# Internal Model Expert control for slow cooling rate bronze casting

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# Internal Model Expert Control for Slow Cooling Rate Bronze Casting

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*Abstract* - **The paper presents a review of the bronze casting methods: the traditional casting in loam or sand molds, issuing high quality products thanks to the slow cooling rate that produces a favorable granularity and the modern precise, fast and cheap casting. We propose a new coated casting method. Coating/uncoating the cooling casting with few flexible insulating layers with different thermal resistances enable us to precisely control the heat flow, and thereby the cooling rate and the granularity. An expert system provided with an internal model, built out of generic visual commands (charts), controls the process.**

## I. Introduction - the Importance of the Cooling Rate for the Metal Casting

The bronze casting, one of the oldest human technologies, shows a continuous evolution. Besides industrial or domestic applications, the bronze casting supports decorative and monumental arts and also the manufacturing of a highly significant religious item: the bells.

Two historical stages can be observed in this issue:

a) The traditional casting in loam or sand molds;

b) The modern casting brings different mold materials/ building techniques, gravity/vacuum/low pressure pouring, stabilizing thermal or shock/vibrations treatments, and other technological features.

A great deal of the casted objects' properties, most of all the granular macrostructure, is determined by the features of the cooling process, usually represented by the cooling curve.

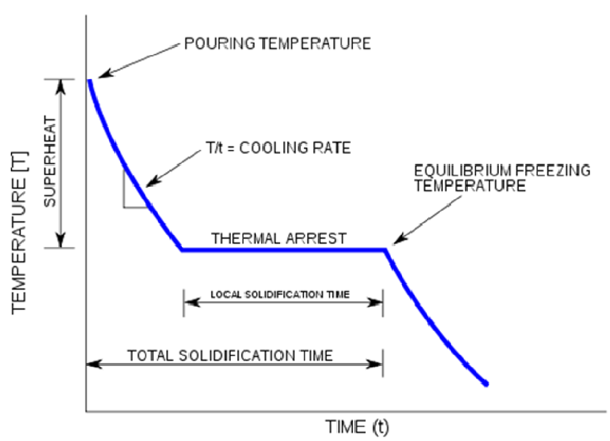



Fig. 1. The cooling curve

As showed in Fig. 2, at most castings the grain macrostructure, have three distinct zones: the chill zone, the columnar zone, and the equiaxed zone. The chill zone is named so because it occurs at the walls of the mold where the wall *chills* the material. Here is where the nucleation phase of the solidification process initiates. As more heat is evacuated the grains grow towards the center of the casting. These are thin, long *columns* that are perpendicular to the casting surface, which are undesirable because they have anisotropic properties. In the center the equiaxed zone contains spherical, randomly oriented crystals. These are desirable because they have isotropic properties. Long thermal arrests produce coarser granular crystallizations and favorize the equiaxed zones. In fact, the ideal bell would be monocrystalline: a single equiaxed nucleation. Traditional loam casted bells produce wonderful sounds thanks to their high quality resonating features, induced by very slow cooling processes.

On the other hand long cooling times are expensive. When the liquid material is poured into the relatively cooler mold, the cooling begins. The cooling rate is largely controlled by the mold material. Molding materials transfer heat from the casting into the mold at different rates, but anyway, low cooling rates demand heavier and complicated molds.

Besides the material costs the rigid conventional mold, that is designed to slow the cooling rate during the solidification stage, becomes inadequate for the last, but very long stage of the cooling. Although the metallic structure is already established, the cooling rate is now too low, which is rather useless and expensive. In fact, during the final stage, one should add another constraint to the cooling rate, aiming to minimize the internal stress of the casted product.

Our goal is to imagine a simple adaptive casting method, blending the traditional and the modern technologies.

