HILL K. NANDI AND WILLIAM A. RUHE | COMPAS CONTROLS, INC., INDIANA, PA

Adaptive Control System Under Development for Continuous Furnaces

THIS ARTICLE DESCRIBES A STATE-OF-THE-ART UNIVERSAL SUPERVISORY CONTROL SYSTEM THAT IS UNDER DEVELOPMENT FOR MONITORING, CONTROLLING AND DIAGNOSIS OF CONTINUOUS FURNACES. WHEN APPLIED TO A FURNACE EQUIPPED WITH PROPERLY FUNCTIONING PROCESS CONTROLS, THE SYSTEM CAN HELP DETERMINE FURNACE OPERATING PARAMETERS FOR NEW PRODUCTS WITHIN THE FURNACE DESIGN CONSTRAINTS.

Sintering is a critical process in the production of powder metallurgical (P/M) parts. Since the resulting properties of these parts are direct functions of the heating environment existing in a sintering furnace, monitoring and control of the cycle parameters is extremely important. Currently, the adaptive control system described here has been applied successfully to operational sintering furnaces; however, the system may also be applied to other industrial furnaces and heat treating processes.

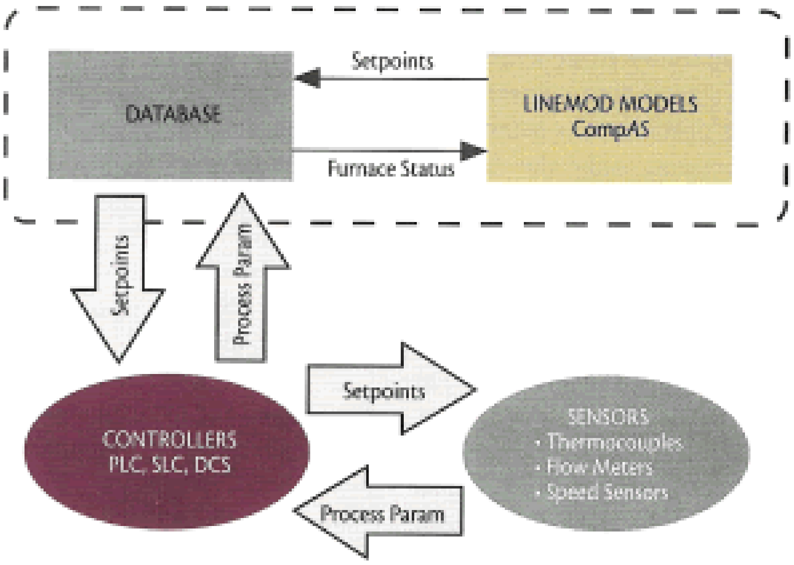

Fig. 1 Control schematic of the on-line model in the adaptive learning control system.

A "supervisory" system is one used to augment the physical controls on a furnace by performing functions that are otherwise performed by an operator, e.g., specifying setpoints and recording process variables. Some of the furnace parameters that need to be controlled in sintering application include temperature, pressure, oxygen and dew point, and carbon potential.

COMMUNICATION IS IMPLEMENTED BASED ON THE ABILITIES OF THE FURNACE CONTROL DEVICES.

This supervisory control system, known as LINEMOD, includes models for off-line simulation and on-line control. The off-line model uses a furnace simulator for furnace inputs while the on-line model monitors an actual furnace. Both systems utilize computer-aided design (CAD) descriptions of the parts that enable the models to calculate the thermal conditions inside the parts being processed. The off-line model enables furnace or process designers to simulate a product run and estimate the process variables before parts are placed in production. The on-line model is responsible for real-time tracking of the parts while under production. The unique feature of the supervisory control system is its ability to generate real-time set-point parameters using optimization techniques. Moreover, it has the ability to adjust the parameters utilizing statistical process control and adaptive learning.

The system is a multi-tasking, multi-user software system capable of performing charge scheduling, product tracking, communication, mathematical modeling, set-point management, adaptive learning, data collection, and report generation. The underlying concepts for the above features are explained in the following paragraphs. The major elements (subsystems) of the core software work together to facilitate the control and provide operational insight into the process.

CONTROL SOFTWARE ELEMENTS

In order for an adaptive control system to control and monitor a furnace, it must be configured and interfaced to the Level 1 systems (controllers) of an operational furnace and must know the configuration of the parts to be heated. The system must then run the necessary models before tracking the parts as they move through the furnace. A system overview and the data communication path are shown in Fig. 1.

COMMUNICATIONS

To control the furnace parameters and to receive feedback on the operation of the process, the control system needs to communicate with the furnace sensors and controllers. These controllers may be single loop controllers (SLC), programmable logic controllers (PLC), or distributed control systems (DCS). Based on the feedback, the control parameters are modified to achieve the processing requirements for the parts.

