Special Section on Industrial Systems Control

Editor’s Note: The Guest Editor of this special section of the Magazine is Eugene King of Alcoa who is Chair of the IEEE Control Systems Society Technical Committee on Industrial Systems Control. Part of the technical committee activities is to help organize invited sessions each year at two meetings: the American Control Conference and the IEEE Conference on Decision and Control. Selected papers from the invited sessions can serve as the nucleus for a special edition of the Magazine. Gene helped organize an invited session at the 1987 American Control Conference and then served as Guest Editor, evaluating these candidate papers and others included here. We thank Gene for his efforts and look forward to additional special sections proposed by technical committees.

Application of Modern Control to a Continuous Anneal Line

Christopher D. Kelly, Dhani Watanapongse, and Kenneth M. Gaskey

ABSTRACT: This paper presents the development of a state-variable design approach to control strip temperature in a continuous anneal process producing a variety of high-strength low-alloy steels. In this process, a steel strip passes continuously through five consecutive heat-treating operations to achieve desired metallurgical properties for the automotive market. Each operation is controlled by an individual controller designed to maintain the tight strip temperatures required for the product mix. To achieve this goal, linear quadratic Gaussian control techniques were used to develop the control system.

Introduction

In the late 1970s, the Inland Steel Company recognized the increasing need in the marketplace for high-quality, high-strength steels, particularly in the automotive industry. Studies were conducted to develop the steel compositions and to establish the process for producing these high-strength steels. It was determined that the ability to manipulate and control the heating and cooling of a steel strip is an effective way of achieving a wide range of high-strength products with unique properties from a limited number of compositions. This effort culminated in September 1983, when a state-of-the-art continuous anneal line (CAL) was brought on stream at Inland [1].

The decision to apply modern control to the CAL was based on a belief that superior strip temperature control performance could be achieved. For a typical heating furnace control [2], when measurements deviate from the desired value, new steady-state set points are calculated from an implicit heat-transfer model using an iterative procedure. The control system’s response is inherently very slow due to a transport delay in strip temperature measurement and the need to wait for a new steady state to be reached before taking the next control actions. Using modern control, explicit linear equations represent the dynamics of the heating process, with a Kalman filter to predict strip temperatures in the furnace. This allows strip temperature deviations anywhere in the furnace to be predicted in real time and control actions taken even before the confirming measurement is made. Further, the multiple-input/multiple-output variables typically associated with a heat-treating process are systematically coordinated based on linear quadratic control design so as to yield the best possible control performance.

In this paper, the CAL process is described, the design of the strip temperature control system as applied to a furnace section of the CAL is presented, and performance of the control system is discussed.

Process Description

The CAL process is designed to produce steel strips with thicknesses ranging from 0.48 to 2.16 mm and widths from 610 to 1525 mm. The maximum line speed is 137 m/min and the maximum furnace capacity is 65 metric tons/h, with a yearly production rating of 363,000 metric tons. The line is designed to produce a diverse range of products with tensile strengths ranging from 275 to 1380 MPa.

The strip heat-treating units of CAL are the annealing furnace, water quench, and the aging furnace, as shown in Fig. 1. The annealing furnace has a preheat, heat, soak, and gas-jet cool section. The three sections of the aging furnace are reheat, overage, and fast cool. Strip temperature is measured by
infrared radiation pyrometers located at the exit of each section. Typical strip measurement cycles for the processing of high-strength and ultrahigh-strength products through the furnace sections are shown schematically in Fig. 2. Included in this figure are the design exit strip temperature tolerances, which must be maintained to achieve quality CAL products.

The objective of the process control system is to achieve and maintain the desired exit strip temperature tolerances, which must be maintained to achieve quality CAL products. The control system adjusts the zone temperatures of each section and the line speed on a continuous basis to assure that the strip is heated or cooled to the desired strip temperatures. (Zone temperature is an input for a second control that uses a thermocouple reading of zone temperature and the zone temperature set point to control fuel flow and airflow to obtain the desired zone temperature.) In addition, the transitions from coil to coil are controlled precisely to ensure that each coil is within its metallurgical aims. These functions are performed by the strip temperature control system (Fig. 3) using setup models, adaptive update models, transition strategy, and individual section controllers. The setup models are heat-transfer equations that determine the steady-state operating conditions needed to achieve the desired exit strip temperatures for each product. The adaptive update heat-transfer models use process measurements to establish update coefficients that correct the setup models to account for changes in furnace performance and strip surface condition. The transition strategy contains the logic that determines the timing for and adjustments to the line speed and furnace operating conditions required to minimize strip temperature variation during product size and product cycle changes. Individual section controllers, developed using modem control, establish the adjustments to the operating conditions to correct for process variations so that a tight control of strip temperature can be accomplished.

