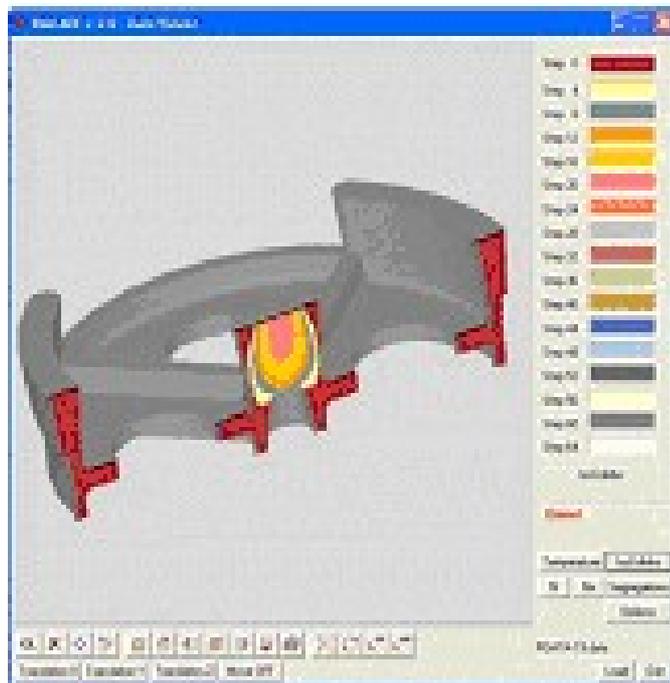# NON DESTRUCTIVE CONTROL
TITANIUM ALLOY CASTINGS

NON DESTRUCTIVE SOFTWARE CONTROL FOR POROSITY
TI6AL4V TITANIUM ALLOY CASTINGS

− 2011 -
Industrial Soft

Industrial Soft

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:
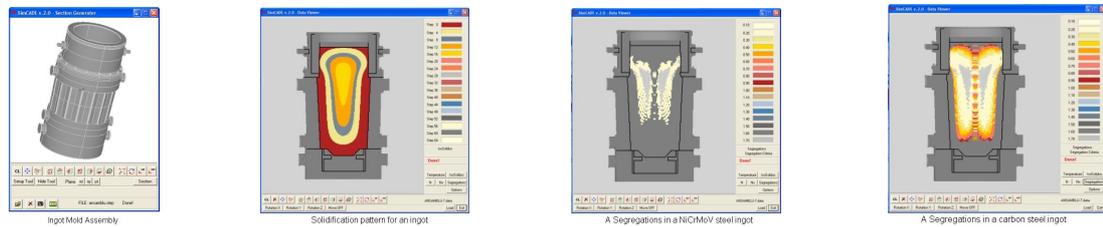
1. Non destructive control service for porosity in castings

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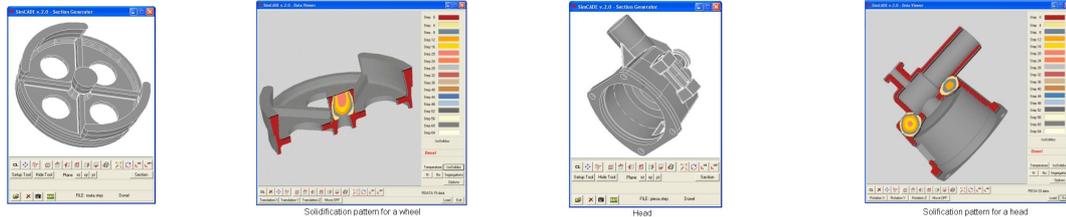
2. Non destructive control service for macro-segregation in steel ingots and forgings

