Digital Solutions for the Hot Strip Mill: Leveraging Industry 4.0

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST’s strategy to become the epicenter for steel’s digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

In today’s rapidly changing and competitive steel industry, producing consistent and high-quality products while reducing energy consumption and carbon footprint is a complex challenge. To add to the pressure, the industry must also remain nimble in the face of hectic market conditions and shifting workforce dynamics, all while tracking progress toward sustainability goals. Cyberphysical systems (CPS), digital twins and other digital solutions have emerged as valuable tools for navigating these challenges and reducing risks, while increasing the chances of success. These concepts are fundamental to the ideas expressed in Connected Industries, Industry 4.0 and the Industrial Internet Consortium (IIC). This article will examine the digital solutions that are being used in the hot strip mill. It will also explore the building blocks behind mill simulation technology and how they, combined with the significantly reduced cost and increased performance of sensors and computers, have become the basis for modern digital twins for the hot strip mill.

Brief History of Hot Strip Mill Automation

Before the 1990s, the main requirement for a metal rolling plant was to maintain operational productivity with high product quality for various steel products produced in diminishing batch sizes due to the just-in-time procurement practices of downstream customers. Beginning in the 1990s, steel producers were

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also burdened with additional demands for increased energy efficiency and profitability. In the 2000s, the challenges facing the steel industry increased further with the growing demand for specialty-grade steels produced to exact tolerances. In each era, steel producers overcame the new challenges presented to the industry with the higher speeds and accuracies provided by adopting the latest control and automation technologies. These new technologies leveraged the speed, quantity, and variety of data made available by ever-increasing computing power to build and analyze system models of production equipment, operating practices, and rolling processes to improve the speed and accuracy of process automation.

Procedural problem-solving approaches were developed and applied that created solutions to specific problems. These solutions were then applied in real time by the control system. However, in recent years, the rolling process has become more complicated and accurate modeling of the process has become increasingly difficult. If the process cannot be modeled for all conditions of line operation, and for all product types, situations will exist where the control system cannot be relied on to provide proper operation. In these situations, proper line operation becomes dependent upon the experience and skill of human operators or on control engineers constantly adjusting the tuning parameters of mill setup models. To meet this challenge, it is necessary to employ more advanced models built on big data and analytics technologies, the Industrial Internet of Things (IIoT), and machine learning/artificial intelligence (ML/AI).

Leveraging Digital Solutions to Optimize Hot Strip Mill Operations
Illustrated by the examples listed in this section, although not new in terms of control systems, the rise of digitalization has led to a shift toward predictive analytics and a broadening of optimization goals. To ensure accurate predictions and measurement of more complex performance metrics, a wealth of data is needed, including information from level 2 systems, laboratory testing, sensors and IoT devices. When implemented alongside automation and optimization best practices, digital solutions can have a profound impact on optimizing plant operations in key areas such as productivity, sustainability, quality and maintainability, as shown in Fig. 2.

- **Sustainability**: Optimized energy management is essential for the steel plant to maintain its energy efficiency and work toward a more sustainable future. However, achieving this can be a challenging task due to the complexity of the production process. IoT-enabled sensors and devices can be employed to monitor hot strip mill production processes and provide real-time data on various aspects of energy consumption. An energy consumption and prediction system can help factories optimize their energy usage by accurately predicting energy consumption and identifying areas for improvement, thereby improving energy efficiency and improving control over energy costs. Furthermore, this technology can contribute to reducing the factory’s environmental impact, helping to build a greener future for all. By embracing sustainable energy management practices, factories can become more environmentally conscious and play their part in creating a more sustainable world.

- **Maintainability**: Maintaining the rolling equipment is essential to minimize downtime and prevent productivity losses. Early detection of
anomalies in the rolling process is critical for scheduling maintenance and avoiding costly equipment breakdowns. However, due to the vast amount of data generated by the equipment and control system, it’s challenging for human operators to detect all relevant signals. Therefore, collecting signals from the process, equipment sensors, and control system that correlate to specific mechanical, operational or control system problems is necessary.

- Quality: In a rolling process, the causes of product quality problems are by mechanical, operational or control system problems. It is well known from experience that a specific mechanical (or operation or control) problem can create a product quality defect. Users can potentially detect these unique signal patterns and investigate the causes. However, it generally takes a long time for human analysts to uncover causal relationships and find the root cause of a problem, even if a unique rolling signal pattern is detected. To assist the decision-makers, intelligent interpretation of data is essential.

