# A New Generation of Adaptive Supervisory Control and Monitoring System for Sintering/Heat-Treating Furnaces

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## ABSTRACT

The heat treatment and sintering processes are dependent on time, temperature, and atmosphere. Precisely monitoring and controlling each of these parameters can result in higher productivity and improved part quality. The LINEMOD supervisory control and monitoring software addresses these issues by estimating the thermal and physical conditions inside a furnace using mathematical models.

## Introduction

Sintering is a complex process in the production of powder metallurgical (P/M) parts. Important part properties (e.g., density, hardness, strength, etc.) change as a part travels within a continuous belt furnace. Since the final mechanical properties of the parts are direct functions of the heating environment existing in a sintering furnace, monitoring and controlling these parameters are important and essential. In this study we have analyzed the changes in the temperature and density of P/M parts during a sintering operation inside a continuous belt furnace by using LINEMOD™ a new generation supervisory control system. The data from the analysis has been used to calibrate some of the parameters in the predictive model residing inside the supervisory system.

## LINEMOD™ – new generation of furnace supervisory controls system

LINEMOD™ supervisory control system has been designed to control sintering furnace parameters by predicting the part properties as it traverses the furnace length. 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 set-points and recording process variables. Some of the furnace parameters that need to be controlled in sintering application include temperature, dew-point, and oxygen and carbon potentials.

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 specific component being processed. The off-line model enables the furnace or process designers to estimate process variables before the parts are placed in production. The on-line model is responsible for real-time tracking of parts while under production. The unique feature of the system is its capability to generate 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, adaptive learning, data collection, and, report generation.

In order for the LINEMOD™ system to control and monitor a furnace, it needs to be configured and interfaced to the level I system (controllers) of an operational furnace and must know the configuration of the parts to be heated. The system must then run the necessary models while tracking the parts as they move through the furnace. The system overview and the data communication path are shown in ***Figure 1***.

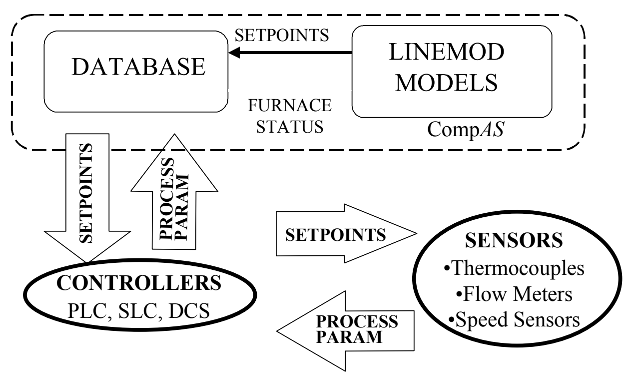


*Figure 1* LINEMOD™ system overview and communication path diagram

## Test plan

The goal of the following test plan is to establish the dependencies of key parameters in the LINEMOD™ sintering model. The model is mechanism based and includes the effects of grain boundary and volume diffusion. The governing equations for each of the micro-mechanical mechanisms are taken from various works by M.F. Ashby [1-2]. These equations relate the time rate of change in the relative density to material properties, powder characteristics, and the driving forces for densification.

Within this framework the sintering process is divided into two stages due to the very different local geometry of the porosity. In stage I (relative density < 92%) the powder particles just touch and form small necks between each other while the porosity is essentially continuous and open throughout the powder compact. In stage II (relative density > 92%) the pores are mainly closed and the material is basically a solid with isolated pores.

Currently, LINEMOD™ uses estimates for the material properties taken from literature and typical iron powder characteristics. These values need to be determined more exactly using a small set of well controlled sintering experiments and metallography if available.

The sintering experiments should be conducted using identical parts of the same green density. These specimens should be sintered in groups (~ 5-10 parts each) changing the furnace operating conditions in a systematic way. The relative density before and after sintering should be measured and averaged for each of the groups. This data and the mean particle size determined from metallography will be used to calibrate the LINEMOD™ sintering model. Note that all other furnace parameters (delubing temperature, atmosphere, cooling conditions, etc.) should be held as constant as possible during the tests.

## Mathematical modeling

The mathematical model used in the LINEMOD™ system is key to predicting the physical and metallurgical transformation in the parts. In order to monitor or predict the changing parameters inside the part, the system has to generate a boundary condition profile inside the furnace and run finite element models to calculate the part parameters.

