operation, the focus is on mill-sourced surface defects, such as those attributed to equipment failures and/or incorrect setup. The primary objective is to prevent batch quality spills. Subsequently, operation works with process members to explore complex root causes of surface defects, fine-tune the rolling operation and bring the rolling process to a tightly controlled norm based on the surface quality data.

Execution — During the initial phases of the SQIP execution, the team faced some implementation challenges. These challenges were overcome by the team members working together, resulting in the successful implementation of the SQIP goals, improving the surface quality and reducing the mill costs attributed to surface defects.

1. Challenges: The adoption of a new inspection technology posed a change in the mill practices, and it took time for the mill personnel to accept the new equipment and technology as part of the rolling mill process. The issues ranged from lack of proper knowledge/experience in operation and maintenance in the beginning, to the inadequate ability of reconciling the images of defects to the physical rod surfaces, and misalignment between the inspection criteria and the detection settings in HotEye. Even though the mill selected a mature surface inspection system, there are still disparities from one mill to another in terms of inspection standards and practices. The team initially invested much effort and time to set up the different settings based on material grades and customers, and to understand the causes of surface quality spills as it relates to equipment/process issues.

The management was aware of the challenges, and proceeded forward in a phased approach, setting up the change in paradigm of the mill from "having a piece of new equipment" to "fully effectively practicing the SQIP."

2. Phased Approach: The phased approach comprises a few steps.

Upon the installation of the new surface inspection equipment, the team was made aware of its existence and the mindset of "Having ≠ Using." While it is apparent that the equipment would not result in any benefit unless someone uses it, the equipment could not be used unless it is properly maintained and operated.

The mill management set up a maintenance schedule that covers weekly, monthly, quarterly and semiannual maintenance. The most important task is the weekly maintenance, which covers the upkeep of optics, cooling air supply, equipment exterior appearance and software/computing unit. The new surface inspection equipment must be taken as, though not physically being, part of the rolling process because the mill management understood that the mill personnel had to 100% incorporate the quality data provided by the surface inspection equipment as part of the rolling procedure to achieve the goals of the SQIP project. Additionally, a monthly incentive bonus was set in place to reward the individuals on the maintenance crew if they could keep the surface inspection equipment 100% in service during the individual's responsible shifts.

The next mindset to address is "Using ≠ Useful." With the sustaining operation of the surface inspection equipment, the very next step to follow is to use the equipment, or more precisely, the data generated

Figure 4

Exposed optics in regular cleaning.

Table 2

Major Hurdles Preventing the Use of Surface Quality Data

Hurdles to use surface quality data	Resolving measure
Blurry image	Regular maintenance to set standards
Could not trace back to the exact coil	Fully integration into mill L1/L2, including billet ID and hook number
Lack of attention by operators	Incentivizing by event-driven reward
No result for a prolong period	Phased approach, from low-hanging fruits to in-depth applications
Inconvenience of data review	Populating data terminals to team member positions
Improper training of software operation	Teaming up with equipment supplier for proper training

