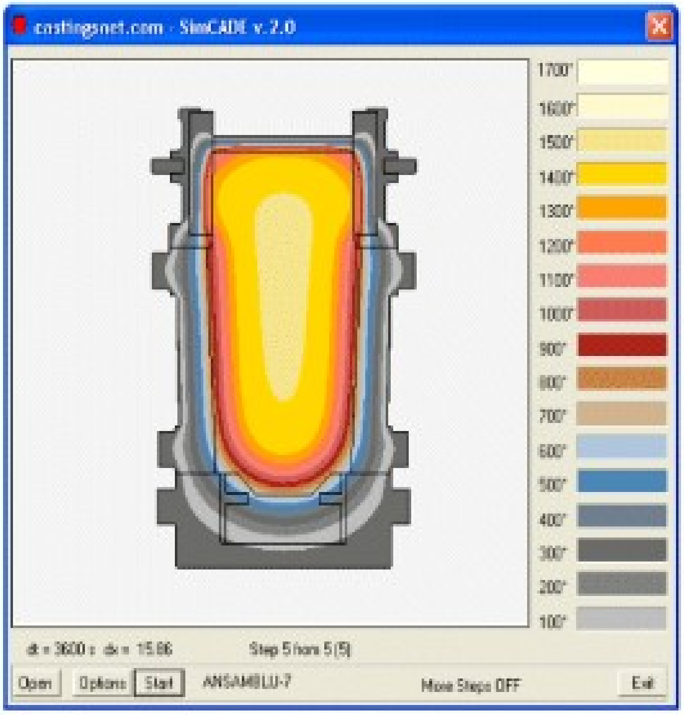
NON DESTRUCTIVE CONTROL
MACRO-SEGREGATION
50T STEEL INGOT

NON DESTRUCTIVE SOFTWARE CONTROL FOR MACRO SEGREGATION IN AISI4340 50T STEEL INGOTS



– 2011 -
Industrial Soft

Industrial Soft

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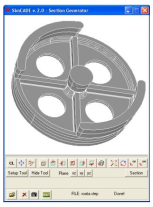
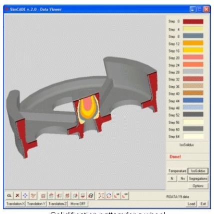
Industrial Soft is a cost effective engineering and software development company **specialized in metal industry applications**. We are located in **Montreal, Canada** but we can serve you wherever you are in the world. We provide the following products and services:

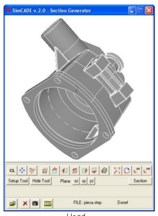
1. Non destructive control service for porosity in castings

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.

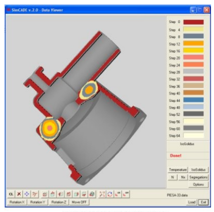




Solidification pattern for a wheel



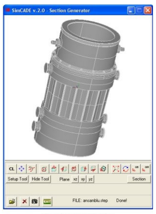
Head



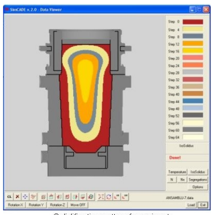
Solification pattern for a head

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

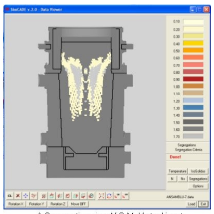
This service allows to check by simulation if the ingot size, shape and chemical composition of steel poured are appropriate to avoid mechanical properties heterogeneity of steel ingots and forgings and minimize macro-segregation detected by ultrasonic inspection.



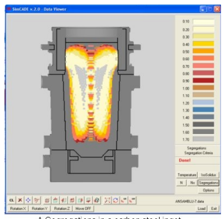
Ingot Mold Assembly



Solidification pattern for an ingot



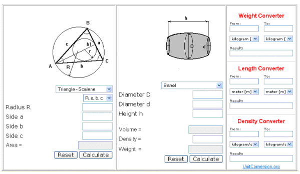
A Segregations in a NiCrMoV steel ingot

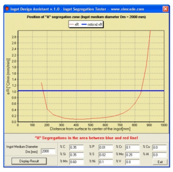


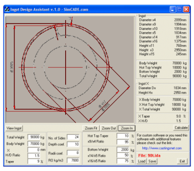
A Segregations in a carbon steel ingot

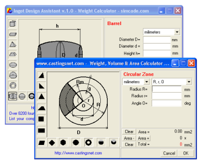
3. Custom solidification and heat transfer simulation software for design, engineering and scientific applications.

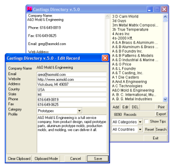
Our software comes with simple and easy installation programs, intuitive graphical user interface, and informative help files with instruction manuals.











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).

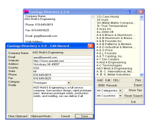
4. Mold assembly projects for big and small ingots

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.

