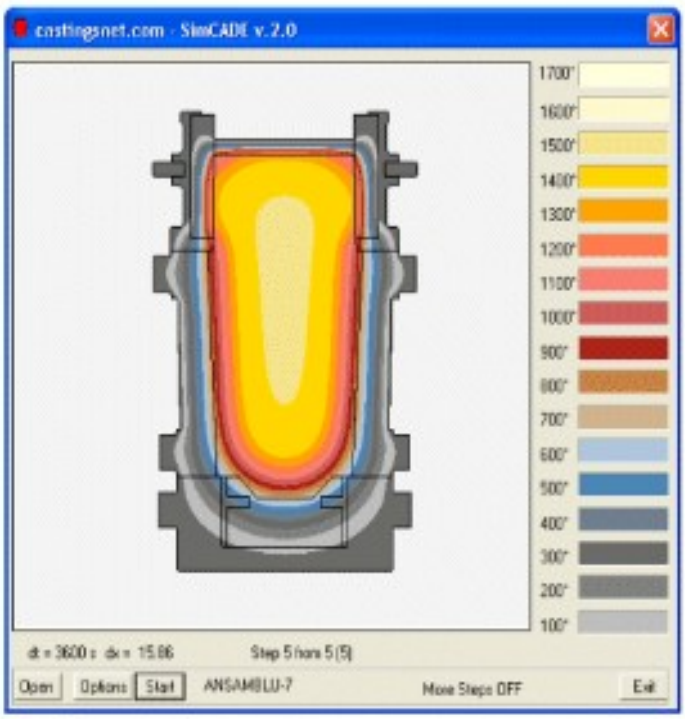
SIMCADE V.2.0
Solidification and Heat Transfer Simulation Software

SOLIDIFICATION AND HEAT TRANSFER SIMULATION SOFTWARE
DESIGN, ENGINEERING AND SCIENTIFIC APPLICATIONS



– 2011 -
Industrial Soft

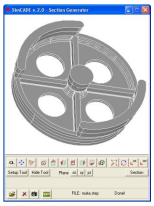
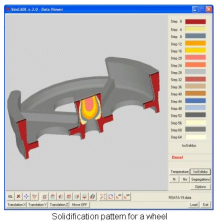
Industrial Soft

341-5 Graham, Montreal, Quebec, H3P 2C7, Canada - Phone: 1-(514) 342-5833 - info@castingsnet.com

Industrial Soft is a cost effective engineering and software development company **specialized in metal industry applications**. We are located in **Montreal, Canada** but we can serve you wherever you are in the world. We provide the following products and services:

1. Non destructive control service for porosity in castings

This service offers to the casting part manufacturer or buyer a tool to evaluate the internal quality of the final product. Using the manufacturing information as input data of the solidification simulation software the client may choose a product without porosity.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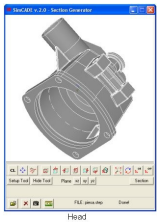
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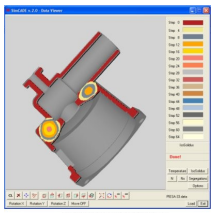
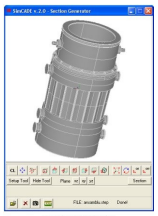

