In the hot processing of steel to a formed product, the reheat furnace performs the function of raising the steel from the charge temperature to a discharge temperature suitable for rolling. Not only must the discharge temperature be in the correct range, but temperature differentials within the heated steel must be minimized. It is difficult to precisely manage this heating process since there is no way to obtain this information through direct measurement.

To solve this problem, level 2 reheat furnace control systems have been developed that include mathematical modeling of heat transfer. These models calculate the temperature of the steel, usually in multidimensional matrices so that bulk temperature as well as temperature distribution can be evaluated. Tenova Core has developed such a thermal model, and its accuracy has been tested and confirmed in many applications involving the capture of thermocouple-measured temperatures of steel concurrently with model-calculated temperatures.

Steel Temperature Calculation Using Heat Transfer Modeling

— In a reheat furnace, there are the three modes of heat transfer which must be considered when doing thermal modeling: radiation, conduction and convection.

Radiation heat transfer is from a hot source to a cold object. Heat radiates from the hotter burner flames and refractory to the colder steel billets. Heat also radiates to the billet from the billets on either side. The amount of radiation that can be absorbed by an object depends on the surface emissivity.

Conduction heat transfer occurs through a material. Heat flows from the hotter nodes to colder nodes. Steel in contact with colder beams will lose heat via conduction.

Convection heat transfer occurs when gases or liquids move past objects at different temperatures. The flow of waste gases through the furnace transfer heat to the steel billets via convection.

The Tenova Core thermal model configured for a furnace heating billets takes the billet cross-section and...
divides it into a two-dimensional matrix. Each element of the matrix is called a node. The top and bottom nodes receive radiant and convective heat transfer from the furnace. The side nodes receive similar heating from the furnace, affected by adjacent billets. The corner nodes receive combined radiation heat from the surface and the side. The internal nodes receive heat via conduction only from the adjacent nodes.

Figure 2 illustrates the heat transfer flow.

The steel heating is dynamically simulated by the on-line two-dimensional mathematical model, which calculates the temperatures through the cross-section of the product as it moves along the length of the furnace. This temperature distribution is obtained by solving a system of Fourier differential equations for heat conduction.

The heat exchange between the furnace and the steel billets is calculated for each piece as a function of the furnace enclosure temperature and the piece temperature itself. This model analytically considers all heat and mass transport phenomena among the various elements of the furnace (charge, walls, roof, hearth, burners and gases).

At each calculation time interval, the model determines how much heat has entered the pieces since the previous calculation cycle. The temperature of each piece is derived from its position and furnace temperatures.
The principal purpose of mathematical modeling by the level 2 control system is to determine the temperature of each billet in the reheat furnace. This important and valuable information, the temperature data, as well as oxidation and decarburization information which can be calculated with knowledge of the steel temperature, is typically saved for later reporting and analysis.

**Determination of the Furnace Temperature Profile** — The model uses the readings from the thermocouples along the length of the furnace to construct the furnace temperature profile. The temperature in the furnace determines the amount of heat exchange between the furnace environment and the steel being heated. Therefore, a “furnace temperature” profile is found for entire length of the furnace.

The characteristics necessary for determining the heating profile of each piece are the following:

- Piece dimensions.
- Steel grade of the piece.
- Charge temperature of the piece.
- Position of the piece in the furnace.
- Temperature distribution within the piece, which is determined in the preceding calculation cycle.
- Temperature of the furnace at the mean position of the product over the last cycle.

Using the chemical composition of the steel, the mathematical model determines the following steel characteristics:

- Density.
- Emissivity.
- Temperature-dependent thermal conductivity.
- Temperature-dependent enthalpy.

Using these data, the mathematical model calculates the temperature of each piece in the furnace using a two-dimensional matrix in real time.

**Furnace Heating Control** — The primary function of the reheat furnace level 2 control system is to control optimum furnace zone temperature setpoints based on the following primary control objectives:

- Provide properly heated steel at the discharge end of the furnace to meet the mill requirements.
- Operate the furnace in an efficient manner, minimizing specific fuel consumption and the oxidation and decarburization of the steel.