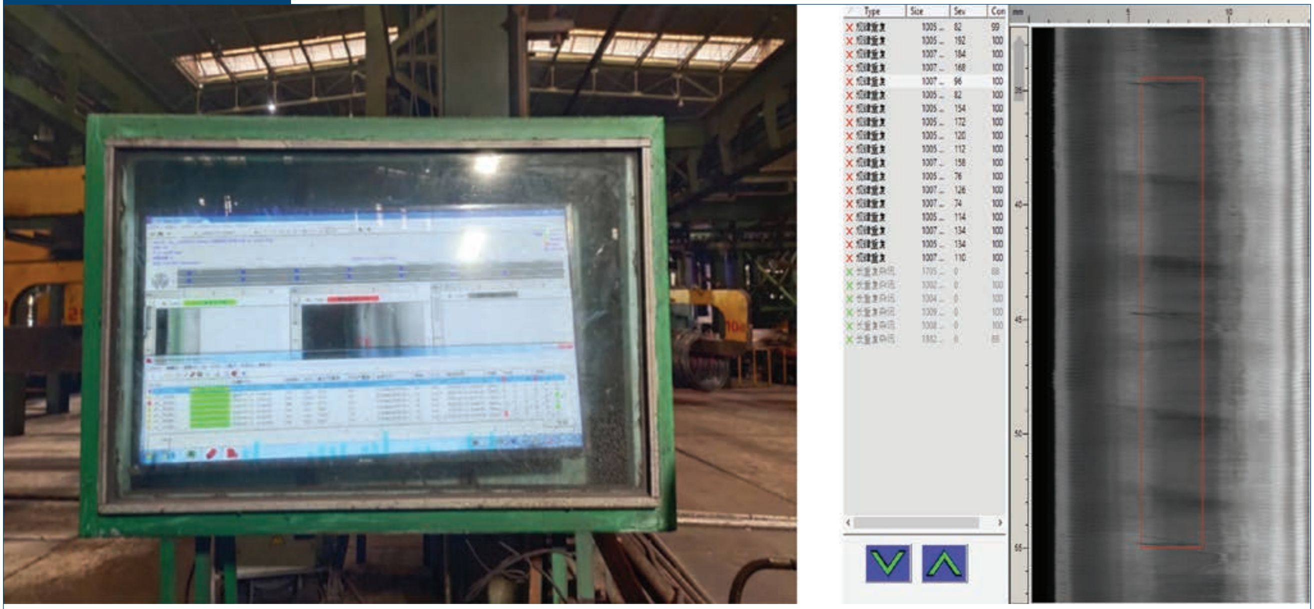
by the equipment. The team identified major hurdles, as listed in Table 2, that prevented the surface quality data being used in a useful manner. A series of resolving measures taken to overcome the problems is also included. The baseline notion is that the equipment is to serve the needs of operations to produce a quality ton of steel, and that the production team shall pay attention to the equipment.

To use the data, it would be necessary to render good surface quality data in front of the users, namely the SQIP team members, in order to reach the objective of improved wire rod surface quality. However, "rendering good surface quality data in front of the users" is easier said than done. As an easy first step, data terminals were installed in various locations such as the mill control pulpit, shop floor (for operators), inspection station (for quality) and offices (for process engineers and management) so that the users can visually see real-time information and/or query historical data. The rolling quality data displayed in the terminals was generated and sent from the inspection system over the mill network.

To jump-start the team and demonstrate the effects, an alarm was initially set up to alert for quality issues dealing with mill equipment such as roll marks and scratches throughout an entire coil. The results of these alerts were immediate. There were four instances of equipment/setup failures being stopped in a month after the data terminal installations. Such an accomplishment, though not reaching the SQIP objective yet, boosted morale and affirmed the confidence of the team in the SQIP. The incentive plan provided as part of the SQIP to the operators for each successful use of the surface quality data in stopping batch scrap (quality spills) ensured that the team members shared the monetary benefits of surface quality improvement.

The team also carried out other work, including the alignment of defects and defect types, as well as collecting more matched defect examples. These constituted the basis for enhancing the alarming accuracy on different defects and different coil products. A daily log was registered to document the activities of the team. By the end of 2019, roughly one year after the installation of the new surface inspection equipment,

Figure 5



(a) (b)

Surface quality data terminal on shop floor (a) and roll mark (repeating) identification/alarming (b).

#3WRM was capable of not only limiting the loss of any equipment failure to an average of two coils, and no more than three coils per instance, but also having all the quality data (defect mapping) for those coils having defects so that they may be properly evaluated by the quality department as to whether they could be shipped to a customer. With this implementation, there has been no batch quality spill since January 2020.