The individual section controllers are the elements of the strip temperature control system that utilize modem control. In order to provide an in-depth discussion of the theory, this paper will focus on the derivation and development of the heat section controller. The same methodology applies to the other section controllers.

### Process Model

The physical layout of the heat section is shown in Fig. 4. The steel strip travels a distance of 210 m, stays in the section 2–5 min, depending on line speed, and is heated to 600–800°C. The heat section has 10 furnace temperature control zones, with the temperature in each zone labeled $T_{zn}$ $(n = 1, 10)$. The strip travels within a control zone and between adjacent control zones. The strip is, therefore, affected by a given zone more than once during its travel in the heat section by traveling between heating tubes of the same zone or between the heating tubes of two different heating zones.

The thermal process in the heat section can be represented by a nonlinear heat-transfer equation describing the dynamic response of...
strip temperature so that the temporal change in heat energy at a particular location is equal to the transport heat energy plus the radiation heat energy, where \( c_s \) is the specific heat of steel, \( \rho \) the density of steel, \( v \) the strip velocity, \( TS \) the strip temperature, \( t \) the time, \( V \) the volume element (width \( \times \) gage \( \times \) node length), \( L \) the node length, \( A \) the radiation surface area (width \( \times \) node length), \( F \) the view factor, \( \sigma \) the Stefan-Boltzmann constant, \( e \) the emissivity of the steel, and \( TZ \) the zone temperature.

\[
dTS/dt = -udTS/dL + K(TZ^4 - TS^4)
\]

where \( K = (A\Phi c_s)/(c_s \rho V) \).

The heat section controller is shown schematically in Fig. 5. The controller consists of a predictor, Kalman filter, and linear controller. The predictor calculates the strip temperature along the entire length of the strip. The Kalman filter then ensures that the calculated strip temperatures are correct by using the exit strip temperature measurement. The linear controller then adjusts the control set points to minimize any differences between the calculated and desired strip temperatures along the length of the strip.

**Strip Temperature Predictor**

The predictor is a linearized model that calculates strip temperature changes caused by process perturbations around a nominal operation condition. The predictor calculates the strip temperatures in real time. To develop the predictor, the transport term in Eq. (1) is linearized by dividing the strip length into segments or nodes using the following difference approximation for the partial difference, with \( L \) being the length between temperature measurements and \( TS_{-1} \) being the previous node’s strip temperature.

\[
dTS/dt = (TS_i - TS_{i-1})/L
\]

The radiation term in Eq. (1) is linearized around a nominal operating condition using the Taylor series expansion. In addition, the radiation from the zones on each side of the strip is accounted for by separately considering the left and right zone temperatures. Substituting the linearized transport and radiation expressions into the nonlinear equation yields the following linear state-variable form, where \( \Delta TS, \Delta TL, \) and \( \Delta TR \) represent the deviation from nominal of the strip temperature, left control zone temperature affecting the strip, and right control zone temperature, respectively, and \( TS_i, TL_i, \) and \( TR_i \) are the nominal operation point conditions.

\[
dTS/dt = -(v/L)(\Delta TS - \Delta TS_{-1}) + 4K(TL_i^4 \Delta TL + TR_i^4 \Delta TR
\]

\[- TS_i^4 \Delta TS)
\]

This equation represents the response of one strip temperature node along the length of the strip. Twenty nodes were chosen to provide a good approximation of strip temperature in the heat section.

The predictor matrix equation has 20 strip temperature nodes developed using Eq. (3) and their physical relationship to the other strip temperature nodes and the control zone. The 20 nodes were chosen according to the 20 distinct heat-transfer regions a strip would pass as it traveled upward through each zone and between adjacent zones as it traveled.
down to the next zone. In addition, an entry node is included to allow for variation in the entry strip temperature. This node is modeled as an exponential decay. The complete predictor then has 21 strip temperature states and 10 zone temperature inputs.

The zone temperature could be directly measured with sufficient accuracy using this process. Therefore, zone temperature was used as an input and was not modeled as part of the strip temperature predictor. The zone temperature response will have to be added later to develop a control system.

A proprietary detailed heat-transfer model of the heat section was used to generate the nonzero elements in the matrix for a number of nominal operating conditions that would satisfy the thermal requirements of Inland’s product mix, i.e., strip width, gage, line speed, and thermal cycle. The values for each of the nonzero elements are updated for each new operating condition, such as a new coil entering the line. The detailed heat-transfer model was also used to obtain the coefficients in the development of the Kalman filter and controller.

Kalman Filter

The Kalman filter adjusts for predictive errors in the predictor due to factors that were not modeled, coefficients in the predictor matrix that may not be exact, or unforeseen furnace operating problems such as zone temperature measurement errors. Without the Kalman filter, the calculated strip temperatures could consistently be in error.