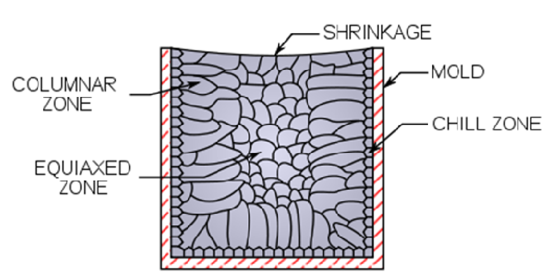



Fig. 2. The grain macrostructure

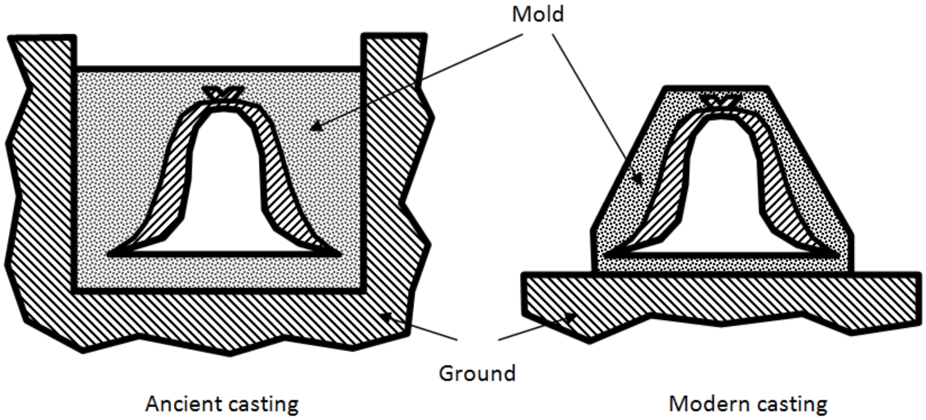



Fig. 3. The conventional castings

## II. The Complete Coating of the Cooling Mold

The active control of the cooling rate is possible, and able to essentially increase the quality of the casting. When heat must be removed quickly the mold may be provided with special heat sinks, called chills or with fins that can be later removed, in order to increase the cooling heat flow. When heat should be removed slowly, a riser or some padding may be added to the casting.

We are assuming that the padding of the casting may be transformed into an authentic coating. Few flexible insulating layers, with different thermal resistances, enable us to precisely control the heat flow from the casted metal to the natural environment (see Fig. 4).

In this perspective we must cope with some particular obstacles. However, we can find simple and cheap solutions for each of these obstacles:

1) The most important issue is the managing of the heat that is embedded into the metal. The conventional solution (large molds, sometimes buried into the ground) allows us to use steel or even aluminum in order to frame the molding.

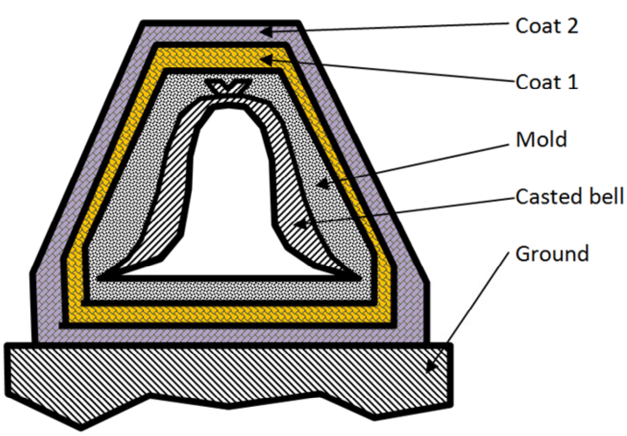



Fig. 4. The complete coating of the cooling mold

Since we want to transfer towards the flexible coats a great part of the insulating task, we will use thinner molds with steel frames, able to resist to the almost 1000°C temperature of the liquid bronze.

2) The cost of coated casting reduces because we use smaller molds. A further cost reduction appears by using recyclable insulating coats. The coats will be assembled out of insulating patches, made of ceramic fiber wool. Such way the overall thickness of the coat may be quickly changed in order to adjust the cooling rate.

The insulation used for controlling the cooling rate of the casted bronze may be made of layers of ceramic fiber wool (IBI-WOOL) sleeves or molds. IBI-WOOL is a ceramic fiber made from high-purity alumina (aluminum oxide $Al_2O_3$) and silica ($SiO_2$) melted in an electric furnace and finished to a fibrous state with compressed air [2].

IBI-WOOL can withstand service temperatures of 1,300 °C to 1,400 °C (melting point 1,760 °C), and has a much higher refractoriness and heat resistance than conventional refractory heat resistant materials. IBI-WOOL is used in bulk and molded form in place of conventional heat-resistant materials of all kinds (heat insulating fire bricks, castable, etc.), and is used in a broad range of kilns, furnace materials, casting materials, high-refractoriness heat-resistant materials, home appliance parts materials and automotive parts [2]. Its main physical characteristics are the following [3]: the useful temperature limit 1,300 °C, the melting point 1,760 °C, the specific gravity 2.7g/cm$^3$ and the specific heat 0.26 Kcal/kg·°C at 500-700 °C and 0.27 Kcal/kg· °C at 700-1000 °C.