Other functions of the level 2 control system typically include:

- Providing a real-time map of the furnace contents.
- Providing real-time information about the thermal conditions inside the furnace.
- Data archiving and reporting.
- Alarm and event generation and logging.
- Data communication with other systems.
- Oxidation and decarburization calculation.

**Model Predictive Control**

Model-based predictive control (MPC) has been used for more than 20 years in a variety of industries. MPC algorithms are based on developing empirical process response models that can, in real time, predict the future state of the process variable. Based on this prediction, the model can then calculate the optimal control moves to make, so as to minimize the square of the error over the prediction horizon. When an MPC algorithm can also evaluate its model in real time and adjust the model and control parameters, it is called an adaptive MPC algorithm. Adaptive Resources has deployed its QuickStudy™ adaptive MPC technology in hundreds of applications.

Each adaptive MPC controller block is designed to be a multiple-in-single-out (MISO) block and takes in one process variable, controls one manipulated variable, and can manage up to 14 disturbance variables. These blocks can then be further connected together to create even more complex multiple-in-multiple-out (MIMO) or matrix control strategies.

**Adaptive Control** — In recent years, there has been an extensive and growing interest in feedback control systems, which automatically adjust their controller settings to compensate for changes in the process or the environments.

In adaptive control, the relation of the input (manipulated variable) $U$ and the output (process variable) $Y$ is modeled by the regression model (Equation 1):

$$
Y(k) = \sum A_i \cdot Y(k-i) + \sum B_i \cdot U(k-i - td) + e
$$

$$
A = 1 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2} + \cdots + a_n \cdot z^{-n}
$$

$$
B = b_0 + b_1 \cdot z^{-1} + \cdots + b_m \cdot z^{-m}
$$

(Eq. 1)

where

e is the “white noise” and
unknown polynomial coefficients $A_i$ and $B_i$ are identified in real time by recursive least square method.
The model transfer function can be expressed as:

$$G(z) = \frac{B(z)}{A(z)}$$

(Eq. 2)

To be able to predict and/or control the output $Y$, the conditional probability density functions with boundary conditions are employed. The theory of the Bayesian system classification has appeared to be a suitable tool to solve this class of problems. This approach also yields stability and robustness with respect to unmodeled terms, and it has good disturbance rejection properties.

A control algorithm is, as a rule, only a small part of software ensuring the digital control. The dominating part is computer activity associated with data management. The choice of sampling rate becomes an integral part of the control design because it heavily influences the discrete output signal to be processed. Very fast sampling makes it possible to observe high-frequency disturbances and the optimal controller tries to eliminate them, sometimes uselessly or even harmfully complicating its function. On the other hand, very slow sampling may bring too little information, and the control quality decreases. The period should be selected as small as possible. However, in practice, other factors must also be taken into consideration when choosing the sampling period, such as process dynamics (dominant time constants of the controlled process), the spectrum of the disturbances and the computational requirements.

**Important Modeling Considerations** — The validity and accuracy of the models identified depends on the accuracy of the data being submitted for modeling. Process knowledge is important in order to specify the correct modeling parameters.

The first step toward model identification is analyzing the process. This includes identifying all the variables that may have an effect on the desired controlled variable (process variable). This includes, as a minimum, the manipulated variable. This may also include estimating the transportation delays for the manipulated/disturbance variables and determining the gain sign if possible.

The sampling period determines the span over which models are identified. It is imperative that the model sampling or execution period be based on the process time constant. As a rule of thumb, the model execution period should be selected such that the model-controller can execute 5–10 times within one time constant. This allows for the controller to be able to modify the process behavior using optimal control trajectories.

**Key Model Parameters** — Key parameters used in modeling include the following:

- **Gain Sign** — If a change in the manipulated variable or disturbance variable results in an increase in the process variable, the gain sign between those variables is considered to be positive. Conversely, if the change results in a decrease in the process variable, the gain sign is negative. If the gain signs between the manipulated variable and disturbance variables to the controlled variable are known, the model identified may be improved by constraining the gain signs.