- Productivity: Reducing unplanned stoppages with a predictive maintenance program increases the overall productivity of a plant. Effective strategies also include reducing or eliminating inefficiencies of material flow during rolling, “ghost rolling” to verify operation after a downturn or prior to introducing a new product, as well as simulation or shadowing of the running mill before introducing changes to control algorithms or equipment.

Digital Solution Application Examples

Intelligent Energy Savings
For the purposes of this article, energy-saving solutions applied to various steel facilities and processes can be considered in four classes. These are illustrated on the lefthand side of Fig. 3. The first class involves supplying basic packages with high-efficiency equipment and energy control with a feedback loop. The second class is an intelligent energy-saving method that leverages predictive information from other functions, such as hot strip mill models and controllers. The third class is another form of intelligent method that seeks to optimize energy use on a larger scale. Finally, the fourth class is focused on electricity management for the plant and utilizes predictive information.

For classes 2, 3 and 4, predictive control is essential for achieving greater energy savings. Fig. 3 illustrates the relationship between the hierarchy of automation systems in rolling mills and the energy solution classes. It is important to note that this hierarchy exists not only in rolling mills but also in other types of plants. The level 3 system manages production and products to meet customer requests, while computers in the level 2 system receive production schedules and product specifications from the level 3 system and provide setup commands to the level 1 controllers. Sometimes, the control functions are implemented in level 2 computers. The level 1 controllers are responsible for dynamic control of the entire length of products to maintain target quality and stable operation. Level 0 consists of motors, drive units and hydraulic systems that directly actuate equipment in the rolling mills to follow given commands by the level 1 controllers.

In general, upper-level systems have access to more information that can be used for prediction than lower levels, as shown in Fig. 3. For example, level 2 computers have access to the next several slabs’ information, including chemical composition, size and temperature, and upper-level systems know the product targets. Using this information, the setup function in level 2 computers calculates how the targets will be achieved. Predictions of torque for rolling, strip speed changes and the quantity of water for strip cooling are made in the setup functions. While level 1 functions can obtain this information from level 2, they mainly
use simpler methods such as feedback control and sequential procedures to calculate manipulation values.

“Intelligent Energy Saving Control” is defined as the energy-saving control that uses predictive information from upper-level systems. The control methods of classes 3 and 4 use predictive information to manage and optimize electricity, production, and product qualities. Therefore, classes 2, 3 and 4 can be considered intelligent methods in a broader sense.

Managing Energy Consumption in Rolling With Control Parameter Optimization
The energy optimization system is an example of a digital solution that addresses sustainability and energy savings. Even small optimizations can contribute to overall energy savings. Fig. 4 shows the configuration of the energy optimization system for the hot strip mill (HSM), which aims to find the optimum setup for the operators or the level 1 control to use.

The system uses Product Data Input (PDI) data sent down from the level 3 system to provide the initial calculation of the dynamic control and rolling model setups for the mill. The Energy Consumption Prediction System (ECPS) projects the total energy required to roll the material based on the input from the model’s setup, while the Material Properties Prediction System (MMPS) calculates the strength and elongation of the material. These calculations form an iterative loop between the setup models, energy prediction system and material properties prediction to arrive at an optimal value.3

The results are then either sent to the level 1 controller or provided as information to operators. The energy consumption prediction system calculates the energy used to roll the product when the slab is in the reheating furnace, after all setup calculations have been made. At the same time, the material properties are calculated and optimized. This information allows the operator and engineer to check the energy usage for rolling the coil.

Energy Optimization for a Steel Plant
Energy savings are crucial for the efficient operation of a steel plant to reduce costs and meet ESG targets. One effective way to do this is by keeping peak electric energy levels under a certain threshold. By doing so, the capacity of equipment and contract electricity demand can be reduced, thereby avoiding costly penalties that electric power consumers must pay when their electricity use exceeds the contracted amount.

Hot strip mills and plate mills are challenging production lines from an electrical supply perspective, as their electricity demand varies significantly between periods of rolling and periods of idle operation. However, these production lines can also present opportunities for energy savings and peak demand reduction. To address this issue, an electrical prediction and control system can be implemented, as illustrated in Fig. 5.

The prediction system (shown on the left side) includes two key components: the ECPS, which predicts the electric power to be used, and a rolling timing prediction function. The control system (shown on the right side) includes a load-leveling function that can utilize batteries or production rescheduling to reduce peak electrical demand.3

Currently, the prediction system can predict electricity demand up to 30 minutes in advance,3 providing operators and engineers with the information they need to make informed decisions to reduce electricity consumption. Interventions may include reducing operation speed or increasing idle time to avoid exceeding the peak electric energy threshold. By optimizing energy consumption, steel plants can reduce costs and improve their overall efficiency.