IBI-WOOL sleeve is a feeder heat insulation sleeve of high thermal insulation molded cylindrically from bulk material with addition of an inorganic binder, and has numerous advantages over conventional feeder sleeves. It is widely used for casting, ranging from nonferrous alloy castings, including copper alloy and aluminum alloys, to ordinary castings. IBI-WOOL Sleeve can be manufactured in special shapes, sizes and harnesses other than the standard ones to meet customer's requests. IBI-WOOL molded articles are products molded from bulk material with addition of an inorganic binder and a trace organic binder, into shapes of all sorts meeting specific applications. Where combustion gas of an organic binder is undesirable, a special treatment is also possible to remove the gas [2].

3) The supervision of the controlled cooling casting needs specific adapted knowledge, and we need to achieve this supervision with as few sensors as possible. This can be done with the help of the computer modeling. A computer model of the thermal behavior of the casting system may assist the design of the mold and the real-time reconfiguration of its insulating coating system.

4) The major shortcoming of this method is inherent: extra room for the slow cooling molds is needed.

The development of a generic coated casting follows the next steps:

a) Pouring the liquid bronze into the mold;

b) Coating the mold with a first coat that is controlling the cooling rate of the liquid bronze, until the first signs of the solidification;

c) Coating the mold with a second coat which will reduce the cooling rate and allow the bronze to develop large equiaxed zones;

d) Removing the second coat when the solidification is done;

e) Removing the first coat when the desired properties of the bell are considered to be reached. In short time the casting will be accomplished.

This procedure can be further refined, by using more insulating coats.

The key issues of the method are the following:

- The correct sizing of the insulating coats, in the sense of the precise setting of the heat transfer coefficient. This can be done with the help of the mathematical model of the coated casting system;
- The precise determination of the right moments for installing the coats and for their removal. This can be done by special sensors [4] or with the help of a mathematical model.

## III. The Mathematical Model of the Cooling Casting

In some previous works we used a structural mathematical model that was successfully applied in the computer modeling of some thermal systems: air conditioned railway coaches (compartmented or no compartmented) and of greenhouses. This model can be adapted as well for the bronze casting. Essentially the model is represented by a first order equation (the Newton's law of cooling) with time varying coefficients:

$$\mathbf{V_b \cdot \rho_b \cdot c_b \cdot \frac{dT_b(t)}{d(t)} = \alpha \cdot S_b \cdot [T_e(t) - T_b(t)]} \qquad (1)$$

The model's variables are $\mathbf{T_b}$ the temperature of the casted bell and the environment temperature $\mathbf{T_e}$. Since the model is a structural one, we use physical parameters: $\mathbf{V_b}$ [m$^3$] the volume of the casted bell, $\boldsymbol{\rho_b}$ [kg/m$^3$] the density of the bronze and $\mathbf{c_b}$ the specific heat capacity of the bronze [J/kg·m$^3$] and $\mathbf{S}$ [m$^2$] the surface of the mold. The specific parameter, which captures the essence of the cooling process, is $\alpha$ [W/m$^2$·K]: the coefficient of the heat transfer through the surface of the mold. In fact $\alpha$ cumulates the insulating effects of the mold and of the insulating coats.

We have to observe that this model simplifies the complicated structure of the casting, by using the casted bell's data for the left member of the equation that is representing the heat source, and the mold's surface data for the right member, which models the heat flow. This assumption is correct only when the temperature of the casting is very homogenous, which is our case: a slow insulated process, where the most part of the heat transfer takes place at the interface between the mold and the environment.

However this is only an overall linear model, missing the essential stage of the solidification. During the solidification the mobile atoms of the liquid metal are conceding a part of their energy. That is why the model must be completed with $\mathbf{P_{sol}(T_b, t)}$ [W], the power conceded during the solidification, which is a nonlinear term.

$$\mathbf{V \cdot \rho_b \cdot c_b \cdot \frac{dT_b(t)}{d(t)} = \alpha \cdot S_b \cdot [T_e(t) - T_b(t)] + P_{sol}(T_b, t)} \qquad (2)$$

The precise identification of each coefficient may be done after experimental tests performed under controlled conditions. For a "first guess" we use step responses: we measure the evolution of the casting's temperature during cooling. The first guess is then optimized on behalf of other experimental training data. For the optimization stage we can use genetic algorithms, neural networks or different other optimizing methods as for instance one of the gradient techniques.

The model can be used as well for the calculus of temperature needed by the liquid metal when pouring it into the mold.

## IV. On the Implementation of the Model

We used a Matlab-Simulink implementation to test the model. Yet the model's simplicity facilitates its implementation in virtually any possible programming environment. The core of a C$^{++}$ like code may be constituted by the following expression:

**Tin[k]=Tin[k-1]+Ro·Cb·Alfa·S·(Tex[k-1])·Ts/(V·Rob·Cb)**

**+ Psol[k-1]·Ts/(V·Rob·Cb)** (3)

The discrete time is represented by the integer number of sampling periods: time = **k·Ts**. The simulation consists in the integration of the equation with the help of a **for** cycle.

