SBIR Phase I Final Report

Capability of Rolling Efficiency for 100M High-Speed Rails

A Project under Award

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EXECUTIVE SUMMARY

OG Technologies, Inc. (OGT), along with its academic and industrial partners, proposes this *CORE* project for the *Capability of Rolling Efficiency for 100m high-speed rails*. The goal is to establish the competitive advantage, and thus the sustainability of the US-based rail manufacturers by greatly enhanced efficiency through innovative in-line metrology technology, in-depth process knowledge, and advanced process control to overcome detrimental factors such as higher labor costs that are saddling the US manufacturing sector.

This Phase I project was carried out by an industrial-academia team over 9 months. The R&D team successfully completed all technical tasks and accomplished the objectives for the Phase I. Specifically, during the Phase I project period, the R&D team designed, implemented and tested a test unit. The test unit allowed the team to perform laboratory development of the proposed technological approaches as well as verifications in a production line at a test site. Various operation conditions were engaged for evaluation. The team members, including individuals from the awardee, the industrial partners and Prof. Shi from Georgia Tech, contributed scientific, engineering and process insights.

In addition to the technical efforts, the introductory information of this project as well as anticipated progress was disseminated to steel mills interested in the project. As a result of the Phase I, there are steel mills committed to support and take part in the Phase II development with not only in-kind, but also cash contributions.

The Phase I project has established the technical and commercial basis for additional development. There are needs to further completing the in-line sensing capability, deepening the capability of metamodeling, and supporting the process monitoring and control. The R&D team plans to submit a Phase II proposal based on the findings.

SUMMARY OF RESULTS

This Phase I project was carried out by an industrial-academia team over 9 months with the goal to address the need of a sustainable high speed rail manufacturing in the US. The R&D team successfully completed all four technical tasks and accomplished the objectives for the Phase I, in that the R&D team has implemented and demonstrated:

- An in-line metrology system with a novel optical design as accurate as +/-0.050 mm for hot rolled rails;
- Efficient metamodeling for issues associated with the rail dimensional variations; and
- A practice of process control based on the metrology data and the metamodels.

Specifically, during the Phase I project period, the R&D team designed, implemented and tested a test unit with two imaging sensors. The test unit allowed the team to perform laboratory development of the proposed technological approaches as well as verifications in a production line at a test site. Various operation conditions were engaged for evaluation, including trials by the participating industrial partner (a rail mill) during its day-to-day operations for a period of four weeks. The data collected from the operations formed the basis of the metamodeling and the process control. The team members, including individuals from the awardee, the industrial partners and Prof. Shi from Georgia Tech, contributed scientific, engineering and process insights.

In addition to the technical efforts, the introductory information of this project as well as anticipated progress was disseminated to steel mills interested in the project. As a result of the Phase I, there are steel mills committed to support and take part in the Phase II development with not only in-kind, but also cash contributions.

With the progress, the following Phase I questions have been answered:

(1) The proposed in-line metrology technology is feasible and performing as expected.

(2) Metamodeling is an approach for the rail rolling process with fast response, accuracy and reliability.

(3) Process control based on the in-line data and the metamodeling has been demonstrated.

(4) The commercial potential of the CORE technologies goes beyond the rail mills, into the section mills as well as the rod and bar mills; additional applications in 3D printing is being developed.

The Phase I work established the technical and commercial basis of additional development. There are needs to further completing the in-line sensing capability, deepening the capability of metamodeling for the multi-stage process, and supporting the process monitoring and control. The R&D team plans to submit a Phase II proposal based on the findings.

SNAPSHOTS OF DEVELOPMENT WORK

(1) Development of the In-line Instrumentation

A two-camera test unit was designed and implemented based on the novel planar optical design (patent pending lens-shift design). Depending on the mill configuration, the test unit was designed to either measure the height of the rail or the widths of the rail at the head, web and base section.