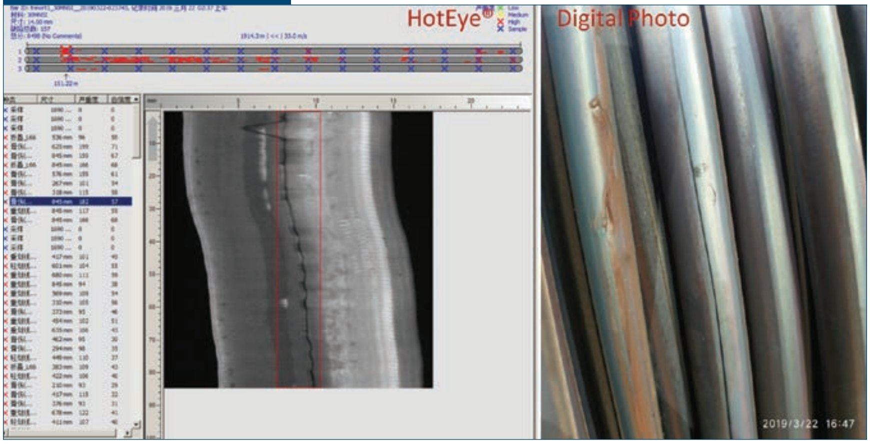
The work did not stop, because "Useful ≠ Full Effective." The team continued its effort by expanding the surface quality control on the wire rods beyond equipment failures to all kinds of surface defects, such as scabs and seams, as shown in Fig. 7.

The practices of SQIP are continuously refined, reviewed and implemented. The benefits, aside from the improved efficiency and safety of the operation and quality personnel, can be concluded to have impacts on three aspects at the #3WRM:

1. Detecting surface defects in time to prevent batch quality spills and loss.
2. Identifying defect patterns from fully digitized and traceable surface quality data, so to improve over time through data analytics.
3. Supporting quality certification requirements demanded by high-end customers.

As an example of the ongoing efforts of the SQIP team, the in-depth root-cause investigation was conducted on sporadic small scabs on spring steel materials. Based on the surface quality data, process engineers were able to link the presence of such small scabs to the grinding practices of the billets by way of statistical analysis. It concluded that grinding marks on the billets of the spring steel materials may sporadically lead to scabs on the final wire rod products. Upon further investigation, the engineers discovered that the scabs could be prevented by implementing changes to billet reheat practices. This would have not been possible had there not been the fully digitized and traceable surface quality data.

Figure 6



Alarm example of the scratch/lap defects through a coil.

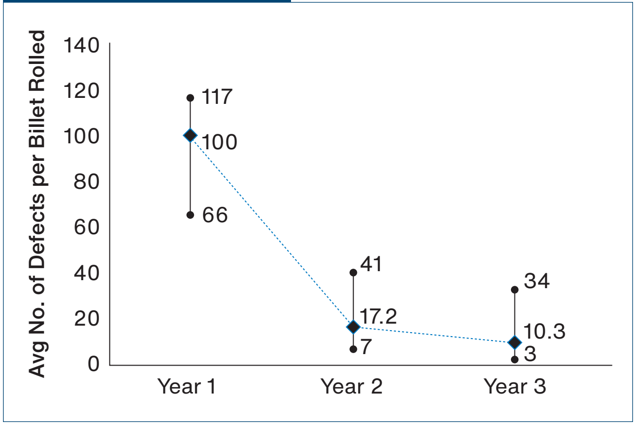
Results

To evaluate the SQIP results, #3WRM employed three measurable metrics: the average number of surface defects per billet rolled (per wire rod coil), the quantity of rejects due to surface quality, and the loss per production ton due to surface quality. All metrics show that the surface quality of the

Figure 7

Alarm examples of severe individual defects: scab (a) and seam (b).

Figure 8



Normalized average number of defects per billet rolled over three years.

#3WRM products improved substantially over a span of three years.