Besides the classic Matlab and C$^{++}$ we decided to test this model with a new software package, which was developed by Logic Programming Associates. This package is targeting the web applications of the custom expert systems. VisiRule is a tool for creating decision support software by drawing charts [5]. WinProlog is a Windows version 4.800 of LPA-Prolog [6]. WebFlex is an Internet enabled version of the flex expert system toolkit. The LPA web based expert system WebFlex is basically an instance of a ProWeb application [7]. It is to remark that this LPA software package has a distinct web and agent orientation that is strongly recommending it for the web and multi agent applications. On the other hand the modeling of the differential equations is not taken into account.

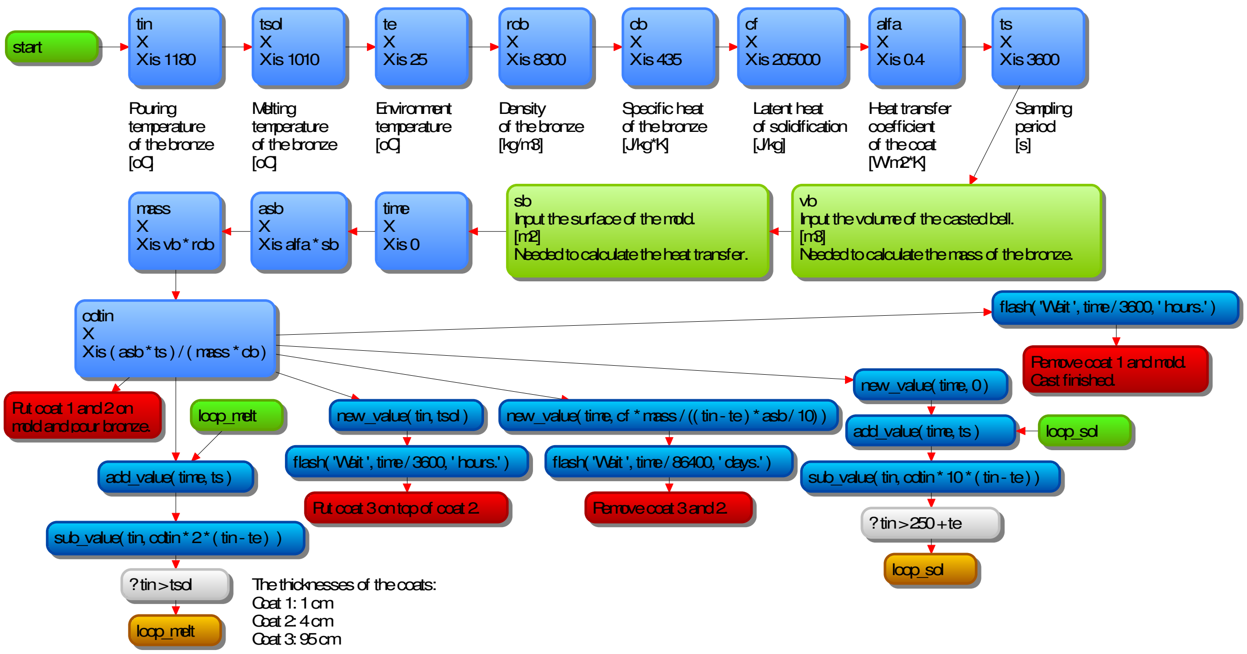



Fig. 5. The Visirule implementation of the control algorithm

## V. The Internal Model Expert System

We wish to introduce and to develop the concept of *Internal Model Expert System* IMES – an expert system provided with built-in internal models. Besides usual input variables the IMES inference uses the simulation results of the model.

For the LPA implementation we consider that the cooling process is controlled with three different insulating coats. Their thicknesses are calculated in order to ensure the heat transfer rate needed in different stages of the casting process.

The main model's inputs are the casted bronze volume and the mold's exterior surface. We use the mathematical model as an internal model, implemented inside the control software. The model calculates the cooling rates needed during the various stages of the cooling process and outputs the instructions for the human operators, namely the precise moments for the coating/uncoating of the mold with the three insulating coats.