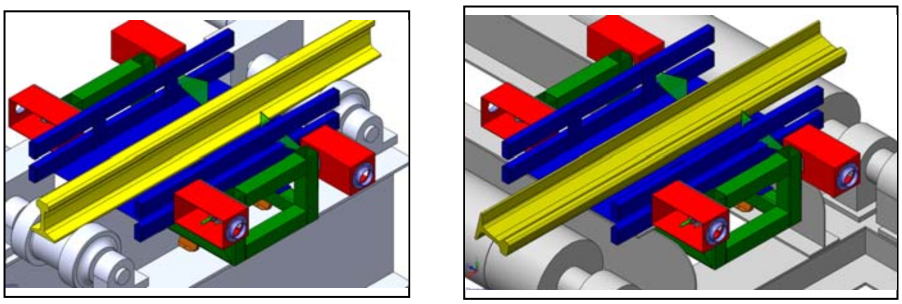

Figure 1. CAD models of the test unit, illustrating its use with two common rail orientations in a mill.
(Left) Rail is presented to test unit at a vertical orientation for width measurements.
(Right) Rail is presented to test unit at a horizontal orientation for height measurements.

With the planar optical design, the pixel resolution is uniform in the field of view of the cameras. This greatly simplified the calibration process into two independent steps. First, the camera/lens assembly was individually calibrated for the lens distortion. Then, the combination of two camera/lens sets was calibrated by using a simple hexagon calibration piece, positioned normal to the laser plane. The precisely made hexagon provided NIST-traceable measurements for face to face distances as well as angles (Figure 2). As a result, each camera would image three edges, which provided one distance (the length of an edge) as well as two 120° corners with accuracy. The three conditions formed the constraints for defining the pixel sizes as well as relative position and orientation of the camera coordinate to the world coordinate.

Figure 2. Calibration using a hexagon master piece.
(Left) The hexagon set up in position, illuminated by laser lines
(Middle) Images of the hexagon taken by two cameras
(Right) Constructed hexagon profile after calibration

The test unit was fully tested in the laboratory for not only the measurement accuracy, but also the stability under environmental factors such as temperature variation, surface reflectivity and sample motion. For an object size of 90.6 mm, as an example, the measurement accuracy was 0.0065 mm (0.007%). This is well within the industrial standard.

After the laboratory verification, the test unit was installed in a rail rolling facility to perform the width measurements (Figure 3). The on-site trial commenced on January 19 and ended on February 18 of 2014. Width measurements were the most challenging ones as the contours along the rail width had more sharp curvatures. The chosen setup also provided the evaluation of the novel optical design on both convex and concave contours. This was for the R&D team to better evaluate the sensor design and performance. Three dimensions of the rails were measured for each rail profile section (Figure 4).

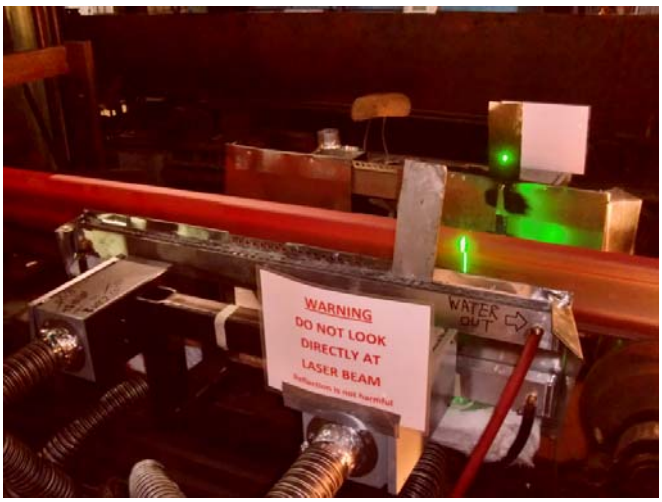

Figure 3. Test unit measuring a red hot rail.