The developed Kalman filter was different from traditional Kalman filter applications. The traditional discrete Kalman filter with a continuous estimator configuration can be separated into a three-step sequence: continuously predict, obtain a measurement at a given instant, and update for an instant at measurement. In this Kalman filter, the estimated strip temperature had a sawtooth response during steady-state operation. This effect was found to occur when the model’s prediction of steady state differed from the true steady state. The strip temperature, after being updated by the Kalman filter, would (one end of the sawtooth), over time, drift back to the model’s prediction (opposite end of the sawtooth). This is understandable, as the model’s process dynamics would cause the estimates to drift back or settle back to the model’s prediction regardless of any update.

Thus, useful information gained from the Kalman filter was lost. A possible solution would have been to obtain process measurements more often; however, this was not always possible. The final solution was to attempt to add an integral-type compensation with the estimator, thereby allowing the Kalman filter to properly compensate for the differences in the two steady states.

The Kalman filter that was finally implemented does not directly update the strip temperature as in the traditional Kalman filter approach. To achieve the integral type of control desired, a two-step approach was used. A Kalman filter was developed to estimate only the bias, or difference, between the model’s exit strip temperature and the measured strip temperature. Therefore, the Kalman filter does not directly update the strip temperature measurements. This prediction of a bias adjustment becomes the integral-type action needed to provide accurate estimates of strip temperatures. In the second step, the bias adjustment is then translated to each of the strip temperature estimates along the strip length. The bias was translated to each node using a table created from an off-line model to relate how much error at the exit translated into at each strip node.

This is not an ideal way of accomplishing the required task, however, this simplified design was used and has worked for this process. This design closely followed the design of a Slab Mill Reheat Furnace Control System in which the problems are more apparent [3]. The following discusses the development of the bias and translation adjustment.

Bias Adjustment

The bias adjustment model is a discrete Kalman filter model. It was modeled to have a bias value estimate that would slowly vary over time using random noise. In other words, the bias value was assumed to change from sample to sample because of zero-mean random process noise. The process noise covariance did change to account for increased uncertainty of the process when coil-to-coil transitions occurred by increasing the process noise covariance.

Using the standard Kalman filter equations, the resulting bias adjustment equation is a one-dimensional Kalman filter that determines the bias or provides an integral correction beyond a straight proportional correction. This is done by multiplying the Kalman gain times the difference between the actual measurement and the predicted measurement. The Kalman gain was calculated on-line based on the time since the last measurement, regardless of the number of predictions that occurred during this time.

Translation Adjustment Factor

To translate the bias adjustment to each strip temperature node, translation adjustment factors need to be calculated. This is accomplished by using a proprietary detailed heat-transfer model and running it at different nominal operating conditions. For each strip temperature node, deviations in strip temperature from nominal were noted for variations in gage, width, or furnace zone temperatures. Then, each strip temperature node was normalized to the exit strip temperature node. These translation adjustment factors were then added to translate the exit strip temperature error to the other strip temperature nodes for improved strip temperature estimates.

Controller

The controller was developed by expanding the state-variable matrix to include zone temperature response and integral gain to provide a controller matrix model. After defining the values of the weighting matrices in the quadratic cost function, the Riccati equation [4] was solved to calculate the control gains. The gains were suboptimized for the on-line controller.

Zone Temperature Response

The zone temperature response model is a first-order exponential equation where \( TZ \) is the zone temperature, \( r \) the response time constant of the given zone, and \( TZ_{sp} \) is the zone temperature set point.

\[
\frac{dTZ}{dt} = \left(1/r\right) \left(-TZ + TZ_{sp}\right)
\]  

In this equation, each zone temperature is modeled to act independently, i.e., without being affected by the adjacent zones. This is not entirely correct, but is considered adequate for control purposes.

Integral Gain

Integral gain was included in the last five zones by adding integral states and inputs to the matrix model. This approach was necessary to reduce the size of the control system matrix. The equation for integral control, where \( ITZ \) is the integral control action of the controller, \( ITZ_{sp} \) is the control input to the integrator.

\[
\frac{dTZ}{dt} = ITZ_{sp}
\]

\[
\frac{dTZ}{dt} = \left(1/r\right) \left(-TZ + TZ_{sp} + ITZ\right)
\]

The input to the integrator was a rate of zone temperature change input control. The output of the integrator was then added to the zone temperature in the controller matrix model.
Controller Matrix Model

The final controller matrix model has 36 states and 15 inputs. The 36 states are defined by the 21 strip temperature nodes, the 10 zone temperatures, and the five rate of zone temperature changes (integral). The 15 inputs are defined by 10 zone temperature set points and the five control inputs to the integrators.