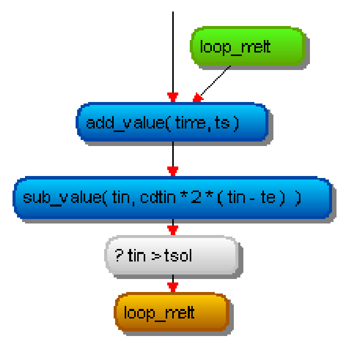
The constants we used in our tests are the following [8]:

- Bronze density: 8300 kg/m$^3$;
- Bronze specific heat: 435 J/kg·K;
- Bronze latent heat of solidification: 2,05*10$^5$ J/kg
- Insulation wool thermal conductivity: 0,04 W/m·K;
- Bronze melting temperature: 1010 °C;
- Bronze pouring temperature: 1180 °C;
- Environment temperature: 25 °C.

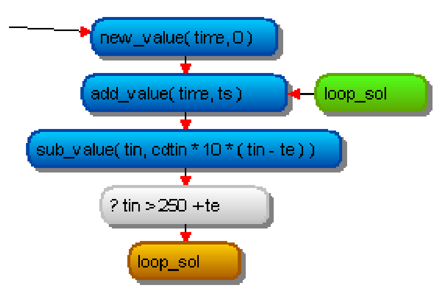
Their values are introduced through the green blocks.

The time evolution of the parameters is calculated by integrating the model's equations. When the model temperature reaches the bounds of the relevant cooling stages (the starting and the ending of the solidification and the temperature that is desired for the end of the slow cooling), the system alerts the human operator (the red conclusion blocks).

The VisiRule implementation of the two cooling stages is achieved by the following charts, which are equivalent to **for** loops, implementing the numeric integration of the model.




a) The cooling of the liquid phase




b) The cooling of the solid phase

Fig. 6. Implementing differential equations in VisiRule

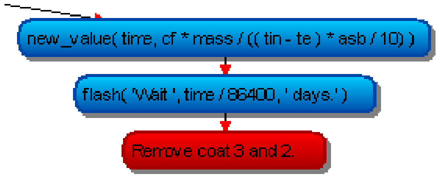



Fig. 7. The model of the solidification stage

The solidification process is modeled by the Fig. 7 block.

The duration of the solidification process is calculated with the following relation:

$$\mathbf{T_s = \frac{m\cdot c_f}{(T_{in} - T_e)\cdot \alpha \cdot S_b}} \qquad (4)$$

where $\mathbf{m = V\cdot \rho_b}$ is the mass of the casted bronze [kg], $\mathbf{T_s}$ [s] is the solidification time and $\mathbf{c_f}$ [J/kg] is the latent solidification heat [8].

For our tests we used a one hour sampling period.

## IX. Conclusions

The paper proposes a new approach for the bronze casting: the coated casting. By coating/uncoating the cooling casting in precise defined time moments, we can control the heat flow and thereby the cooling rate and the granularity of the final product. The flexible insulating coats are built from different thickness layers made of ceramic fiber wool.

The method is exemplified for the casting of the bells, a case where the granulation has a major impact on the product's quality.

An expert system controls the process. The expert system is realized with the help of general purpose expert system development software. The original contribution of the paper is to provide the expert system with an internal mathematical model, built out of generic visual commands (charts). This way we introduce the concept of the *Internal Model Expert System*. The internal model replaces the temperature sensors, which in this case are expensive and inconvenient.

Implementing differential equations by software tools that are initially designed for the linguistic description of the expert systems enriches the expert system technique. The internal model expert systems are able to manipulate new functionalities, which can be hardly described only by linguistic expressions.

Due to the web and agent orientation of the modern expert system software tools, we can anticipate a future development of the internal model web and multi agent applications.

## References

[1]. Wikipedia. „Casting – metalworking". http://en.wikipedia.org/wiki/ Casting_(metalworking)

[2]. Econosto. „Ceramic Fiber & Rock Wool". http://www.econostothai.com /Packing/Ceramic_FiberRock_Wool/ceramic_fiber_rock_wool.html.

[3]. Marujop. „Ceramic Fiber IBI Wool". http://www.maruojp.com/english %20contents/item/itemibiwool.html.

[4]. V.E. Balas, L.C. Jain. World knowledge for sensors and estimators by models and internal models**,** Journal of Intelligent and Fuzzy Systems**,** Volume 21, Number 1-2/2010, pp. 79-89.

[5]. R. Shalfield. „VisiRule user guide". Logic Programming Associates. 2008.

[6]. R. Shalfield. „LPA Win Prolog 4.800 user guide". Logic Programming Associates. 2008.

[7]. A. Westwood. „WebFlex Server user guide". Logic Programming Associates. 2008.

[8]. D. M. Stefanescu. „Science and Engineering of Casting Solidification (2nd ed.), Springer, 2008.

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