Solification pattern for a head

2. Non destructive control service for macro-segregation in steel ingots and forgings

This service allows to check by simulation if the ingot size, shape and chemical composition of steel poured are appropriate to avoid mechanical properties heterogeneity of steel ingots and forgings and minimize macro-segregation detected by ultrasonic inspection.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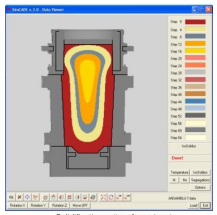
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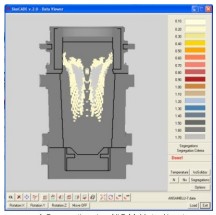
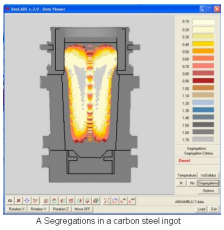
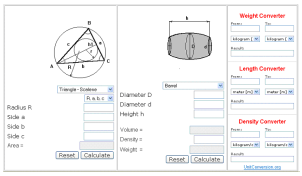
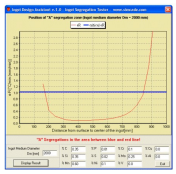
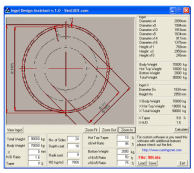
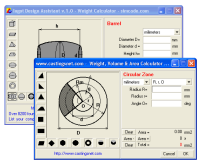
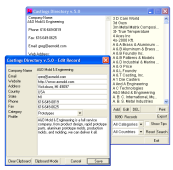

A Segregations in a NiCrMoV steel ingot

A Segregations in a carbon steel ingot

3. Custom solidification and heat transfer simulation software for design, engineering and scientific applications.

Our software comes with simple and easy installation programs, intuitive graphical user interface, and informative help files with instruction manuals.

5. Upgrade or customize your existing software

We have expertise in re-writing, modifying and debugging software code for design, engineering, scientific, databases and online applications using following languages:

- engineering and scientific applications (Visual C++, Visual Basic, Pascal);
- databases applications (mySQL, sqlite3, Visual Fox, DBase, Access);
- online applications (PHP, HTML, JavaScript, Ajax, Flex).

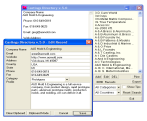
4. Mold assembly projects for big and small ingots

This service provides a complete mold assembly project for pouring ingots up to 350 tons. Also, we offer projects for hollow ingots or 2, 4 or 8 bottom poured ingots. The size and shape of the ingots will be chosen according to the steel type poured and the forging size in order to minimize A-segregations type defects. Contact us if you need more info about this service.


6. Online advertising on castingsnet.com and website design - http://castingsnet.com/premium.htm

castingsnet.com, online since 1999, is the biggest online directory and search engine that lists foundries, foundry equipment and foundry supplies. If you already own a website, we offer cost effective advertising on our online directory; if not, we can build a website that will inform people about your products and services and serve as a 24/7 advertisement for your company. To increase the visibility of your company, we list your website on castingsnet.com for free of charge.

7.Castings Directory v.5.0 – CD-ROM – http://castingsnet.com/cdrom.htm



Castings Directory 5.0 is the CD-ROM version of our online search engine for foundries and related companies – **castingsnet.com** Very simple and easy to use, even by people with only basic computer skills, the software provides virtually instant access to over 8.200 worldwide foundries, foundry equipment and foundry supplies.

SimCADE v.2.0 -
Heat Transfer and Solidification Simulation Software

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Introduction

SimCADE v.2.0 is a computer program developed by Industrial Soft to simulate the heat transfer and solidification process of molten metal. The software can simulate cooling and solidification of metal in the mold taking into account the influence of casting part geometry, phase transformations and environmental conditions upon the solidification process.

The finite element method (FEM) is used to solve the heat transfer equation having in view the initial temperatures, pouring temperature, boundary conditions, material properties and the latent heat of the solidifying metal.

1 Mathematical model used to simulate the heat transfer during the solidification process

The equation used to describe the heat flow during the solidification process in two coordinates for transient regime is the following:

$$\frac{\partial}{\partial x}[\lambda(T)\frac{\partial T}{\partial x} + \lambda(T)\frac{\partial T}{\partial y}] = \rho C_p \frac{\partial T}{\partial t} \qquad (1)$$

where T represents temperature, λ - conductivity, C - specific heat, t - time and ρ - density. The initial condition (2) and boundary condition (3) attached to Equation (1) to obtain a complete model are:

[1] O.Bogdan has been for ten years with the Research & Design Department, IMGB (Dossan IMGB S.A.)

$$T = T_0,\ t = 0 \tag{2}$$

$$\lambda\left(\frac{\partial T}{\partial x}n_x + \frac{\partial T}{\partial y}n_y\right) + \alpha\,(T - T_0) = 0,\ \forall P(x,y) \in S_\alpha \tag{3}$$

where T_o represents temperature at initial moment and α is the heat transfer coefficient on the surface S_α.