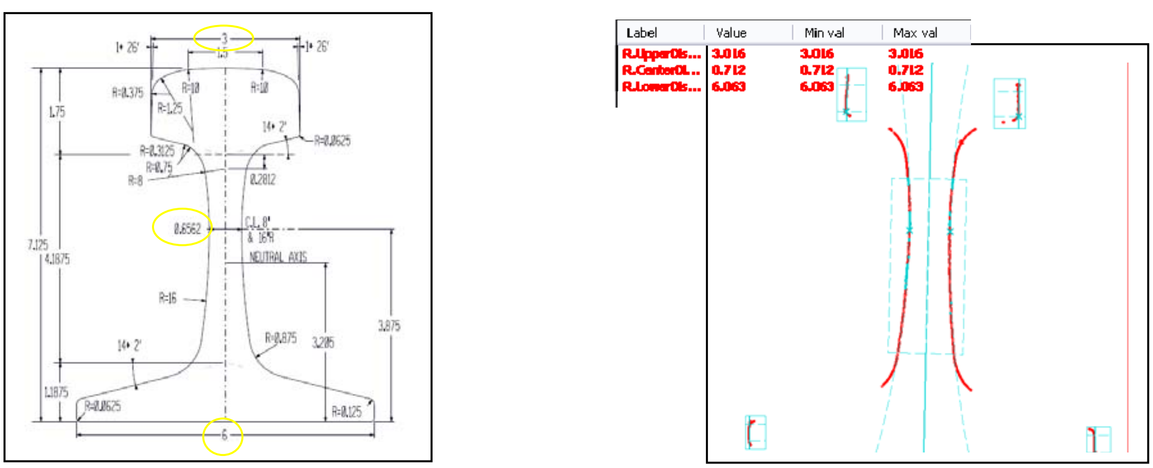

Figure 4. Real-time measurement results of a rail cross-section (unit: inch).
(Left) Rail profile drawing, cold dimensions. (Right) Real-time profile display and measurements.

(2) Variation Analysis of the In-line Instrumentation

The on-site width measurements had standard deviations in the bracket of 0.1~0.2mm, much greater than those of the lab test results. While the magnitude was still acceptable to the test-hosting rail manufacturer, these deviations did include the variations from the instrument, the process and the parts. As an example, the process noise could be from the "size of probe". The test unit acquired the rail profile at each cross-section with an area of 0.35 mm^2, based on the laser line width, the rail moving speed and the exposure time. This was much smaller to a typical micrometer. A ϕ¼" flat tip micrometer commonly used in a tool room has a surface area of 28mm^2, nearly 80 times larger. The measuring instrument would be more sensitive to the surface roughness with a finer probe size. That is, the test unit was subject to the noises from surface roughness. The typical surface roughness for hot rolled products is Rz 0.06~0.40 mm, or Ra of 0.006 mm, where Rz is the peak to valley range and the Ra is the averaged absolute value. One remedy to lessen the impact of surface roughness on dimensional measurements is to apply a Moving Average (MA) window. The MA window size can be selected based on the desired probe size to moderate the process noise.

Product variation commonly exists from part to part. Traditionally, a "golden workpiece" or a designed experiment with known workpieces is used to evaluate the repeatability and reproducibility of a measurement device. However, this approach is inadequate to the hot rolling products, and the product in-situ is constantly changing due to temperature variations. Therefore, a new approach that utilized a bounding mechanism was developed to estimate the instrument capability. Specifically, the goal was to estimate an upper bound on the variance of ε_i, the instrument variation embeded in the measurements for each rail indexed at i = 1, 2, …, n, using only the following assumption on $X_1,\ldots,X_n$:

$$\max|X_i - X_{i+1}| < \delta,$$

where X_i was a vector of the actual width along a rail i, and max was taken over the entire vector and the indices i. The vector of the corresponding measurements of the rail i was Y_i and $Y_i = X_i + \varepsilon_i$. The value of δ should be prescribed using knowledge of the rolling process.

The basic framework employed was the following decomposition of error:

$$\begin{aligned}
2\sigma^2 &= \frac{1}{m}\mathrm{E}\left((\varepsilon_{i+1}-\varepsilon_i)^{\mathrm{T}}(\varepsilon_{i+1}-\varepsilon_i)\right) = \frac{1}{m}\mathrm{E}\left((Y_{i+1}-Y_i-X_{i+1}+X_i)^{\mathrm{T}}(Y_{i+1}-Y_i-X_{i+1}+X_i)\right) \\
&= \frac{1}{m}\mathrm{E}\left((Y_{i+1}-Y_i)^{\mathrm{T}}(Y_{i+1}-Y_i) - 2(Y_{i+1}-Y_i)^{\mathrm{T}}(X_{i+1}-X_i) + (X_{i+1}-X_i)^{\mathrm{T}}(X_{i+1}-X_i)\right) \\
&= \frac{1}{m}\mathrm{E}\left((Y_{i+1}-Y_i)^{\mathrm{T}}(Y_{i+1}-Y_i) - (X_{i+1}-X_i)^{\mathrm{T}}(X_{i+1}-X_i)\right) \\
&= \frac{1}{m}\mathrm{E}(Y_{i+1}-Y_i)^{\mathrm{T}}(Y_{i+1}-Y_i) - \frac{1}{m}(X_{i+1}-X_i)^{\mathrm{T}}(X_{i+1}-X_i)
\end{aligned} \tag{1}$$