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.
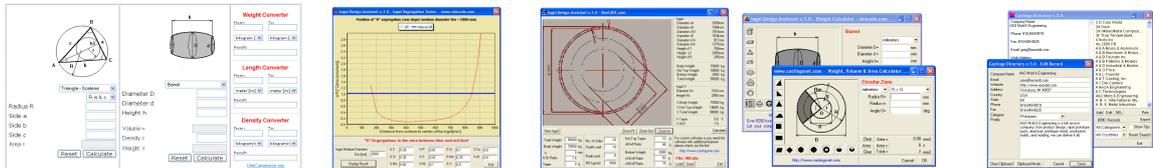
5. Upgrade or customize your existing software

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 titanium alloy casting part please contact Ovidiu Bogdan at bogdan@castingsnet.com

A New Software Tool for Non Destructive Control of Titanium Alloy Castings

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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 porosity in titanium alloy castings. To this purpose, a mathematical model and the computer program SimCADE v.2.0 has been employed to simulate the solidification process of a Ti6Al4V titanium alloy casting part. Cooling rate and temperature gradient calculated by simulation have been correlated with the Niyama criterion, the most used criterion for prediction of porosity in metal casting parts. The results are useful not only for castings manufacturers to optimize their technologies but also for casting parts buyers. Using the manufacturing information as input data for the solidification simulation software, the buyer may choose a supplier that offers a casting product without porosity.

1 Introduction

It is known that one of the most important factors that affect 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 paper refers to the shrinkage porosity. This is one of the most common defect in metal casting due to design technology.

Manufacturing a casting product with a high homogeneity of mechanical properties is impossible without a strict control of the porosity and solidification process variables. In order to verify if the casting part will have porosity or not, we realized a series of numerical simulations, applied the Niyama criterion and plotted porosity area.

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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:

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

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:

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

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

where T_0 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:

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

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:

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

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:

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

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 Porosity Non Destructive Control Module

Porosity non-destructive control module of the software is based on Niyama criterion, a criterion that is presently the most widely used criterion to predict feeding-related shrinkage porosity caused by 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:

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

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 Numerical experiments

5.1 Initial conditions, boundary conditions, material properties and geometry data

The titanium alloy taken into consideration for this simulation is Ti6Al4V, an alloy used for aircraft turbine engine components, aircraft structural components, aerospace fasteners, high-performance automotive parts, marine applications, medical devices, and sports equipment. The chemical composition of Ti6Al4V alloy is shown in Table1. Liquidus and solidus temperature have been 1660°C and 1604°C, respectively.

Table 1.Chemical composition of Ti6Al4V titanium alloy

%Al	%V	%C	%Fe	%O2	%N2	%H2	%Ti
5.60~ 6.75	3.50~ 4.50	max 0.1	max 0.3	max 0.2	max 0.05	max 0.015	balance

The emissivity value on the outside surfaces of the mold and hot top were assumed to be a function of temperature and estimated to be 0.75 - 0.95. The heat transfer convection coefficient on the outside surface of the mold and hot top was 15 kcal/m²h°C. The upper surface of hot top has been taken as insulated. The material data of materials used in these numerical experiments are in Table 2.

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
Ti6Al4V	6.7	526	419	4430
Mold (Grey Iron)	59.0	460	-	7000

Pouring and mold temperature have been 1700°C and 20°C, respectively. The geometry of the cast part taken in simulation is shown in Figure 1.

The simulation has been made with the solidification simulation software SimCADE v.2.0, created by Industrial Soft.

The transitory regime have been used in all numerical experiments to calculate the temperature gradient, cooling rate and Niyama criterion distribution on longitudinal and transverse section of the casting part.
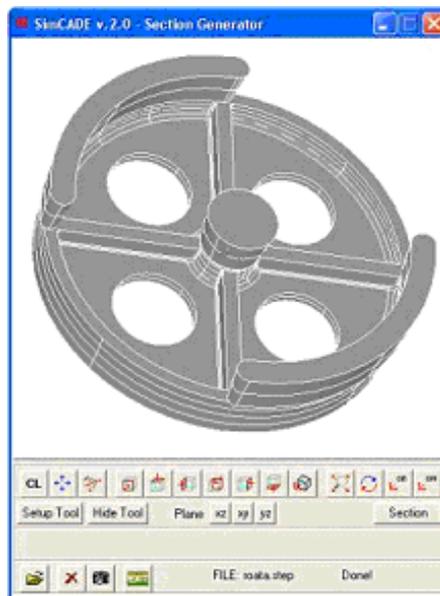