During the solidification process a significant factor is the latent heat which works like an external source of heat. To obtain a valuable model it is necessary to include this factor in our mathematical model. There is a lot of methods to include this external source in the heat transfer model. We use the following relation:

$$C_1' = C_1 + \frac{L}{\delta T} \tag{4}$$

where C'_1 represents the specific heat which include the latent heat, C_1 - specific heat without latent heat, L - latent heat and δT - the differences between liquidus and solidus temperatures.

Because the analytical equations cannot be used to realize the computer program it is necessary to transform it into an integral model. Knowing the differential equation (1), initial (2) and boundary condition (3) the integral equation for mathematical model is:

$$\pi = \int_V \tfrac{1}{2}\left[\lambda_T\left(\frac{\partial T}{\partial x}\right)^2 + \lambda_T\left(\frac{\partial T}{\partial y}\right)^2\right]dV + \int_V \rho\, C_p \frac{\partial T}{\partial x}\,dV + \int_{S_\alpha} \tfrac{\alpha}{2}(T - T_a)\,dS \tag{5}$$

Having in view that the analyzed domain V can be broken into finite elements with quadrilateral shape, using the linear functions we can describe the temperature with the following equation:

$$\hat{T}(x,y,t) = N_1(x,y)T_1(t) + N_2(x,y)T_2(t) + N_3(x,y)T_3(t) + N_4(x,y)T_4(t) \tag{6}$$

where $N_1(x,y)$, $N_2(x,y)$, $N_3(x,y)$ and $N_4(x,y)$ represents shape functions and $T_1(t)$, $T_2(t)$, $T_3(t)$ and $T_4(t)$ the temperatures in finite element nodes. With this last relation and imposing the stationary conditions for Equation (5), we have the following equation:

$$\sum_{1}^{n} \left(\int_{V^e} B^T D B T^e dV + \int_{V^e} \rho C_p \frac{\partial}{\partial t} N dV + \int_{S_\alpha^e} N_{N^T} T^e dS + \int_{S_\alpha^e} \alpha T_\alpha N^T dS = 0 \right) \qquad (7)$$

In matriceal form this equation can now be written as follows:

$$K_1^e \dot{T}^e + (K_2^e + K_3^e) \cdot T = K_4^e \qquad (8)$$

After assembling all elements of analyzed domain we obtain the final equations:

$$K_1 \dot{T} + (K_2 + K_3) \cdot T = K_4 \qquad (9)$$

To obtain the temperatures in transient regime we use finite differences method. The equation which gives the initial temperatures for a new cycle of computing is:

$$\left(\frac{2}{\Delta t} K_1 + K_2 + K_3\right) \cdot T_{n+1} = \left(\frac{2}{\Delta t} K_1 - K_2 - K_3\right) \cdot T_n + (K_{4,n+1} + K_{4,n}) \qquad (10)$$

Using the last equation we can compute all temperatures at time t+dt if we know the temperature at time t.

2 Heat Transfer Simulation Software

Using the mathematical model described, we have developed a computer program, SimCADE v.2.0, to simulate the heat transfer during the solidification process. The software simulates cooling and solidification of metal so that the effects of various manufacturing parameters and environmental conditions upon the solidification process can be examined.

The computer program, written in C++ language, take into account the internal sources and variation of material properties with temperature. The software uses over 450.000 finite elements to obtain an accurate geometrical description of the domain. The necessary time to compose the problem and solve the equations system is about 60 seconds for a PC computer system.