From (1), the following was arrived at:

$$2\sigma^2 \le \frac{1}{m}\ \mathrm{E}((Y_{i+1}-Y_i)^{\mathrm{T}}(Y_{i+1}-Y_i)) \text{ and } 2\sigma^2 \ge \frac{1}{m}\mathrm{E}((Y_{i+1}-Y_i)^{\mathrm{T}}(Y_{i+1}-Y_i)) - \delta^2.$$

The following term was defined for simplicity:

$$T := \frac{1}{2m} \mathrm{E}((Y_{i+1} - Y_i)^{\mathrm{T}} (Y_{i+1} - Y_i)),$$

The exact value of T was unknown, yet could be directly estimated with enough data:

$$\hat{T}_n = \frac{1}{mn} \sum_{i=1}^{\lfloor n/2 \rfloor} (Y_{2i-1} - Y_{2i})^{\mathrm{T}} (Y_{2i-1} - Y_{2i}).$$

Using this estimate, it could be shown that

$$P(\sigma^2 + \delta^2 > \hat{T}_n > \sigma^2) \rightarrow^{n\rightarrow\infty} 1$$

As $\delta \rightarrow 0$, the estimates of the upper and lower bounds would get closer. Thus, this approach would likely be a good estimator where δ be small.

Further involving a Monte-Carlo sampling scheme, a smoothed plot of the posterior distribution of σ^2 of the first width measurement using different numbers of samples was shown in Figure 5. Because of the similarity of the two posterior distrubutions from different sets of data, the team could conclude that the estimate of the variance is stable relative to the data.

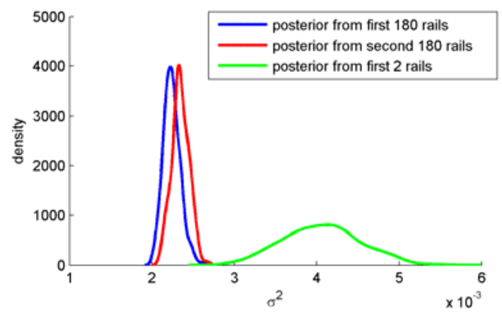

Figure 5. A smoothed plot of the posterior distribution of σ^2 of the measurements using different numbers of samples

The computed estimates of intrument noise from the full data set collected during the on-site trial were 0.035, 0.037, and 0.042 mm for the head, web, and base width measurements, respectively. The values would be reduced to 0.025, 0.026, and 0.030 by applying a 4th order MA window to the data. The results indicated meeting the targeted instrument accuracy of +/- 0.050 mm.

The instrument capability could be evaluated by computing the P/T ratio, defined as the ratio of instrument noise to the tolerances on the products. A smaller P/T ratio indicates a good instrument capability. The industrial standard for is for the P/T ratio to be less than 0.3, preferably 0.1. In this Phase I on-site trial case, the P/T ratio was estimated by:

$$\frac{6\hat{\sigma}}{USL - LSL}$$

and the resulted P/T ratios were 0.194, 0.156 and 0.100 for the head, web, and base lengths. The test unit demonstrated the acceptable capability.

During the trial period, there was no hardware malfunction. Calibration was run at different times to monitor the system drift of the test unit. The overall drift from the start to the end of the

4-week period was 0.245 mm. The main cause of the drifting was believed to be the temperature variation cycle around the test unit. The test unit endured daily heating/cooling cycle with the total temperature variation exceeding 60˚F during January and February of 2014 (record weather conditions in the US). While the slow drift could be compensated by periodic calibrations, the team believes that the drift can be further suppressed by an enclosed sensor design, instead of the open frame design of the test unit, an approach restricted by the time and budget constraints.