Figure 1. 3D geometric model of casting part taken in simulation

5.2 Porosity non destructive control in longitudinal section

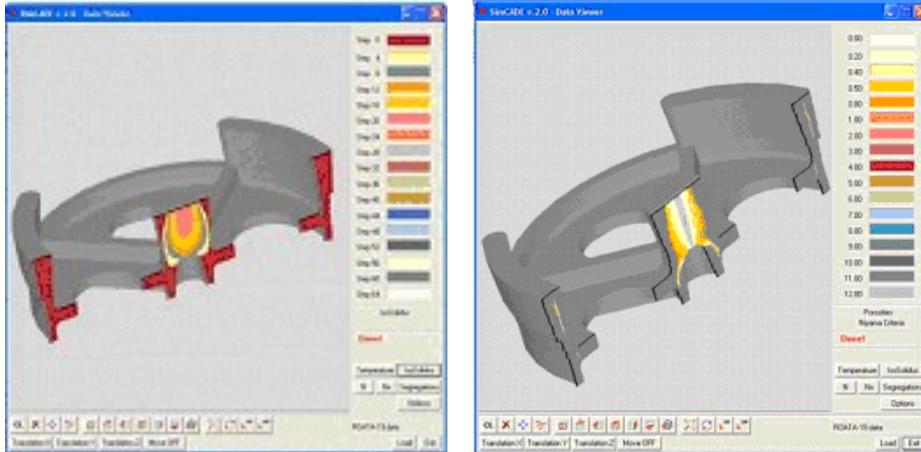The solidus curves of the casting part are shown in Figure 2 and the porosity area in Figure 3.

Figure 2.Isosolidus curves of
Ti6Al4V titanium alloy casting part

Figure 3. Non destructive porosity software 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 for non destructive control of porosity in titanium alloy castings:

(1) The first difficulty is getting the input data required for casting simulation software, especially the geometric information. The 3D solid model of the casting 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. The software requires accurate values of thermo-physical properties and accurate Niyama critical value for titanium alloys. This may not be available in the software database, especially for non-standard combination of

metals and processes, and for this reason the user has to establish a controlled 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 shrinkage defects (porosity, centerline shrinkage, sink and pipe) fairly accurately but other defects related to solidification and subsequent cooling (such as cracks, tears and distortion) 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 as well as the profile of the foundry. 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.

In general, it is possible to reliably non destructive control of porosity in castings even having a complex shape. With customers expecting castings of assured quality delivered within the shortest possible time, using of simulation software for non destructive control has become a necessity.

A cost effective solution for small and medium foundries or casting part buyer to fix the challenges concerning non destructive control of porosity in casting may be the service offered by Industrial Soft.

References

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POROSITY NON-DESTRUCTIVE CONTROL

SERVICE COST ESTIMATION

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Porosity Software Non Destructive Control

Casting Part
Material: Ti6Al4V

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 Porosity Software Non Destructive Control	205	181.67	105	175.00	356.67
	445	**322.00**	**105**	**175.00**	**496.67**
	(7H)		(2H)		USD

				.	0.00
				Total	496.67
				Paid	0.00
				Due	496.67

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Porosity Software Non Destructive Control -
Material: Ti6Al4V

Casting part analysis

	Default values	Analyzed Parameters															
Activate / Deactivate	1																
Number of simulations	1																

Task [min]	Default values [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																		
Porosity prediction	20																20	20
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	**15**	min.
Porosity Prediction Module	**20**	min.
Data analysis & Report editing	**100**	min.