Cost-Weighting Matrices

Given the control model defined, the cost-weighting values must be determined. The design decision was made that relates the balance between the magnitude of the control action (matrix $R$) and the magnitude of error in the strip temperature (matrix $Q$) of the cost-function equation, where $J$ is the scalar cost value, $x$ the strip and zone temperature states, and $u$ the zone temperature set points.

$$J = \int_0^t x'Qx + u'Ru \, dt \quad (7)$$

Both $Q$ and $R$ were chosen to be diagonal matrices. To calculate the $Q$ and $R$ matrices, a design decision is required to define the maximum allowable error for each zone and strip temperature and the maximum allowable control for the integral and proportional action of the zone temperature set points. The cost-weighting matrices are chosen so that $Q$ is the inverse of the square of the maximum allowable error and $R$ is the inverse of the square of the maximum allowable control [5].

The elements in the $Q$ matrix were chosen so that a high-cost penalty was placed on strip temperature errors and a no-cost penalty was placed on zone temperature errors and integral control action errors. This allows the controller to react to strip temperature errors and to be nonresponsive to zone or integral errors. The elements in the $R$ matrix must be nonzero and were chosen to balance the allowable control action with an acceptable strip temperature error. The actual values were tuned using off-line simulation of a heat-transfer model of the heat section and the controller to check if the balance of control action and strip temperature error did not produce poor transient response. This procedure provided good response when the control system was finally used on-line with very little fine-tuning of the gains required.

Control Gains

The control gains were calculated from the controller matrix model and the cost-weighting function. The Riccati equation was used for solving the control gains. This solution was accomplished using the MIT Control Design Package [6].

The control gains were suboptimized for the following reasons. First, any feedback that attempts to correct the integral control action is unnecessary, the gains relating the feedback of the integral control action to the control set points were zeroed. Second, off-line simulations showed that when the desired zone temperatures did not provide the required strip temperatures, the control system tried to achieve the required strip temperatures while maintaining the incorrect desired zone temperatures. Therefore, even though the zone temperature feedback provided a derivative-type feedback, the gains relating the feedback for zone temperature were reluctantly zeroed.

Figure 6 shows detailed controller gains for a typical zone, Zone 5, based on all 21 strip temperature node errors. The strip nodes that Zone 5 directly affects are shown above the bottom axis. It can be seen that Zone 5 responds to each strip temperature node error systematically, i.e., the gains are largest around Zone 5 and trail off on both sides of the zone. This behavior is not unexpected, since the strip should be most responsive to the zone that it is in and should anticipate the strip temperature errors that will enter the zone.

The controller completes the feedback loop of the control system. It is driven by the difference of the Kalman filter strip temperature estimates and the desired strip temperature profile derived from the product thermal cycle requirements. To accomplish this function, the controller is implemented online using a set of algebraic equations.

To allow the controller to operate over the entire operating range, a gain set was calculated off-line for each of the nominal operating conditions. Then, as a new coil enters the line (new operating condition), the appropriate gain set for this condition is used by the controller.

Performance Evaluation

The control system has been in routine operation since July 1984. It is currently on-control 90 percent of the time. The 10 percent off-control is due primarily to nonroutine operations, such as stop and go line operation, and improper transitions resulting in unrealistic control requirements.

The following analysis of the control system performance will focus on the control action for the heat section over a 12-h time period. This analysis also includes a gage change transition.

Figure 7 shows the Kalman filter bias adjustment, the error between the measured and desired exit strip temperature, and the control action of the last zone temperature controller. (Due to labeling convention, the last zone is Zone 9 and not Zone 10.) The top plot shows the Kalman filter bias adjustment
as applied to the exit strip temperature node of the predictor. It shows that a corrective ability such as a Kalman filter was needed to improve the predicted strip temperatures. The middle plot shows that the exit strip temperature is maintained to within the ±10°C well within the required product tolerance of ±23°C. This shows that the overall control was able to achieve the desired objective. The bottom plot shows the last heat zone temperatures. This curve indicates that the control action did occur in a reasonable fashion to control the strip temperature along the length of the strip.

In addition, the bullet at 540 min shows a satisfactory system response at a gage change transition.

Acknowledgments

The development and implementation of this continuous anneal control system was done with the contributions and support of many Inland people. The authors wish to acknowledge the following for their significant contributions to the control system design: Mitch Lapman, Lewis (Skip) Kimberly, Phil Papesh, and Dave Lueck of the Process Automation Department; Jim Cundiff and each of the operators in the Operating Department; and Cliff Smith, Dick Pele, John Sinclair, Bob Gray, Karcy Pieters, Ron Kordys, and Dennis Namovice of the Research Department.

References