The successive approximation method with a variable supra-relaxation factor is used to solve the equation system. The software has routines for auto-meshing the analyzed geometry and displays results in graphical mode.

The main simulation system of the software consists of three processors:
- the pre-processor module for reading the 3D CAD drawing of the analysis model and automatic generation of the finite element mesh;
- a simulator for the solidification process and;
- the post-processor module to display the results.

The software has been tested for industrial conditions in slab reheating and casting solidification applications. The results from heat transfer simulation have been close to data taken in industrial conditions.

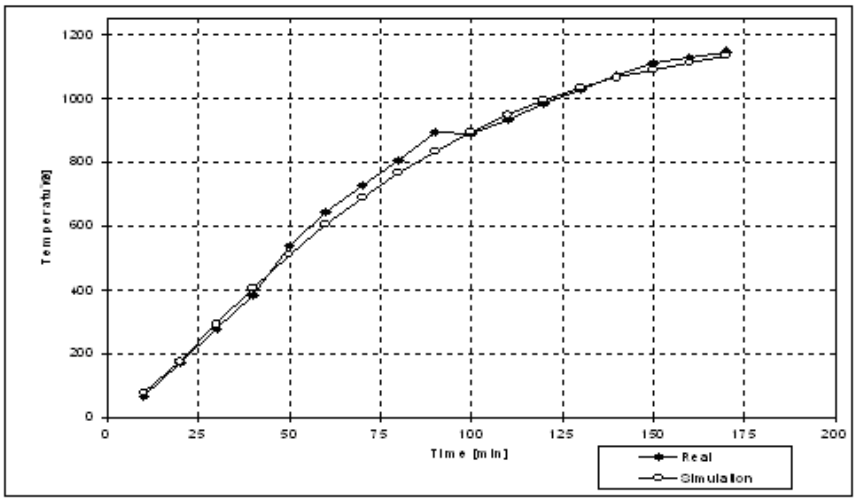

Figure 1. SimCADE v.2.0 - Software validation [20]

3 Macro Segregation Simulation Module

Macro segregation simulation module of the software is based on Suzuki and Miyamoto criterion, a criterion that is presently the most used criterion to predict A-segregation in steel ingots. The solidification simulation software SimCADE v.2.0 calculates the cooling and solidification rate by simulation,

compares it against Suzuki and Miyamoto criterion value and plots the macro segregation area in regions that contain values below a critical value.

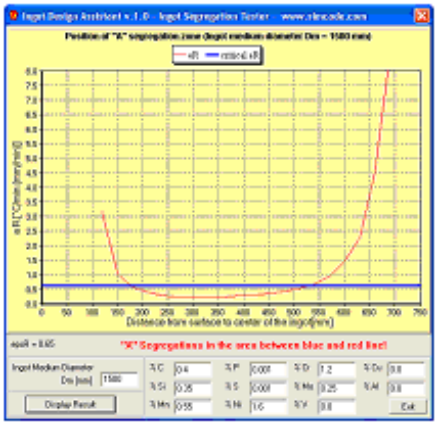

Figure 2. SimCADE v.2.0 - Macro segregation module

Suzuki and Miyamoto criterion is a local thermal parameter defined as:

$$R \cdot V^{1.1} \leq \alpha$$

where R is cooling rate and V is solidification rate, both of them are evaluated at a specified temperature near the end of solidification. The critical value α, has been established function by chemical composition of the steel and material type.

Suzuki and Miyamoto, in their paper, have determined empirically the functional form of this criterion and offered a physical model as justification. The model is based on liquid and solid diffusion equation applied for carbon and Scheil's equation applied for all elements except carbon.

4 Porosity Simulation Module

Porosity simulation module of the software is based on Niyama dimensionless criterion, a criterion that is presently the most used method to predict feeding related shrinkage porosity caused by shallow

temperature gradients. The solidification simulation software SimCADE v.2.0 calculates the temperature gradient and cooling rate by simulation, compares it against the Niyama criterion and plots the shrinkage porosity in regions that contain values below a value established function by material type. The Niyama criterion is a local thermal parameter defined as

$$\mathbf{Ny} = \mathbf{G}/\sqrt{\dot{\mathbf{T}}}$$

where G is the temperature gradient and T is the cooling rate, both of which are evaluated at a specified temperature near the end of solidification.