(3) Demonstration of Modeling and Process Control

There were several "process trends" carried in the collected data. The R&D team focused on a couple of the trends associated with the finishing mill.

<u>*Cyclic Patterns:*</u> Figures 6 and 7 below represent the typical width measurements for rails 115RE and 132RE (115 lbs and 132 lbs per feet, standard shape rails) along the length of a rail. Both show 12 cycles along their lengths, or 88 inches per cycle on average. Instead of a complex material flow model, a simple metamodel with a few parameters, the roll diameter, the slippery factor, and the roll eccentricity, was established to model the effect on rail dimensions. As a result, the model accurately predicted the pitch and magnitude of the cyclic variations exhibited in the figures. For example, the diameters of a roll varied from 26.5 to 29.5 inches, given the contour of a rail. This was equivalent to roll circumferences of 83.25 to 96.67 inches. The average cyclic pattern pitch was right in the middle of this range.

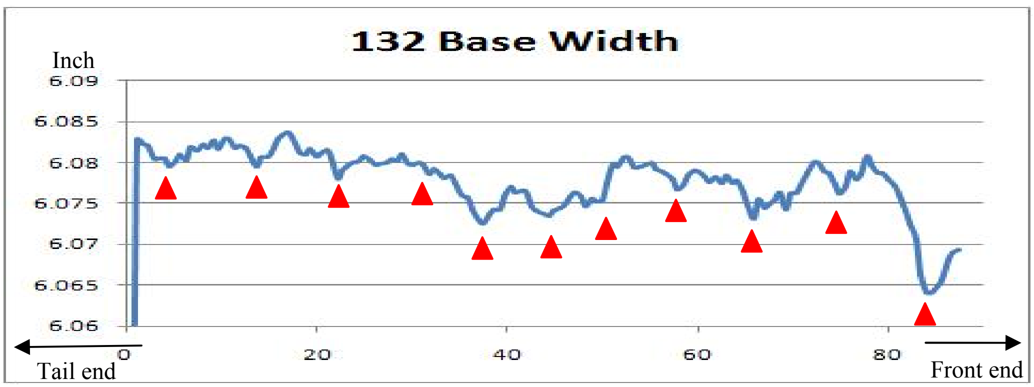

Figure 6. A sample flange width measurements along a 132RE rail. (Red triangles indicating the cyclic dips)

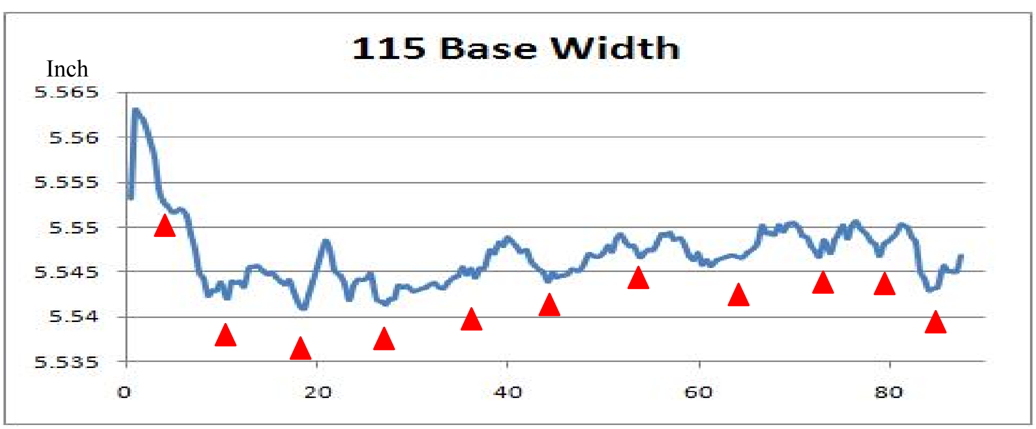

Figure 7. A sample flange width measurements along a 115RE rail. (Red triangles indicating the cyclic dips)

By applying the measurement data to the model, the model estimated the roll eccentricity at the finishing mill to be about 0.0043 and 0.0046 inches, respectively. The eccentricity values were inline with the hosting mill's setup guide line for processing rolls.