If you need this software control made for a particular steel grade or ingot size please contact Ovidiu Bogdan at bogdan@castingsnet.com

A New Software Tool for Non Destructive Control of Steel Ingots and Forgings

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Abstract

The objective of this paper is to analyze the solidification simulation software use as a tool for non destructive control for macro segregation in steel ingots and forgings. To this purpose, a mathematical model and the computer program SimCADE v.2.0 has been employed to simulate the solidification process of a AISI 4340 steel grade ingot. Cooling and solidification rate calculated by simulation have been correlated with Suzuki and Miyamoto criterion, the most used criterion for prediction of macro-segregation in steel ingots. The results are useful not only for ingots manufacturers to optimize their technologies and tools but also for forging parts buyers. Using the manufacturing information as input data for the solidification simulation software, the forging parts buyer may choose a supplier that offers forgings with increased material and mechanical properties homogeneity.

1 Introduction

It is known that one of the most important factors that affect the internal quality of forging products is the solidification process. 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. 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.

In order to use the solidification simulation software to appreciate the macro segregation in ingots and forgings, we realized a series of numerical simulations of the solidification process of the ingot, calculated cooling and solidification rate, applied Suzuki and Miyamoto criterion and plotted the macro segregation area on the longitudinal section of the ingot.

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

2 The mathematical model to simulate 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:

$$T = T_0, t = 0 \qquad (2)$$

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

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:

$$C_1^{'} = C_1 + \frac{L}{\delta T} \qquad (4)$$

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:

$$\pi = \int_V \frac{1}{2}[\lambda_T(\frac{\partial T}{\partial x})^2 + \lambda_T(\frac{\partial T}{\partial y})^2]dV + \int_V \rho\ C_p \frac{\partial T}{\partial x} dV + \int_{S_\alpha} \frac{\alpha}{2}(T - T_\alpha)dS \qquad (5)$$

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:

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

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:

$$\sum_1^n (\int_{V^e} B^T DBT^e dV + \int_{V^e} \rho\, C_p \frac{\partial}{\partial t} NdV + \int_{S_\alpha^e} N_{N^T} T^e dS + \int_{S_\alpha^e} \alpha\, T_\alpha\, N^T dS = 0 \qquad (7)$$

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:

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

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

3 The computer program

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 in 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.

4 Macro Segregation Control Module

Macro segregation prediction 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. Suzuki and Miyamoto criterion is a local thermal parameter defined as:

$$\mathbf{R \bullet V^{1.1} \leq \alpha}$$

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.

5 Numerical experiments

5.1 Initial conditions, boundary conditions, material properties

The limits of the chemical composition of AISI 4340 steel grade are shown in Table 1. Liquidus and solidus temperature taken in simulation have been 1490°C and 1430°C, respectively.

Table 1. Chemical composition of AISI 4340 steel

%C	%Si	%Mn	%Cr	%Mo	%Ni
0.36~ 0.44	0.10~ 0.35	0.45~ 0.70	1.00~ 1.40	0.20~ 0.35	1.30~ 1.70

The emissivity values on the outside surface of the mold has been assumed to be a function of temperature and estimated at 0.75 - 0.95. The value of the heat transfer convection coefficient on the outside surface of the mold has been 15 kcal/m²h°C. The upper surface of the ingot has been considered as insulated. The material data of the mold and AISI 4340 steel used in these numerical experiments are given in Table 2. The pouring and initial mold temperature used in these experiments have been 1590°C and 20°C, respectively.

Table 2.Materials and thermal properties used in simulation

	Conductivity	Specific heat	Latent heat	Density
	W/m°K	J/kg°K	kJ/kg	kg/m³
AISI 4340	33.0	480	267.0	7800
Mold (Grey Iron)	59.0	460	-	7000

The geometry of the ingot used in solidification process simulation is shown in Figure 1.

Figure 1. 3D geometric model of the 50T ingot taken in simulation

5.2 Macro-segregation non destructive control

The isosolidus curves on the longitudinal section of the ingot are shown in Figure 2 and the macro segregation area in Figure 3.

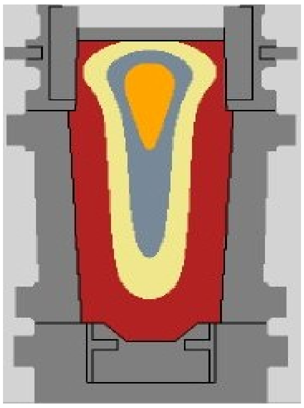

Figure 2. Isosolidus curves of the ingot (longitudinal section)