- **Time Constant** — Time constant is defined as the time it takes for the process to reach 63.2% of its final value once it starts to respond to a change in the manipulated or disturbance variable. This does not include the transportation delay (dead time).

- **Transportation Delay** — Transportation delay is the amount of time it takes for the process variable to start responding to a change in the manipulated or disturbance variable. The transportation delay for different variables for the same process variable may be different. This value is specified in units of sampling period. Transportation delay is
the most important parameter used by the modeling algorithm in identifying models. The modeling algorithm may suggest the transportation delays based on the coefficient threshold. Starting with the transportation delay specified by the user, the modeling algorithm computes the polynomial equation for each variable and discards the smaller coefficients, considering these as transportation delays.

**Reviewing Models** — Open-loop simulation is the single most important mechanism for testing the validity of the model. The Adaptive Resources tool provides the capabilities to create and validate models off-line using historical data. As a rule, the model is tested on at least one dataset that has not been used to create the model, so as to test its validity against unseen data. When analyzing the simulation plot, the following key parameters are noted to determine validity of the model:

- **Phase** — The phase of the predicted PV is to be in phase with the phase of the actual process. This means the rise and fall of the predicted PV should occur at the same time as the actual PV.
- **Gain** — The peak-to-peak gain of the predicted PV should be close to the peak-to-peak gain of the actual PV. There may be a DC offset between the predicted PV and the actual PV, which could be a result of external unmeasured disturbances and may be ignored.
- **Process Direction** — The process direction (i.e., rise and fall) of the predicted PV should be the same as the actual PV.
- **Prediction Horizon** — It should be noted that the prediction may start degrading over longer horizons due to drifts in the actual process and due to the influence of external unmeasured disturbances. If the prediction is good for a reasonable number of sampling periods from the start of open-loop simulation, the prediction may be deemed sufficiently accurate and the model may be considered valid.

**Project Implementation**

The capabilities of steel temperature determination by on-line thermal modeling and the use of an Adaptive Resources’ adaptive process controller (APC) control algorithm were combined to create an effective level 2 control system for the bar mill reheating furnace at the Gerdau facility in Midlothian, Texas, USA.

The control system, based on the combined technologies, was implemented to minimize process variability and respond rapidly to disturbances in the process to achieve the desired goals.

The level 2 software was deployed on a Dell server computer, specified by Gerdau, running the Microsoft Windows server operating system.

**The Furnace** — The bar mill furnace is a walking beam type with a design capacity of 120 tons/hour. This furnace is divided into seven combustion control zones:

1. Preheat top.
2. Preheat bottom.
3. Heat top.
4. Soak top left.
5. Soak top right.
6. Soak bottom left.
7. Soak bottom right.

The control considers the furnace to be divided into three computer control zones along its length:

1. Preheat.

**System Aims** — The new level 2 control system was designed to achieve the following goals:

- Heat the charged steel according to the “optimum cycle” predetermined for each type of material. This is accomplished for the complete range of furnace production rates, including transitions and delays.
- Improve accuracy of controlling the heat supply to the regulation zones due to knowledge of the actual temperatures of the steel.
- Decrease furnace fuel consumption through better regulation.
- Substantially improve control of discharge temperature.
- Reduce scale formation and decarburization of the final product.

**Overview of Control Strategy** — The level 2 control system consists of three different applications. Tenova Core’s on-line thermal model keeps track of billets inside the furnace, calculates product temperatures and generates steel temperature setpoints. The model also
makes available the heating record for each piece, including the temperature distribution and average temperature. An OPC server (KepServerEX) is used to store information in the bar mill reheat PLC controller. Adaptive Resources’ APC reads the information generated by Tenova Core’s model to compare and optimize the steel temperatures. It then modifies the zone temperature setpoints for the furnace to achieve desired steel temperatures.

All seven zones in the furnace are controlled by the APC when level 2 is active. The zone setpoints and actual temperatures are generated by Tenova Core’s thermal model. They are then transmitted into the APC application. The application consists of cascaded control loops for the steel temperature and zone temperature controls. There is a steel temperature controller for each control zone (preheat, heat and soak) based on the furnace temperature model, which generates zone temperature control setpoints for each zone. Bumpless transfer between both systems is achieved by using the tieback feature on both controllers. Figure 7 depicts the control overview for zone 4 in the soak area of the furnace.