Communication is implemented based on the abilities of the furnace control devices. Currently, communication has been established using serial protocols and with interface software from Level 1 control equipment suppliers. As new Level 1 control equipment is introduced, more interface protocols will be developed.

CHARGE SCHEDULING

Configuration data for P/M parts may include part dimensions, time at temperature, initial density, material properties of the powder, etc. This data is provided through the charge scheduling human machine interface (HMI) which allows the furnace operator to identify the properties and processing requirements of the parts to be charged. This data may also be received from a separate scheduling computer or the furnace operator's Level 3 scheduling or management system. The data is then available for editing through the charge scheduling HMI.

PRODUCT TRACKING

The primary function of product tracking is to maintain the identification of all the parts inside a furnace and produce a map of the physical location of the parts inside the furnace. Once parts are loaded into the furnace, the information associated with the parts is transferred from a scheduling subsystem to a tracking subsystem. In a continuous furnace, the tracking subsystem updates the position of each part according to the distance moved. This information is then fed to the mathematical model for updating the part temperature, carbon content, densities, etc.

As parts reach the discharge position and exit the furnace, the tracking system removes the part information from the tracking map and the historical records are compiled for the report generation.

SIMULATOR

The purpose of the simulator in the adaptive control system is to generate furnace setup parameters without being connected to a furnace. In other words, the simulator is a virtual furnace as designed by operations personnel or engineers, with responses typical of a furnace with full communications capabilities. The simulation may include heating response, cooling response and atmosphere response.

The simulator may be applied for operational or engineering purposes including generation of furnace setup parameters for furnaces equipped with controls that do not have communications ability, or testing of multiple furnace designs to achieve processing requirements for specific parts.

> AS NEW **LEVEL 1** CONTROL EQUIPMENT IS INTRODUCED, MORE **INTERFACE PROTOCOLS** WILL BE DEVELOPED.

When running the control system off-line, the simulator receives the set-point parameters from the control system, simulates the response to the set-points and returns the data to the control system. The simulator is totally transparent to the furnace control system.

SET-POINT DETERMINATION AND MANAGEMENT

The unique feature of this supervisory control system is its capability to generate real-time set-point parameters using optimization techniques. At present, only the furnace zone temperatures may be determined, however, in the future optimum gas flow will also be determinable. The model is capable of generating an on-line heating strategy during the heating cycle thereby achieving lower fuel and gas consumption and higher throughput. The cooling zone temperature and the fan speed can also be determined in a similar manner.

In conventional practice, the basic control philosophy is to specify the set-point parameters of each heating zone according to a prescribed heating pattern. In this on-line set-point management system, this concept is abandoned, and the furnace parameters in zones are directly determined by real-time computation using linear programming. When using this method, a set of constraints is applied to formulate the objective function of maximizing efficiency. Examples of such constraints are shown below.

- The mean temperature of the parts at specific locations within a furnace should be higher than or equal to the estimated or target temperature of the parts at those specific locations.
- The temperature differential between the coldest and hottest spot should be less than a certain estimated value or range.
- Each control zone operating temperature should be within a prescribed limit.
- The temperature difference between two adjacent zones should be within a prescribed limit.

The above constraints can be represented mathematically, thus the determination of the zone parameters is a linear programming problem where the control variables are the changes in the zone parameters. The solution is obtained easily in real-time.

MATHEMATICAL MODELING

The mathematical model is the primary component of the adaptive control system and is key to set-point generation and management. The model is required to perform heat transfer and diffusion calculations and heat/energy balance calculations.

Mathematical models generally consist of several equations that enable a system to predict any transformation taking place within a part or system. Some of the mathematical modeling techniques that are used in the adaptive control system include linear/non-linear interpolation, linear programming, finite element analysis, etc.

In order to monitor or predict any change in parameters, the system must generate a boundary condition profile inside the furnace and then run finite element models to calculate this change.

The process of generating a continuous boundary condition is termed "profile generation." In this process, the system reads the actual data points from the sensors located at various locations along the furnace length. These points are then fitted with a curve from one end of the furnace to the other. Providing sufficient sensors to measure real data will guarantee an accurate profile. A typical temperature profile is shown in Fig. 2.