E. Niyama, in his paper, has determined empirically the functional form of this criterion and offered a physical model as justification. The model is based on Darcy's law, which relates the interdendritic feeding-flow velocity to the pressure drop across the mushy zone.

5 Examples and Applications

5.1 Steel Ingot Solidification – Macro segregation simulation

A-segregations commonly known as macro segregation, often found in large steel ingots, present channels enriched by sulfur, carbon, phosphorus and is one of the reasons why the mechanical properties of the final product are anisotropic.

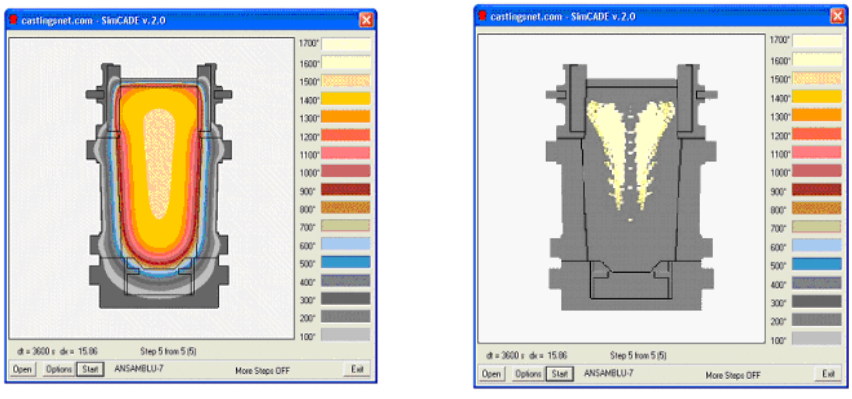

Figure 3. Steel Ingot Solidification - Macro segregation simulation -

Macro segregation forms in the zone of columnar grains at the regions with structure characterized by the transition from the columnar grains to large equiaxed grains.

Using Suzuki and Miyamoto criterion, the solidification simulation software can predict the macro segregation in ingots and forgings.