**Furnace Control Zone Setpoint Control** — The system determines the control zone setpoints for optimum thermal regulation of the furnace. This is achieved by first determining the optimum steel temperature profile in the furnace, comparing it to the actual steel temperature profile from the mathematical model, and making setpoint adjustments to minimize or eliminate discrepancies between the actual and optimum curves.

Under level 2 heating control, the steel heating curve determines the target temperatures that will bring the steel to the proper discharge temperature with the minimum amount of fuel consumption. This is achieved with consideration of the particular product mix, grades of steel and desired discharge temperature.

The model-based APC determines the control zone setpoints for optimum thermal regulation of the furnace. This is achieved by first determining the optimum steel temperature profile (SP) in the furnace for the specific product, grade and desired discharge temperature. The furnace model calculates the actual steel temperatures (PV) and the optimum steel temperatures (SP). The adaptive controller adjusts the zone setpoints so as to eliminate any discrepancy between the actual and desired thermal state of the charge. The adjustment in setpoints is made considering the following:

- Planned production rate.
- Scheduled and unscheduled delays.
- Actual production rate.
- Actual steel temperatures.
- Desired steel temperatures.
- Maximum safe furnace temperature ramps.

It also considers the state of the other disturbance variables (DVs) affecting the specific zone (i.e., temperatures of zones adjacent to the specific controlled zone, production rate, product speed, time, etc.). Using this information, the controller writes zone-specific setpoints to the Level 1 controller to eliminate any discrepancy between the actual and optimum curves.

The setpoints assure neither overheated nor underheated pieces while maximizing furnace efficiency. Due to the fact that this is a completely on-line, real-time system, it responds very quickly to any changes in the operating conditions and adjusts the furnace input with great accuracy and efficiency.

By the suitable regulation and control of the setpoints to the control zones, it is possible to carry out piece heating according to many different heating strategies. The problem is in the selection of the optimum steel heating curve from the many possibilities.

Assuming, for simplicity, that the only important aspect — from the standpoint of optimum thermal
management of the furnace while complying with the constraints imposed — is to minimize fuel consumption, the desired strategy is to hold the steel temperatures throughout the furnace at values as low as possible while still being consistent with the desired steel heating quality at the furnace discharge.

Operating in this way, the geometrical center of heat input along the length of the furnace will be moved toward the discharging end of the furnace with a consequently better utilization of the gas sensible heat, and ultimately, a minimized fuel consumption.

Moreover, this type of practice minimizes all of those undesired metallurgical phenomena whose kinetics are strongly influenced by long periods of time at high temperature (e.g., decarburization and oxidation). In addition to this, it assures a heating profile with minimum temperature gradients (both with regard to space and time) between the temperatures of the charge. This reduces the stresses induced by the internal temperature gradients. Therefore, it is true that, in most cases, minimizing the undesired metallurgical phenomena and losses due to oxidation is achieved by the same technique used for minimizing specific fuel consumption.

Results

Upon the completion of the installation, commissioning and tuning exercises, the new level 2 control system’s performance was measured against the system aims, as previously described.

Optimum Cycle Heating — The first criterion was for the new control system to deliver optimally heated steel. This involves basing the product heating curve on the specific billet size, grade, discharge temperature requirement and furnace/mill pacing. It also requires recognition of transitions in the product mix charged to the furnace, as well as accounting for both scheduled and unscheduled delays.

This aim was achieved using the technology available in conventional level 2 control systems, in which heating curves are tuned and optimized to cover the broad range of production parameters expected to be encountered. Scheduled and unscheduled delays are managed to reduce energy consumption, scale formation and decarburization, and to deliver properly heated steel when production resumes.