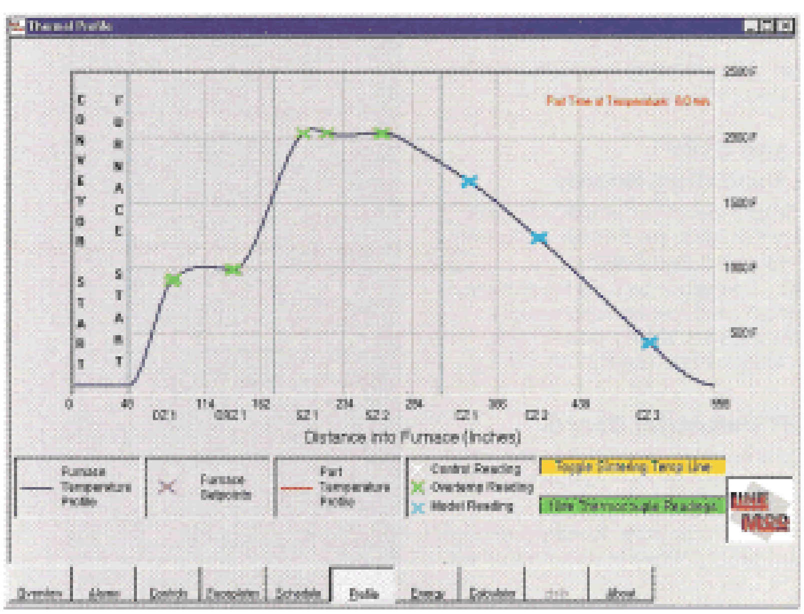

Fig. 2 An example of a sintering furnace production where temperature is the monitored parameter.

The continuum problems that are solved for heat transfer and diffusion by the mathematical model of the adaptive learning control system are usually formulated in terms of governing partial differential equations. For heat transfer, mass diffusion and fluid flow problems, which arise in the analysis of conduction, diffusion, and convection processes, this can be represented by a general transport equation[2] as shown below:

$$\gamma\frac{\partial\phi}{\partial t}+\beta\nabla\bullet(v\phi)-\nabla\bullet(\Gamma\nabla\phi)-\frac{ds}{dt}=0$$

where:

γ, β, and Γ are known specific properties, and

ϕ is the unknown parameter

t is the time

v is the velocity vector

ds/dt is a volumetric source rate.

In addition to the governing differential equations, the appropriate boundary condition must be specified to complete the formulation of the problem. The three types of boundary conditions that are used in the models are:

$\phi=\phi_p$

(the boundary condition of first kind, where ϕ_p is the boundary value);

$-\Gamma\nabla\phi\bullet n=q_p''$

(the boundary condition of second kind, where q_p'' is the normal component of flux, and n is the normal vector direction); and

$-\Gamma\nabla\phi\bullet n=h(\phi-\phi_c)$

(the boundary condition of third kind, where h is the convection coefficient, and ϕ_c is the actual surface value).

The problem needs to be provided with an appropriate initial condition that should be

$\phi=\phi_o$.

The property data used in the above equations is pre-determined as a function of temperature and is stored in a database.

In this approach, the finite element method used to transform the continuum problem to a set of algebraic equations is either the variational principles or, preferably the Galerkin method.[3]

ADAPTIVE LEARNING

To calculate "optimal" setpoint schedules for production, an accurate and robust simulation of zone temperature (or other parameter) is required.[1] "Robust" refers to the accuracy of the prediction over a wide range of operating conditions. It is not sufficient that simulations be accurate for only one specific, repeatable sequence. There must be sufficient accuracy for deviations from this set condition. One way to address this competing issue is to adopt a model based on an adaptive control scheme. In this scheme, an attempt is made to compare the actual measured value with the predicted values from the model. Errors between actual and measured values are minimized by appropriately adjusting the parameters of the model.

DATA COLLECTION/REPORT GENERATION

This element of the control system receives production and part data from the product tracking subsystem, the mathematical modeling subsystem, and the communications subsystem. The module then generates production reports which may include data such as part production rate, number of parts produced, weight production rate, combustion fuel usage, atmosphere usage, electricity usage, and utility usage per unit weight of parts.

Individual part/charge reports may include information such as heating time, cooling time, part temperatures, furnace temperature profiles, estimated part density, carbon content, or atmosphere profiles.

USER INTERFACE

A graphical user interface (GUI) provides a window into the process. The GUI provides the operator with the ability to configure the properties and geometry of the parts and schedule the sequence in which the parts are to be processed. The GUI also allows the user to monitor parts as they track through the furnace, evaluate process data received from

Level 1 controls or the simulator, monitor set-points being generated by the control system, and evaluate part data generated from the mathematical model. The HMI screens may be accessed through "point-and-click" buttons or hot links.

SCOPE

The scope of the system (hardware and software) includes the following:

- the core software control elements discussed above (developed using Visual C++).
- graphical user interface software to communicate with the core software (developed using Visual Basic).
- external interface communications to read/write data from the database and write/read data to the Level 1 controllers. In some cases, the communication package may include a vendor supplied API (Application Programmers Interface).
- In lieu of communication ability with the Level 1 controls or an actual furnace, the simulator reads data from and writes data to the database.
- The database for information being passed between the core software and the communications/simulator (developed using Microsoft Access).

CONCLUSION

The P/M sintering process is dependent on variables such as time, temperature, atmospheric gas composition and flow rate, and production rate. In addition, parts undergoing the sintering process may encounter different temperatures and gas composition at different areas of the furnace. The supervisory control software described here has been developed to address these issues. The incorporation of a mathematical simulator with a Level 1 control system can lead to process optimization and improved part quality.

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