5.2 Steel Ingot Solidification – Porosity simulation

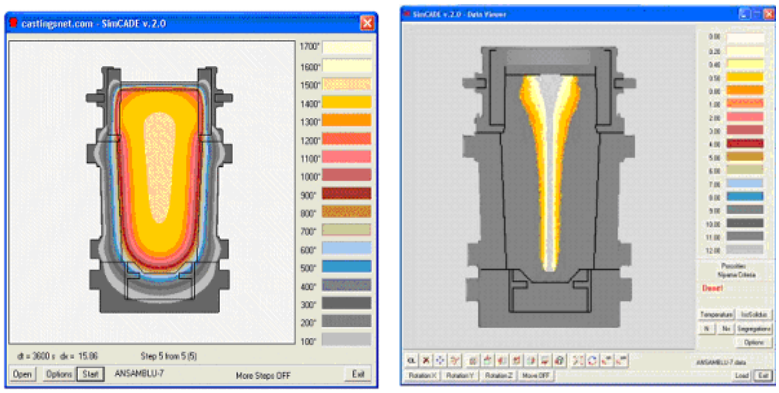

Figure 4. Steel Ingot Solidification – Porosity simulation -

5.3 Simulation of hollow ingot solidification

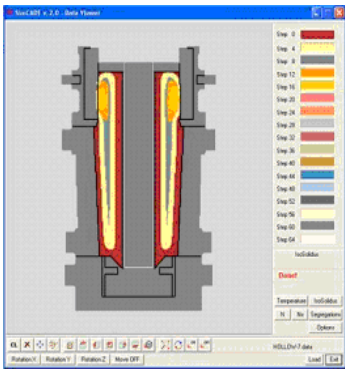

Figure 5. Hollow ingot solidification

5.4 Aluminum Castings Solidification – Porosity simulation

One of the most important factor that affects the internal quality of castings is the solidification process. Voids and porosity in castings are caused either by accumulation of gas or material shrinkage. Gas porosity typically has a smooth regular shape and appears near casting's surface. Shrink porosity is characterized by irregular shape and rough walls and inclusions. It happens in almost all alloys as they contract during cooling from the pouring temperature to the solidus. This is one of the most common defect in metal casting due to design technology.

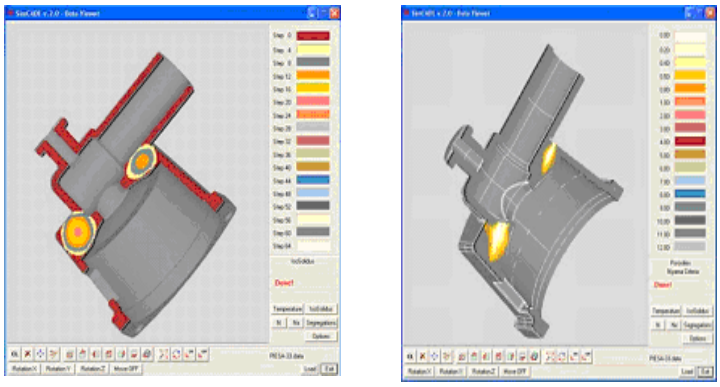

Figure 6. Aluminum Castings Solidification - Porosity simulation -

Using Niyama criterion, SimCADE v.2.0 can predict shrinkage porosity position in aluminum castings.

5.5 Composite materials solidification

To have a composite material with a high uniformity of dispersed material and high mechanical properties is impossible without a strict control of the solidification process parameters. The simulation software allows to analyze the influence of particle material properties and particle temperature over the solidification front geometry.

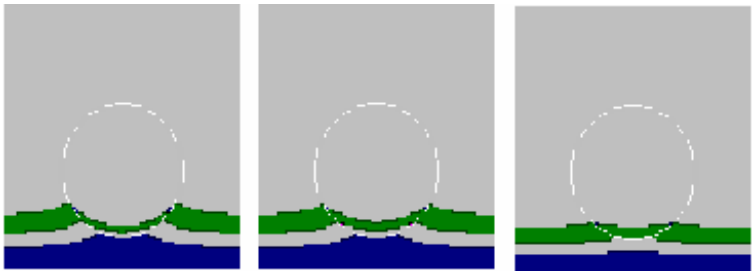

Figure 7. Solidification of composites materials with aluminum alloy matrix

5.6 Titanium Alloy Castings Solidification – Porosity simulation

Using porosity simulation module and Niyama criterion, SimCADE v.2.0 can verify if in a titanium alloy casting part will exist shrinkage porosity or not.

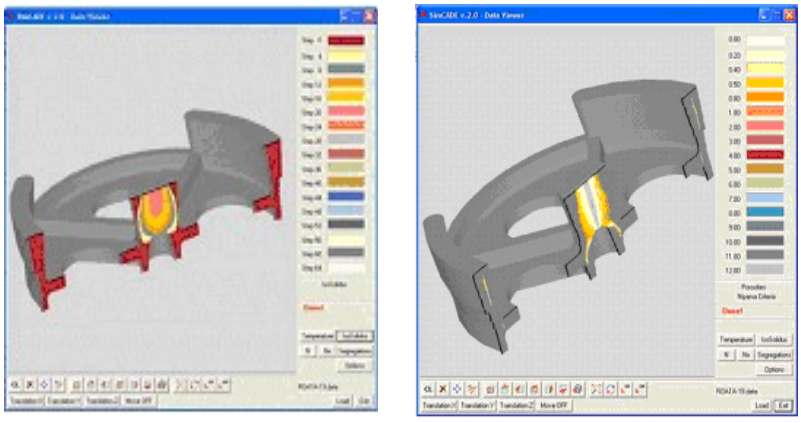

Figure 8. Titanium Castings Solidification – Porosity simulation

5.7 Heat transfer during primary structure growth

This application shows the temperature field by coupling a statistical model, used to generate the primary structure, and SimCADE v.2.0 for heat transfer simulation.