**Profile Generation:** The process of generating a continuous boundary condition is termed as "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 illustrated in Figure 2:

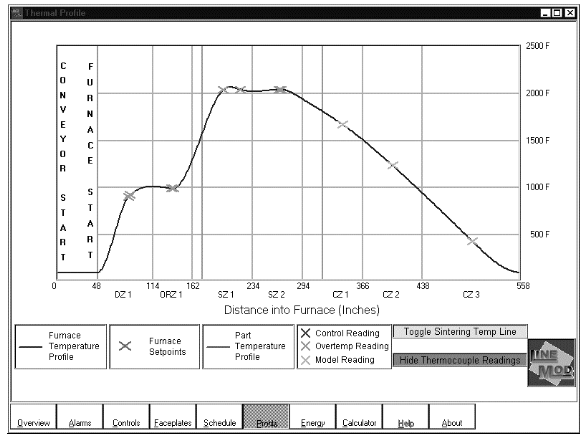


*Figure 2* Typical furnace temperature profile

**Governing Equation:** The continuum problems that are solved by the LINEMOD math model for heat transfer and diffusion calculations 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; can be represented by a general transport equation [4] as shown below:

$$\gamma \frac{\partial \phi}{\partial t} + \beta \nabla \bullet (v \phi) - \nabla \bullet (\Gamma \nabla \phi) - \frac{ds}{dt} = 0 \qquad (1)$$

where:

$\phi$ : is the unknown parameter

t : is the time

$\gamma, \beta, \Gamma$ : are known specific properties

v : is the velocity vector

$\frac{ds}{dt}$ : is a volumetric source rate

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

$\phi = \phi_p$ (2) is the boundary condition of first kind

$-\Gamma \nabla \phi \bullet n = q_p''$ (3) is the boundary condition of second kind, where $q_p''$ is the normal component of flux

$-\Gamma \nabla \phi \bullet n = h(\phi - \phi_c)$ (4) is the boundary condition of third kind, where ***h*** is the convection coefficient.

**Initial Condition:** The problem needs to be provided with an appropriate initial condition. The form of the initial condition should be

$\phi = \phi_0$ (5)

**Data Property:** The property data that are used in the above equations are a function of temperature that are pre-determined and stored into a database.

**Finite Element Method:** This method transforms the continuum problem to a set of algebraic equations either by variational principles or, preferably the Galerkin method [5].

**Density Model:** Sintering is the process of densification for a powder compact achieved through heating. The high temperatures (usually greater than one-half the melting temperature) activates diffusive mechanisms which cause a powder to densify. A sintering model, originally developed by Ashby, including the effects of grain boundary and volume diffusion has been implemented in this new generation supervisory furnace control system. The model also accounts for the generally accepted stages of sintering that reflect large changes in the shape and distribution of the porosity in the powder compact.

Following the conventions used by Ashby, as the initial powder packing densifies, the nature of the porosity changes. Stage I ($\Delta \leq 0.92$) is characterized by long interconnected channels of porosity and the necks between particles are still distinct. Stage II ($\Delta > 0.92$) is typically considered to have individual, isolated porosity and the necks between particles are not distinguishable.

The driving force terms for the above sintering mechanisms within each stage are defined below. These equations are then used to develop expressions for the densification of the powder compact. Therefore, the driving force equation for stage I is given by

$$\tilde{F}_1 = \left[ (P - P_o) + 3\Delta^2 \left( \frac{2\Delta - \Delta_o}{1 - \Delta_o} \right) \frac{\gamma}{R} \right] \frac{\Omega}{kT} \qquad (6)$$

where

$P$ = Applied pressure (normally zero during sintering)

$P_o$ = Atmospheric pressure

$\Delta$ = Relative density

$\Delta_o$ = Initial relative density

$\gamma$ = Surface free energy

$R$ = Particle radius

$\Omega$ = Atomic volume

$k$ = Boltzmann's constant

$T$ = Absolute temperature

Similarly, the driving force equation for stage II is

$$\tilde{F}_2 = \left[ (P - P_i) + 2\left( \frac{6\Delta}{1 - \Delta} \right)^{1/3} \frac{\gamma}{R} \right] \frac{\Omega}{kT} \qquad (7)$$