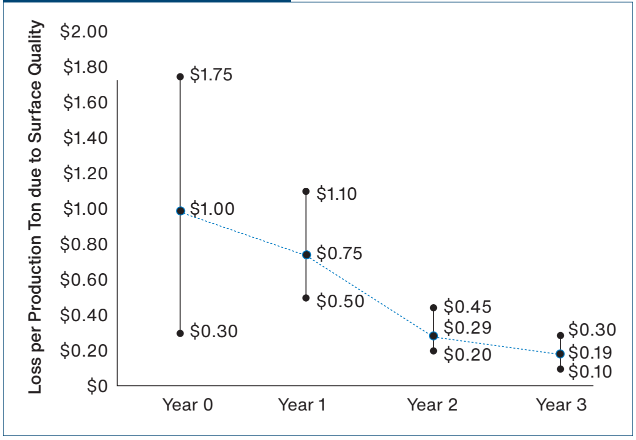
Fig. 8 documents the average number of surface defects per billet rolled based on the HotEye inspection results for three years of SQIP practice. Note that such data did not exist prior to 2019 due to lack of an in-line system for 100% inspection, and thus there was no baseline before the SQIP. In addition to the average numbers of surface defects per coil, the highest and lowest monthly average numbers of surface defects per coil are also included in Fig. 8 to show the range of variation. The data is normalized by setting the Year 1 average number to 100 for quick visual reference of the improvement rate over years of the SQIP practices implementation. The number of surface defects per coil reduced by over 80% (from 100 down to 17.2), and further reduced by another 7% (from 17.2 down to 10.3) within the three-year time frame.

Table 3

Quantity of Rejects Due to Surface Quality

	Year 0	Year 1	Year 2	Year 3
Reject tonnage	6,000	4,544	2,350	1,400
Annual rate of improvement	n/a	24.3%	48.3%	40.4%

Figure 9



Normalized loss per production ton of coils due to surface quality spills.

Table 3 lists the quantity of rejects due to surface quality for the same three-year period, with the addition of Year 0. Such data is available prior to the SQIP implementation. The double-digit annual rates of improvement clearly reflect the SQIP effectiveness. Taking Year 0 as the baseline, the yield (less rejects) increased by 0.6% in Year 3.

To put the improvement in dollar sense, another metric, loss per production ton due to surface quality, was introduced. After all, the purpose of the SQIP is to improve the profitability of the #3WRM production. Fig. 9 documents this index over the same three-year time frame, with Year 0. This index is computed based on dividing the monetary loss due to surface quality by the total tonnage produced per month at the #3WRM. Examples of the monetary loss included in the calculation, if attributed to surface quality issues, are the loss of the conversion cost if a coil is scraped, the price difference in case a coil is downgraded to the secondary market, and the penalty/compensation due to customer complaints. Again, the highest and lowest monthly numbers are also included in Fig. 9 to show the range of variation, and the baseline is normalized to US$1 for Year 0. This metric shows the same trend of improvement as the previous two metrics. The loss is reduced by 81% (from US$1.00 to US$0.19), and the range is narrowed from US$1.45 to US$0.20, leading to the substantial and stable financial benefits with the average monthly production volume of about 62,500 tons at the #3WRM.

Based on the results of the aforementioned data, it can be summarized that:

- All three metrics show the visible and consistent trend of improvement, proving that the SQIP is effective and the payback is substantial.
- The range of variation is narrowed in both Figs. 8 and 9 as the progress of the SQIP implementation over the three-year time frame, and the mean value measured is biased toward the lower end. This implies that the process control toward improved wire rod surface quality is not only effective, but also robust, both technically and economically.
- Both Table 3 and Fig. 9 show that the initial improvement (from Year 0 to Year 1) is moderate, while all three metrics show a steep improvement from Year 1 to Year 2. This is in line with the phased approach taken by the #3WRM.

It took time for the SQIP to be accepted, perfected and faithfully practiced by the team.

A success can be declared and attributed to the systematic approach, rule-based quality improvement plan and enforcement with benefit sharing of the SQIP.

Conclusions

A surface quality improvement plan was established at the #3 Wire Rod Mill of Zenith Steel in pursuit of satisfying the demanding SBQ automotive market. The plan accomplished visible improvements in both technical and financial evaluation metrics for the wire rod mill. Additionally, the data generated from the in-line surface inspection system contributed to the changes in the rolling operation, resulting in best practice procedures developed for the rolling operators. Also, the enforcement rules implemented were critical to achieve the goals of the SQIP. Making the SQIP part of the standard procedures for the rolling practice of the mill operation should be a continuing effort to maintain and improve upon the delivery of defect-free product to the customers of the wire rod mill business.

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This paper was presented at AISTech 2023 — The Iron & Steel Technology Conference and Exposition, Detroit, Mich., USA, and published in the AISTech 2023 Conference Proceedings.