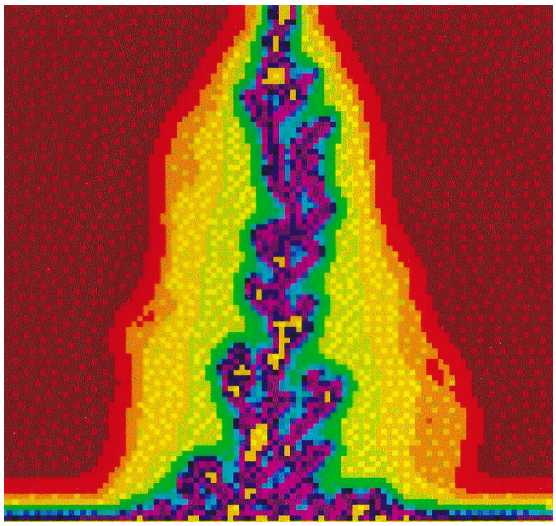

Figure 9. Heat transfer simulation during primary structure growth

5.8 Superficial heat treatment simulation

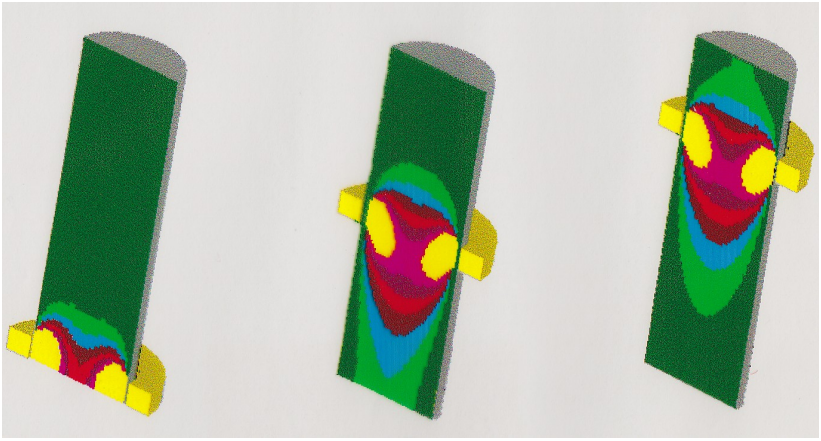

Figure 10. Heat transfer simulation during superficial treatment of a bar

6 Conclusions

Using the simulation software SimCADE v.2.0, there are five technical conclusions. Here is a short description of them:

(1) To simulate the heat transfer or solidification process, the software needs a 3D drawing; it must be complete (no missing faces or dangling edges) and accurate (features and dimensions);

(2) The software requires accurate values of thermo-physical properties and Niyama or Suzuki - Miyamoto critical values. For non standard combination of metals and processes the user has to establish a controlled set of experiments to accommodate the application;

(3) Using the simulation software to analyze the solidification conditions before pouring, the manufacturer can evaluate the technology before committing to expensive tooling and may take better decisions, save time, energy and improves the internal quality of the final product;

(4) With manufacturing records as data input for the simulation software, the casting or forging part buyer can know if the final product has homogeneous mechanical properties and is free of internal defects as porosity or macro segregation. More, the software can give information about the defect position on the section of the final product;

(5) SimCADE v.2.0 can help in identifying the location of shrinkage defects (porosity, centerline shrinkage, sink and pipe) in castings and macro segregation in steel ingots fairly accurately but other defects related to solidification and subsequent cooling (such as cracks, tears and distortion) are difficult to predict reliably.

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