where

$P_i$ = Internal pore pressure

The overall densification rate of a powder compact can then be expressed using the driving force terms. The densification rate is derived by calculating the rate of mass diffusion from the particle contact areas to either the free surfaces (stage I) or to closed porosity (stage II). After performing such an analysis, the densification rate for stage I is

$$\dot{\Delta} = 43 \left( \frac{1 - \Delta_o}{\Delta - \Delta_o} \right) \frac{(\delta D_b + 3\rho D_v / 4)}{R^3} \tilde{F}_1 \qquad (8)$$

where

$\delta$ = Grain boundary thickness

$\delta D_b$ = Grain boundary diffusion coefficient

$\rho = R(\Delta - \Delta_o)$ = Curvature of the neck between particles

$D_v$ = Volume diffusion coefficient

Again, in a similar fashion, the densification rate for stage II is given as

$$\dot{\Delta} = \frac{4\ (\delta D_b + 3 r D_v / 4)}{R^3} \tilde{F}_2 \qquad (9)$$

where

$r = R\left( \frac{1 - \Delta}{6\Delta} \right)^{1/3}$ = Pore radius

## Test Performed

The tests ware performed at Innovative Sintered Metals in St. Marys, PA. Due to production constraints some of the tests that were planned earlier could not be performed. The tests that were undertaken are explained in the following paragraph.

The tests were run on a 2 preheat zone, 2 sintering zone and 2 cooling zone continuous furnace. The furnace sketch is shown in Figure 3.

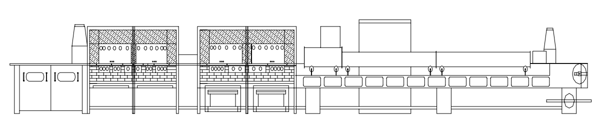

*Figure 3*: Furnace used for the test

The furnace is equipped with a LINEMOD™ system that enables automatic data gathering and report generation. Before the test, the furnace profile in the LINEMOD™ system was calibrated with actual thermocouples. Eleven slugs (cylindrical shapes) were prepared. The slugs were made out of 3 different powders (FC0208, F0008, 316L-SS). The diameter, height and the density of the slugs were measured and recorded (see Table 1). Two sets of tests were run. In the first set the sintering zones were set at 1127º C and the belt was set at 108 mm/min. In the second test the sintering zones were set at 1132º C and the belt speed was set at 82.6 mm/min. The details of the test settings are summarized in Table 2. LINEMOD™ system captures the real-time furnace temperature and part temperature profile. The profiles from both the tests are shown in Figure 4. As the slugs came out of the furnace the diameter, height and the density were again measured. The data are shown in Table 3.

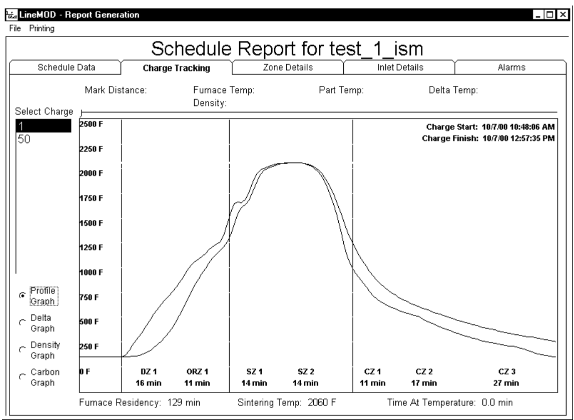


*Figure 4*: The furnace temperature and the part temperature profile

## Computer Simulation

The above tests were simulated in the off-line LINEMOD™ software. The data gathered from the sintered slugs and furnace zone temperatures were fed in to the system. The results from the computer runs were recorded and compared with the actual data. More simulation runs were attempted after modifying some of the model parameters. The density data from the actual test and simulations are compared in Table 5.

## Analysis and Discussions

From the data it is evident that some of the key parameters of the sintering model have profound effects on the predictions of sintered density for the slugs that were tested. Among the seven parameters, only particle radius and the grain boundary diffusion activation energy have been found to have an effect on the sintered density. From Figure 5 one can see that the density increased from first test (sinter temp: 1127º C, belt speed: 108 mm/min) to second test (sinter temp: 1132º C, belt speed: 82.6 mm/min) for the slugs made out of F0008 powder. One can also notice that the calculated density is much closer to the actual sintered density in case 3 where the particle radius is 2.0E-05 meters. Also in case 4 (grain boundary diffusion activation energy of 157 KJ/mol.) the calculated density is closer to the actual sintered density. From Figure 6 one can see that for the same parameters the changes in the density are more pronounced for 316L-SS (stainless) than FC0208 or F0008.