Improved Zone Control Accuracy — By utilizing the model-based predictive control algorithm, a higher level of zone control accuracy was achieved. Conventional PID-based control loops receive dynamic zone temperature setpoints as the level 2 provides updates to the level 1 controller. In this new system, zone temperature regulation has proved to become much more accurate. To achieve this, the new system takes into account the impact of all the disturbance variables that could affect the zone temperature. So, with a statistical understanding of parameters — such as steel temperatures, pacing, adjacent zone firing rates and temperatures, and the unique thermal inertia of each control zone — the specific zone firing levels can be specified, as opposed to merely a zone temperature setpoint. The result of this is a predictive system, where the zone firing rates are adjusted during both periods of steady temperature control and periods of temperature transitions.

The improved zone control was made apparent by examining the billet discharge temperatures, which proved to be more consistent, as will be discussed below in the Improved Discharge Temperature Control section.

Decreased Fuel Consumption — The most common performance criterion used to evaluate the success of a new level 2 control system is the energy savings, as measured by the decrease in fuel consumption per unit of steel heated. The fuel savings are achieved through two process control improvement areas: steady-state production and transient production.

Steady-state production energy savings are delivered by having the control system optimize the product heating cycle and discharge temperature control. The optimum heating cycle is based on heating the product as late in the furnace as possible. As the furnace control system recognizes the interactions between the steel and the zone conditions, the specific heating curve required for each specific billet at the specific furnace pace can be better controlled. Again, the predictive element of this new level 2 control system allows for closer coordination of heating practices.

The other improvement in steady-state heating performance comes in being able to better control the consistency of billet discharge temperatures. Typical process control establishes a target temperature with tolerances above and below the target. Due to a normal amount of variability in the control, billet target discharge temperatures are set slightly higher than necessary, so that deviations to the low end of the control spectrum can still be rolled. With this new system, the Gerdau reheat furnace was able to discharge billets with slightly lower target discharge temperatures, while having the confidence that the deviations to the low side are not as far out of specification as was previously expected. The result of lower billet target discharge temperatures is a reduction in fuel consumption.

Finally, in transient production, specifically during scheduled and unscheduled delays, level 2 control systems deliver energy savings by being able to better manage how quickly the furnace temperatures can be reduced. Unique to the predictive control algorithm is that the ramp-up in anticipation of a resumption of production can be better managed. With this newfound confidence, operators can be more aggressive in controlling temperature reductions during the delay period, thus resulting in decreased energy consumption.

The new level 2 control system at Gerdau was implemented to replace an already existing level 2 control system, yet still reduced energy consumption by approximately 3%.

Improved Discharge Temperature Control — The most significant result of the new level 2 control system was the noted improvement in the control of billet discharge temperatures. As was described previously, the bar-to-bar mill pyrometer temperature consistency was
better than anticipated. Prior to the implementation, over a six-day period of production, including product changes and delays, the mill pyrometer temperature deviation (actual minus target) had an average of +28.7°F and a standard deviation of 33.7°F. Once the new system was implemented, a comparable production dataset showed an average deviation of only 17.1°F, with a tighter standard deviation of 25.4°F. The results are plotted in histogram form, as shown in Figure 8.

**Reduced Scale Formation and Decarburization** — The final performance metric was reduced scale and decarburization. At the time of publishing, no explicit data was available to quantify the reduced scale and decarburization. However, with the optimization of heating curves that resulted in reduced discharge temperatures, coupled with improved delay management, it is a natural result to achieve improvements in these areas as well.

**Summary**
The first reheat furnace level 2 control system coupled with a model-based predictive control algorithm was implemented on Gerdau Midlothian, Texas, bar mill. The control system utilized leading-edge technology for thermal modeling and predictive control algorithms that accounted for the numerous complexities and influences of furnace control. As a result of this new system, the facility realized improved bar-to-bar temperature consistency, which has resulted in smoother furnace operation and reduced fuel consumption. The resulting improvement in process control performance suggests that the new level 2 control system has substantial realized and unrealized potential for operational benefits.

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The authors wish to thank Gerdau for the company’s continued interest in supporting this project work, for working to achieve the desired results and for providing the data in this report.

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**Figure 8**

(a) Mill pyrometer temperature distribution: (a) prior to new level 2 control system and (b) using new level 2 control system.
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