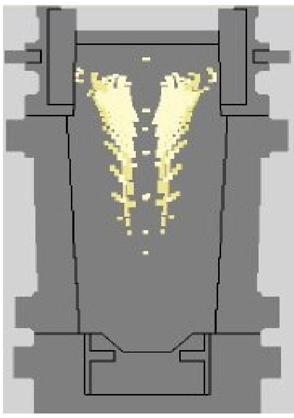

Figure 3. Macro segregation area and non destructive control results

6 Conclusions

Using the simulation software, there are three technical and two related to human and material resources conclusions. Here is a short description of the problems the user may encounter using the solidification simulation software as a non destructive control tool for macro segregation in steel ingots and forgings:

(1) The first difficulty is getting the input data required for solidification simulation software, especially the geometric information. The 3D solid model of the mold assembly is required; it must be complete (no missing faces or dangling edges) and accurate (features and dimensions);

(2) Another major challenge is material data information and the critical value of Suzuki and Miyamoto criterion. The software requires accurate values of thermo-physical properties and heat transfer coefficient. This may not be available in the software database, especially for non-standard materials and, for this reason, the user has to establish a set of experiments to accommodate the application;

(3) The last technical difficulty is correct prediction of a specific defect. Solidification simulation software can help in identifying the location of macro segregation fairly accurately but other defects related to solidification and subsequent cooling (such as cracks and tears) are difficult to predict reliably.

Even if the user can overcome the above technical difficulties, there are two more challenges in terms of resources:

(1) The first resource challenge is the technical expertise required to implement and use the software, which greatly depends on the complexity of the software. Most of the simulation software needs weeks of technical support for engineers to learn about all the features of the software and use them effectively;

(2) The second resource difficulty is about the economic viability of the simulation software. Most of the simulation software available today are relatively expensive for small and medium companies.

With customers expecting ingots and forgings of assured quality delivered within the shortest possible time, using of simulation software as a tool for non destructive control has become a necessity.

A cost effective solution for small and medium companies or forging part buyer to fix the challenges concerning non destructive control for macro segregation and material heterogeneity of steel ingots and forgings may be the service offered by Industrial Soft.

References

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2. *Critical Conditions for the Formation of "A" Segregation In Forging Ingots* - Hitohisa Yamada, Takashi Sakurai and Tomoo Takenouchi

3. *Estimation of Forming Condition of Center Porosity In Forging Ingot - Hitohisa* Yamada, Takashi Sakurai, Tomoo Takenouchi and Yoshiyuki Iwanami

4. *Estimation of the Formation of A-Segregation In Steel Ingot In Terms of the Chemical Composition of Steel* - Osamu Haida, Shinobu Okano, Toshihiko Emi, and Goro Kasai

5. *Appearance of "A" Segregation In Forging Ingots and Influencing Factors* - Hitohisa Yamada, Takashi Sakurai and Tomoo Takenouchi

MACRO SEGREGATION NON DESTRUCTIVE CONTROL

SERVICE COST ESTIMATION

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Macro-segregation Non Destructive Control -

50T Ingot
Material: AISI 4340

Task		Task duration		Software amortization		Total Cost
		Time [min.]	Cost USD	Time [min.]	Cost USD	USD
1	3D Drawing	240	140.00			140.00
2						
3						
4						
5	Macro-segregation Non Destructive Control	205	181.67	105	175.00	356.67
		445 (7H)	322.00	105 (2H)	175.00	496.67 USD
			.			0.00
					Total	496.67
					Paid	0.00
					Due	496.67

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Macro-segregation Non Destructive Control -
Material: AISI 4340
Ingot analysis

	Analyzed Parameters			
	Default values			
Activate / Deactivate	1			
Number of simulations	1			
Task	**[min]**	**Time per task [min]**	**Total min**	**Cost USD**
Section generation	15		**15**	**10**
Geometrical model generation	20		**20**	**13**
Physical model generation	20		**20**	**13**
Heat transfer simulation	15		**15**	**13**
Isosolidus curves	15		**15**	**13**
Segregation prediction	20		**20**	**20**
Porosity prediction				
Data analysis & Report editing	100		**100**	**100**
Total	205		**205**	**182**
Software amortization	105		**105**	**175**
			USD	**357**

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Rate per task

3D Drawing	**35**	USD/hour
Step file generation	**40**	USD/hour
3D Section generation	**40**	USD/hour
Geometric model generation	**40**	USD/hour
Physical model generation	**40**	USD/hour
Heat Transfer Simulation	**50**	USD/hour
Isosolidus curves	**50**	USD/hour
Segregation prediction	**60**	USD/hour
Porosity prediction	**60**	USD/hour
Data analysis & Report editing	**60**	USD/hour
Software Amortization Rate	**100**	USD/hour

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Task Duration

3D Drawing	**240**	min.
Step file generation	**10**	min.
3D Section generation	**15**	min.
Geometric model correction	**20**	min.
Physical model generation	**20**	min.
Heat Transfer Simulation	**15**	min.
Isosolidus curves	**15**	min.
Segregation Prediction Module	**20**	min.
Porosity Prediction Module	**20**	min.
Data analysis & Report editing	**100**	min.