## Conclusion

P/M sintering process is dependent on variables such as time, temperature, atmospheric gas composition and flow rate, and production rate. In addition, the parts undergoing the sintering process encounter different temperatures and gas composition at different area of the furnace. From the study it can be concluded that a calibrated model can predict some of the key material properties undergoing sintering process. In this study we have focused on the prediction of density of the sintered material. However, this study can be extended to determine other key parameters e.g., strength, hardness, carbon diffusion etc. LINEMOD™ supervisory control software uses mathematical models for process optimization. This study has been conducted to demonstrate that an on-line system with measured data can tune some of the key model parameters that can be later used for accurate prediction.

**Table 1: Measured data before sintering**

| Slug # | grade | pressed ton | weight gm | dia mm | height mm | Volume cc | Density gm/cc |
|---|---|---|---|---|---|---|---|
| 1 | FC0208 | 32 | 9.97 | 14.376 | 9.174 | 1.489 | 6.695 |
| 2 | FC0208 | 32 | 10.01 | 14.376 | 9.233 | 1.499 | 6.679 |
| 3 | FC0208 | 40 | 10.18 | 14.384 | 9.195 | 1.494 | 6.813 |
| 4 | FC0208 | 40 | 10.18 | 14.384 | 9.195 | 1.494 | 6.813 |
| 5 | F0008 | 20 | 9.78 | 14.389 | 9.731 | 1.582 | 6.181 |
| 6 | F0008 | 28 | 10.08 | 14.371 | 9.441 | 1.531 | 6.582 |
| 7 | 316L-SS | 40 | 9.00 | 14.379 | 8.585 | 1.394 | 6.456 |
| 8 | 316L-SS | 40 | 9.22 | 14.379 | 8.763 | 1.423 | 6.479 |
| 9 | 316L-SS | 28 | 9.18 | 14.371 | 9.268 | 1.503 | 6.106 |
| 10 | 316L-SS | 28 | 8.95 | 14.371 | 9.025 | 1.464 | 6.114 |
| 11 | F0008 | 20 | 9.55 | 14.389 | 9.421 | 1.532 | 6.234 |

**Table 2: Test settings**

| Slug # | grade | belt speed (mm/min) | Zone Temp (1) (deg C) | Zone Temp (2) (deg C) | Zone Temp (3) (deg C) | Zone Temp (4) (deg C) |
|---|---|---|---|---|---|---|
| 1 | FC0208 | 108.0 | 482 | 635 | 1059 | 1127 |
| 2 | FC0208 | 108.0 | 482 | 635 | 1059 | 1127 |
| 3 | FC0208 | 108.0 | 482 | 635 | 1059 | 1127 |
| 4 | FC0208 | 108.0 | 482 | 635 | 1059 | 1127 |
| 5 | F0008 | 108.0 | 482 | 635 | 1059 | 1127 |
| 6 | F0008 | 108.0 | 482 | 635 | 1059 | 1127 |
| 7 | 316L-SS | 82.6 | 482 | 635 | 1066 | 1132 |
| 8 | 316L-SS | 82.6 | 482 | 635 | 1066 | 1132 |
| 9 | 316L-SS | 82.6 | 482 | 635 | 1066 | 1132 |
| 10 | 316L-SS | 82.6 | 482 | 635 | 1066 | 1132 |
| 11 | F0008 | 82.6 | 482 | 635 | 1066 | 1132 |

**Table 3: Measured data after sintering**

| Slug # | grade | pressed ton | weight gm | Dia Mm | height mm | Volume cc | density gm/cc |
|---|---|---|---|---|---|---|---|
| 1 | FC0208 | 32 | 9.97 | 14.376 | 9.154 | 1.486 | 6.709 |
| 2 | FC0208 | 32 | 10.01 | 14.376 | 9.182 | 1.491 | 6.716 |
| 3 | FC0208 | 40 | 10.18 | 14.384 | 9.131 | 1.484 | 6.861 |
| 4 | FC0208 | 40 | 9.98 | 14.384 | 8.956 | 1.455 | 6.857 |
| 5 | F0008 | 20 | 9.78 | 14.369 | 9.708 | 1.574 | 6.213 |
| 6 | F0008 | 28 | 10.08 | 14.371 | 9.403 | 1.525 | 6.609 |
| 7 | 316L-SS | 40 | 9.00 | 14.338 | 8.509 | 1.374 | 6.551 |
| 8 | 316L-SS | 40 | 9.22 | 14.341 | 8.679 | 1.402 | 6.577 |
| 9 | 316L-SS | 28 | 9.18 | 14.333 | 9.177 | 1.481 | 6.200 |
| 10 | 316L-SS | 28 | 8.95 | 14.336 | 8.961 | 1.446 | 6.188 |
| 11 | F0008 | 20 | 9.55 | 14.366 | 9.375 | 1.520 | 6.284 |