Benefits of a Hot Strip Mill Digital Twin
It is safe to say that all contemporary rolling mills make use of various types of digital processors and software that monitor, mimic and interact with the physical system. When all such processing is consolidated into the same digital solution, the resulting “twin” has additional benefits within the optimization target areas described earlier.

• Sustainability — Model energy consumption in what-if simulation exercises to select optimum motor sizes.4
• Maintainability — Ghost rolling reduces risk of equipment damage when new products are introduced.

• Quality — Ensure reliable and timely application of product references for the correct piece of material.

• Productivity — Increase material flow while managing collision avoidance.

A digital twin is a virtual representation of a physical object, system or process that allows for real-time monitoring, simulation, and analysis of its performance and behavior. Interestingly, much is made of the digital twin concept as a novel approach sprung from Industry 4.0, but those who have worked in the metal rolling industry will recognize characteristics of digital twins as they have existed in metals production lines for decades. Computerized material tracking and flow control, ghost rolling, and simulation are not new. In many mills, these multiple capabilities are supported by a single software system solution which may be considered a digital twin that pre-dates Industry 4.0. Applying recent advances in computing and network technologies to such a system presents a simple path toward realizing the promise of Industry 4.0 digital twins.

For example, a level 2–based transport director is a consolidated rolling mill twin that supports the following activities.

• High production rolling:
  • Precise material head and tail tracking by intelligently combining multiple inputs (speeds, metal presence, etc.).
  • Active control flow (table speeds and direction) for anti-collision in reversing mills and plate mills.

Figure 5

Energy optimization with prediction for a steel plant.\(^3\)

Figure 6

Transport director/digital twin for hot strip mill transport and rolling execution system.
• Just-in-time reference distribution to level 1 for each mill stand or area.
• Resilience in case of sensor failures as it automatically detects and simulates the sensor to continue level 2 and level 1 processing.
• Self-tuning algorithm based on “perfect sensors.”
• Ghost rolling:
  • Simulate rolling a scheduled product according to the actual mill configuration.
  • Operators verify anticipated level 2, level 1 and mill equipment behavior in real time.
  • Automatically simulate head and tail tracking events and send references to level 1.
• Off-line simulation:
  • Same twin can be “untethered” from the production system and provide a platform which is identical to the actual mill.
  • Conduct what-if scenarios to investigate new products and energy demands under various rolling conditions.
• Mill shadowing.
• As a “read-only listener” of actual mill activity, provide a more rigorous test of models prior to deployment on the production system.

Advantages of the Transport Director Approach
Using a transport director–based digital twin provides precise tracking and timing capabilities during production, which allows for tighter gaps between products and more productivity from the mill. Simulation capabilities allow for testing and verification of mill behavior in advance, which reduces the risk of unplanned downtime. Realistic testing of the complete system before it leaves the automation vendor and integrated simulation of the mill on-site reduces commissioning time and risks and provides a valuable tool for ongoing system support throughout the life of the system.

Opportunities for Expansion of Transport Director Digital Twin
Leveraging the latest technology and Industry 4.0 techniques and a transport director implemented with a flexible, configurable level 2 platform facilitates the addition of ML/AI analytics for modification of production system parameters, integrated VR visualizations with real-time information for operators, and higher fidelity monitoring and prediction of wear or damage to rolls and equipment.

Anomaly Diagnosis System of Equipment and Rolling
The Anomaly Diagnosis System of Equipment and Rolling monitors the rolling process by collecting signals from various sources such as the equipment sensors, process and control system. The system analyzes equipment parameters, including rolling force, motor current, strip tension, line speed, and other relevant data to identify anomalies and their symptoms in equipment and rolling. With this system, engineers can quickly identify specific mechanical, operational or control system problems that would be difficult or impossible for humans to detect due to the sheer volume of signals in an operating plant.

Continuous monitoring of equipment and rolling health conditions using the Anomaly Diagnosis System of Equipment is a critical step toward addressing maintenance key performance indicators. This digital solution helps prevent unplanned line stops, equipment breakages and defective products, thereby contributing to the efficient maintenance of line equipment. In addition, it increases the probability of avoiding these problems and contributes to efficient maintenance of line equipment. The system provides engineers with information to investigate the location and causes of anomalies, which aids in identifying potential problems and implementing measures to avoid them.
Digital Transformations

Process data of rolling mills, such as roll force, motor torque and motor current, etc., are collected and stored by IoT Edge Database. The anomaly detection function monitors the status and change in the equipment data of rolling mills and detects the failure of mills. An example of condition monitoring is shown in Fig. 8. The general flow of condition monitoring starts with collecting data, such as mill roll force and motor current, during hot strip mill rolling. The collected data is then processed to identify attributes, including equipment, item number, absolute and deviation. The processed data is analyzed using various techniques, such as basic statistics, probability density, autoregressive models and fast Fourier transform. Tools such as the Hotelling Index and T-squared distribution, control chart with skewness compensation, and threshold are used to make judgments based on the analyzed data. The final step involves diagnosing the issue, providing the reasons for failure or likely causes and then recommendations for treatment or countermeasures.