The metamodel associated with this cyclic pattern was stable because the measurements had monotonic responses to the changes in the roll eccentricity and roll diameter. As long as the roll eccentricity and the roll diameter were bounded, the metamodel would not deliver any singular points. With the monotonicity, this metamodel, once established, could be used to estimate the roll eccentricity based on the measurement data. The estimated roll eccentricity could be monitored for trend shifting at the mill and alarm with an upper bound.

Roll Pass Alignment: Another trend embedded in the Figures 6 and 7 was the tail end expansion of ~0.01 inch (0.25 mm) for the 115RE rail. This was not seen on the 132RE rail. Mill configuration was believed to be the cause of this behavior.

The finishing mill at the test site had a down slope when feeding the steel into the mill. Namely, there existed an attack angle θ, as illustrated in Figure 8. The down slope and the upper roll were fixed. To adjust the roll pass aperture, the bottom roll was raised or lowered. As a result, the relative position between rolls and the down slope changed as illustrated. The 115RE rail had a smaller cross-section and the bottom roll would be up. This configuration would cause the steel to be bent more when going through the rolls, until the very end of the steel piece (released due to the distance between the rolls and the down slope). On the other hand, a rail with a larger cross-section, such as the 132RE, would be less bent during rolling.

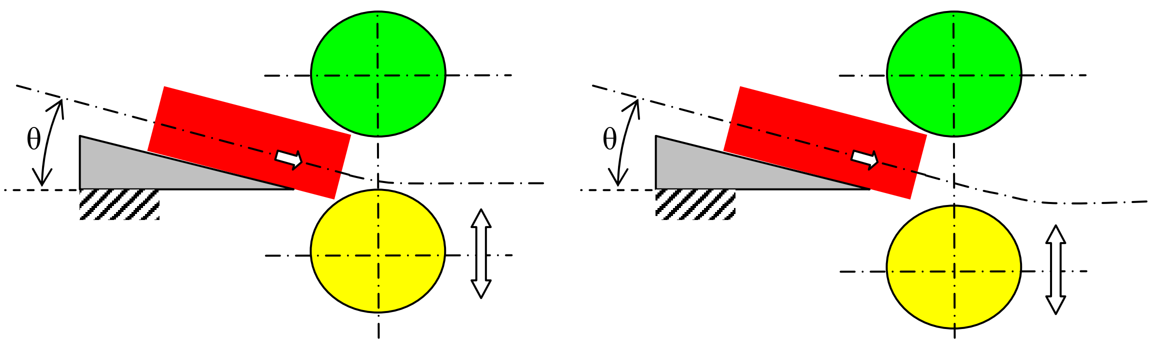

Figure 8. Effect of the down slope and the roll pass aperture.
(Left) Smaller roll pass aperture; (Right) Larger roll pass aperture.

A metamodel with factors such as the attack angle θ, the bottom roll position, the distance between the down slope and the rolls, the size of the feed, and so forth, was constructed. Although θ was a constant, the actual roll pass aperture was determined by it as Roll Gap timed cosθ. When θ→0, as getting toward the tail end of a 115RE rail, the actual roll pass aperture increased as cosθ→1. The transition of size variation was affected by the distance between the down slope and the rolls. This model successfully explained the data collected on 115RE and 132RE. While the effect of this attack angle was currently acceptable, it would be a factor to further improve the uniformity of the dimensions along a rail. That is, precision adjustment of the rolls along with the down slope would be essential for precision rail manufacturing. However, relying on off-line measurement of cold rails to fine tune the roll adjustment was nearly impossible. This could detrimentally compromise production efficiency. The proposed inline sensing technique, along with the metamodel, provided the feasibility to make the roll adjustment to compensate various dimensional errors.

<u>*Other Trending Information:*</u> There were other trends discovered in the collected data in addition to the width variations within a rail caused by the setup of the finishing mill. For instance, the R&D team also identified a rail-to-rail variation, as shown in Figure 9. In this figure, all the base width readings within a rail were condensed into a single averaged value. The averaged base width value for each rail was then plotted on a time axis. Each dot in the figure represents the reading of a rail. Figure 9 clearly exhibits a "batch variation" pattern. The magnitude was 0.04 inches, or 0.1 mm. Because each cluster of the data in Figure 9 was associated with a batch of rails, with a time gap of roughly 30 minutes between 2 adjacent clusters, the R&D team believes that this "batch variation" pattern was caused by the "batch" operation of billet heating at the test hosting site.