**Table 4: Parameters in the sintering model**

| | | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| Rad Particle | m | 1.00E-05 | 1.10E-05 | 2.00E-05 | 1.00E-05 |
| Surface free Energy | J/m^2 | 2.1 | 2.1 | 2.1 | 2.1 |
| Atomic Volume | m^3 | 1.18E-29 | 1.18E-29 | 1.18E-29 | 1.18E-29 |
| Pre-exponential for boundary diffusion | M^3/s | 7.50E-15 | 7.50E-15 | 7.50E-15 | 7.50E-15 |
| Activation Energy for boundary diffusion | KJ/mol | 143.0 | 143.0 | 143.0 | 157.0 |
| Pre-exponential for volume diffusion | m^2/s | 1.80E-05 | 1.80E-05 | 1.80E-05 | 1.80E-05 |
| Activation Energy for volume diffusion | KJ/mol | 230.0 | 230.0 | 230.0 | 230.0 |

**Table 5: Comparison of the density**

| Slg # | Start dens | Final dens | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|---|
| 1 | 85.17% | 85.36% | 89.02% | 88.28% | 86.05% | 87.29% |
| 2 | 84.97% | 85.44% | 88.80% | 88.06% | 85.84% | 87.16% |
| 3 | 86.68% | 87.29% | 90.64% | 89.87% | 87.57% | 88.95% |
| 4 | 86.80% | 87.25% | 90.77% | 90.01% | 87.70% | 89.08% |
| 5 | 78.63% | 79.04% | 82.00% | 81.35% | 79.41% | 80.47% |
| 6 | 83.74% | 84.08% | 87.47% | 86.75% | 84.59% | 85.79% |
| 7 | 81.20% | 82.40% | 85.50% | 84.67% | 82.17% | 83.68% |
| 8 | 81.50% | 82.73% | 85.82% | 84.98% | 82.46% | 83.99% |
| 9 | 76.80% | 77.98% | 80.71% | 79.95% | 77.68% | 79.04% |
| 10 | 76.90% | 77.83% | 80.94% | 80.06% | 77.79% | 79.15% |
| 11 | 79.31% | 79.95% | 83.43% | 82.63% | 80.24% | 81.60% |

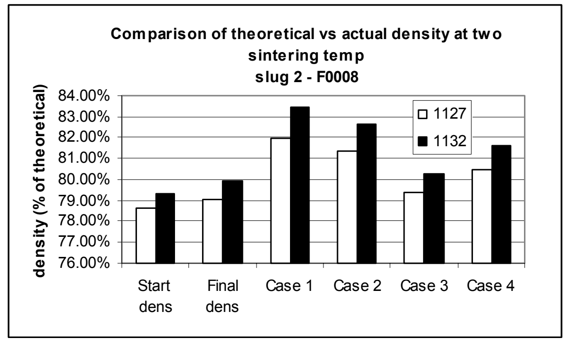


*Figure 5*: Comparison of density at two different temperature

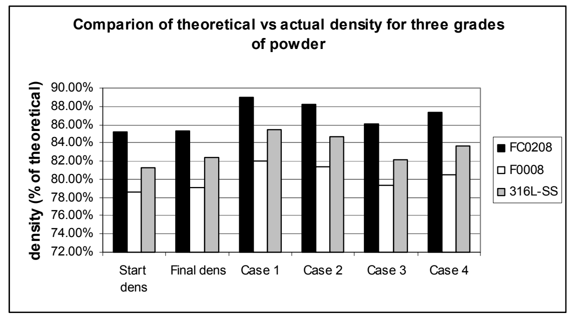


*Figure 6*: Comparison of density for three grades of powder

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