Anomaly Analysis System of Product Quality

The Anomaly Analysis System of Product Quality is designed to identify causes of product quality problems in a rolling process, which can be attributed to mechanical, operational or control system issues. Although these are common root causes of product defects, identifying the specific root cause is often difficult and resource consuming. Users can detect unique signal patterns that may indicate the underlying causes of these issues. It often takes a significant amount of time for human analysts to investigate these patterns and identify the root cause of the problem, even for experienced users. To aid decision-makers, it is crucial to have an intelligent interpretation of data.

The anomaly analysis system uses automatic clustering techniques for abnormality detection and analysis of product quality. By analyzing data related to coil parameters and rolling conditions, the system can quickly identify and distinguish “something different” and “unique patterns.” This allows for the rapid detection of issues and speeds up finding the root cause of problems, enabling faster resolution of product quality problems.

Two approaches are the following:

1. Anomaly Analysis of Product Quality: This feature provides users with detailed quality analysis information, such as tolerance classification, trend chart clustering, correlation of quality parameters and identification of potential causes of quality problems. By leveraging these capabilities, users can take the necessary next steps in root-cause analysis of quality issues.

2. Clustering Analysis of Quality Charts: Anomaly Analysis System of Product Quality automatically classifies the quality charts of all coils by capturing waveform characteristics. This feature records the common causes of defects and rolling conditions for each classified group, enabling users to quickly identify and address issues.

By providing in-depth quality information and insights, Anomaly Analysis System of Product Quality empowers users to identify quality issues faster and with greater accuracy. With these features, users can take proactive measures to improve product quality and minimize risks, leading to better business outcomes.

Sample Analysis

Fig. 9 illustrates clustered examples of strip width data. Using the original data set of width deviation from the target (which consists of approximately 730 coils), the tool clusters the typical change pattern for the head, body, tail and the entire part. This example automatically clusters 12 typical behavior patterns, dividing and classifying the original data into 12 different patterns. Users can pre-select the number of patterns in the cluster.

In the graphs, the y-axis represents the width deviation and the x-axis shows the normalized length. For example, in the upper-left frame, a red-lined category of charts of 128 coils shows that many coils have similar behavior of width deviation where the head part gets wider than the target. By reviewing the categorized results for the body part, the user can identify the majority of fluctuations, such as skid marks or tapered width. This information helps the user to identify effective methods to improve width accuracy, such as tuning short stroke control at the head part.
Moreover, a coil list is generated that includes the category number and other information such as the steel grade, product thickness and width. This list allows users to identify what products display similar behavior of width deviation.

The fluctuation pattern analysis function is a valuable tool for quickly identifying common patterns in product quality data. When reviewing product quality data over a long period, it can be a tedious and time-consuming task for the user to manually review sampling chart data coil by coil and identify fluctuation patterns. However, this function automatically identifies typical patterns of fluctuation and anomalies, reducing the user’s workload in identifying and addressing these issues. Additionally, this function can also examine other quality issues, such as thickness and temperature, providing a comprehensive analysis of product quality data.

Conclusions

The steel industry faces pressure for sometimes conflicting priorities to produce consistent and high quality across an ever-changing and expanding range of products, be nimble in the face of changing market conditions, reduce energy consumption and carbon footprint, all while tracking and reporting on progress toward these goals. Successfully navigating these complex and intertwined challenges, especially in real time, is not intuitive or straightforward, so the benefits of cyberphysical systems, digital twins and digital solutions that reduce the risk and increase the chances of success are greater than ever. These benefits, when combined with the drastically decreased cost and increased performance of sensors and computers, are driving adoption across industries. This article provided some real-world examples of how these approaches can provide benefits in hot strip mill applications.

With practical, proven applications and the increasing relevant experience within the industry, hype and buzzwords around digitalization have transformed into fit-for-purpose solutions and real results. It is even becoming difficult in some cases to drive further improvement in sustainability, maintainability, quality, and productivity without adopting digital solutions that include modeling, simulation, predictive analytics and widespread connectivity.

References