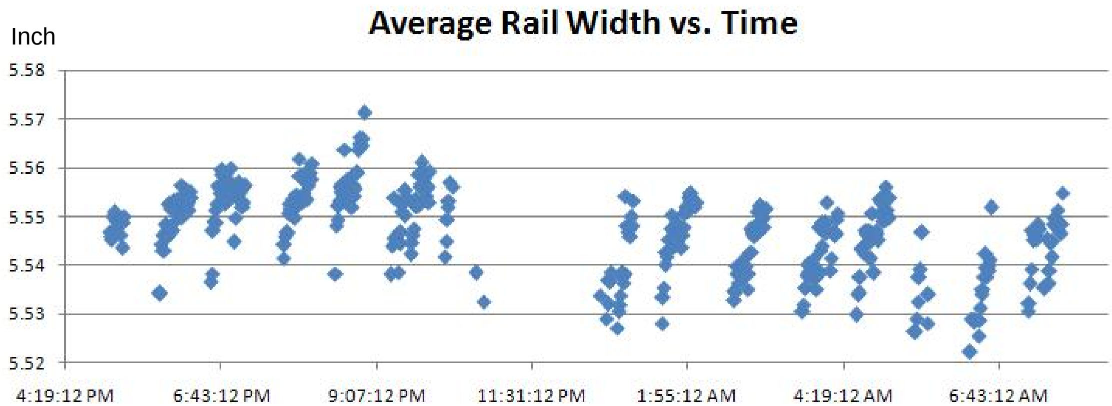

Figure 9. Averaged base width of a rail vs. time.

This "batch" operation was a temporary practice at the hosting site due to the fact that one of their two reheat furnaces was being overhauled. The reduced heating capacity forced the mill to run the production in batches in order for the reheat furnace to bring the temperature up. According to Figure 9, the averaged base width of a rail gradually increased in a batch, but reset when a new batch was charged into the mill. This scenario could be a result of a few possibilities in the mill. The first possible cause was the variation on the test unit due to the thermal effect. However, thermal heating on the test unit should have caused the measurement readings to shrink, instead of expand. Thus, the R&D team believed that the test unit for the in-line metrology was not the source of this variation.

Other factors were reviewed. One reason was the reduced soaking time for the last billet. Shorter soaking implied lower core billet temperature. As a result, the steel being rolled would have a higher spring-back due to lower temperature, and thus a larger final dimension. This could also be due to the machinery heat up over a period of continuous operation, and cool down during the recess. Limited by the Phase I project period and the complexity of the modeling from the reheat furnace to all the rolling mill stands in the forming strand, the R&D team did not construct a metamodel for this issue. Additional development would be necessary to identify the root cause and establish the process monitoring and control of such dimensional variations.

(4) Development of the Geometrical Defect Detection

Adding to the application of the profile measurements on process monitoring and control, the R&D team further developed the algorithm that automatically detected localized contour deviation. The rail logos printed on the side of the web surface were used as the test samples. These marks were automatically detected and highlighted in red in Figure 10. The defect size can be configured by the minimum distance deviation or minimum enclosed area.

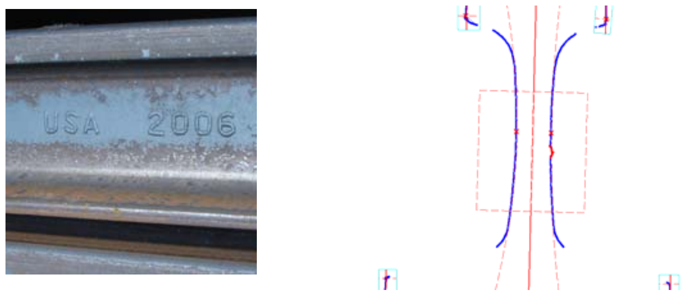

Figure 10. Print on the rail web and the detection with the in-line metrology

For a simpler geometry, such as circular or hexagon cross section (Figure 11), the deviation against the ideal contour could be exaggerated on the user interface to alert the operators.

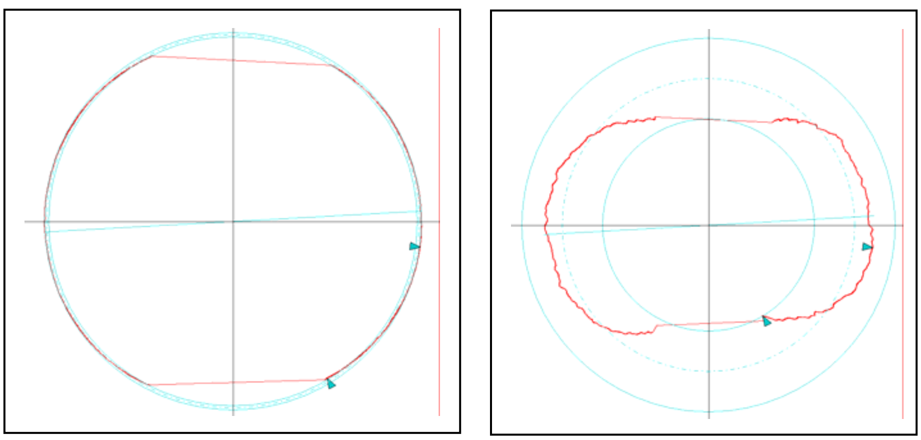

Figure 11. Profile of a circular object.
(Left) Displayed in scale; (Right) Displayed with the deviation from the nominal amplified.

CONCLUSION

The Phase I project has been carried out in accordance to the proposed tasks, schedule and budget. We conclude that:

- The technical objectives of the Phase I project were met or exceeded;
- The feasibility of the technical approaches has been proven; and
- The market interest has been confirmed.

Although the baseline technology was proved to be technologically feasible, its commercial viability requires additional work to make the CORE technologies more comprehensive and more beneficial in broader applications. The following needs were identified during the Phase I work and interactions with the potential customers.

- *Integration of the 3D profiling and imaging-based surface condition monitoring.*

  The Phase I test unit successfully demonstrated the 3D profile measurement capability on an object of a complex geometry with loose motion control and in a harsh environment. Additional in-line surface information may be beneficial. There is a need to integrate the 3D profiling capability with an imaging-based visual inspection. Although the imaging-based visual inspection technology has been available for many years, there will be challenges in the integration, such as avoiding cross interference between the two optical modules. The integration will bring the rail rolling into a total control for geometry and surface quality.

- *Development of metamodeling with a multi-stage process.*

  Hot rolling is a multi-stage process. Although the Phase I has demonstrated the effectiveness of metamodels for the finishing rolling, there is a need to model the entire rolling strand for issues such as the "batch variation" illustrated in Figure 9. There are several challenges. As an example, it is difficult to find two steel mills with exactly the same layout. That is, the modeling shall be modular, and be arranged by cascading of independent machine/process models. Furthermore, the cascaded metamodels may have to remain reversible if the metamodels are to be used in processing monitoring and root cause analysis. Yet, the benefit of having such modeling capability is obvious, as demonstrated in the Phase I.

- *Development of a data processing scheme for user interface.*

  As the in-line data can be reliably available, the need is to have a good presentation of the information to the users. There is a need to design the data structure for efficient storage, management, query and analysis. Furthermore, there should be meaningful indexes derived from the data, or from the metamodels using the data, that reflect the process and product conditions. There could be real-time display, monitoring, and thresholding for alarm, as well as statistical analysis.

- *Development of advanced process control scheme for root cause analysis.*

  As demonstrated in the Phase I, some issues, such as the cyclic variation within a rail, can be easily analyzed for their root causes. However, there could be issues, such as the batch variations, that are resulted from one or more of the manufacturing stages in the rolling strand. In addition to the need of modeling the multi-stage process, there is a need to identify the actual root cause, among the possible sources, based on the models and the data. At least there shall be a rank of the likelihood among the possible sources. This is especially true if the metamodel(s) are not reversible.

The R&D team plans to submit a Phase II proposal based on the above-identified tasks, for the further development of the CORE technologies.