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A predictive model for the micro-porosity quantitative in Al-Si alloy

Abstract The fatigue is the most important criterion for the securities parts (brake system for example). The increasing use of shaped cast aluminium in the security automotive parts has focused interest on the fatigue of theses alloys. The effect of the casting defects on has been recognized. The foundry men have mastered the behaviour of the almost defect apparition. However the micro-porosity shrinkage defect caused some problem to be correctly predicted. The shape of this kind of defect make it non neglected. The small size of this defect with respect to the size of the casting makes the prediction unreliable. The specific foundry software use empirical laws that do not fit with the reality, above all concerning the aluminium alloys. At the first time of solidification of a binary alloy, the dendrites (aluminium solid) growth into a liquid media. This region "Mushy Zone" (mix of liquid and solid) appears. Theses dendrites are growing until forming a connected network. This network can be view as a porous media. The displacement of the liquid still present into the porous matrix (inter dendritic liquid) can compensate the volumetric shrinkage during the solidification. Nerveless the permeability of the mushy zone increases with the solid fraction. Thereby according to the value of permeability and on the solidification rate, the liquid phase can not fill the shrinkage zones. We proposed a new physical parsimonious model of the micro-porosity shrinkage behaviour. This model is based on the fundamental heat and mass transport equations. Theses equations are implicitly coupled. A finite element method is used in order to simulate the governing equation. A sensitivity analysis permits us to explain the significance of the initials and limits conditions which have be prove in an industrial production plant.

Keywords Micro-porosity – Aluminium alloy – Permeability – Mushy zone – Semi solid media –

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1 Introduction

In the brake system the use of foundry aluminium component is usual. This kind of security system requires a good liability on components, which leads to the necessity of mastering the quality of the material itself of the components. If most of the defaults are quickly controllable, (macro-shrinkage, crakes), one kind of default remains a problem for the foundry man: the micro-porosity.

Industrial experience in the field shows that this default is very sensitive to boundaries conditions in the steel shell process.

The micro-porosity Nowadays, apparition mechanisms of micro-porosity aren't well known. As we will see, two kinds of porosity exist.

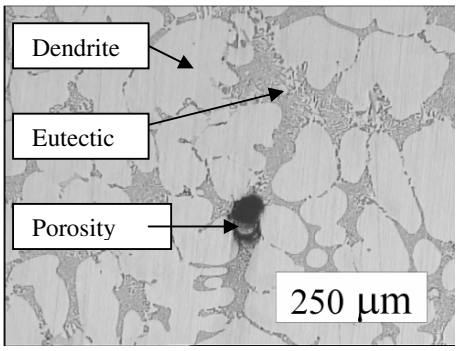

Figure1: Gaz micro-porosity

The first one is named gas porosity (Figure 1). Its apparition is due to higher hydrogen of solubility in liquid than in solid. So during solidification hydrogen is produce is gaseous form in the still liquid part. The gas takes a bubble shape.

Consequently, the aluminium gets solid around the spherical shape bubble. Industry deals with this problem making nitrogen bubbling, which has a much weaker solubility than hydrogen, go throw the liquid aluminium. We call it ungassing. By saturation of the liquid with nitrogen, we take out hydrogen.

Yet some times, in spite of complete ungassing, we still can have apparition of other kind of micro-

porosity. This type of defect, takes in the inter-dendritic shape.

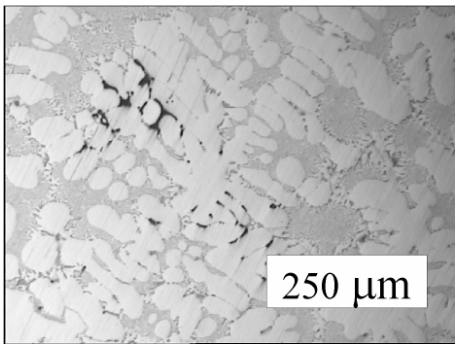

Figure 2: Shrinkage micro-porosity

Given, the absence of gas in the aluminium liquid, we could deduct a default due to the volumic contraction while solidification, called shrinkage (Figure 2).

Mechanisms of micro-porosity apparition The description of the mechanism apparition the micro-shrinkage is a continuous phenomenon. Nevertheless, in order to explain it we will describe it step by step. Aluminium alloy solidification appends in two steps. During the first solidification the dendrites aluminium crystals grow up and meet in liquid media, making this media richer in solution.

Slowly, these dendrites make a connected web. This semi solid media is physically very much like a porous media. When the solid media reaches silicon concentration of 12.7%wt, then, the remaining liquid solidifies under the shape called eutectic.

The remaining liquid solidifies as a pure metal of two heterogeneous phases. In order to compensate the volumic contraction during solidification, the liquid aluminium has to find its way in this porous media which slow down its flow. As shown by measurements of temperatures during solidification, the porous media moves and extend itself. When permeability gets too important the flow stops. From this point the micro-porosity takes place.

2 Model

Assumptions

- The assumption of semi solid domain temperature equilibrium [1] is verified. Effectively, the spatial step size Δx and the time stepping Δt verify [1]. With L being the system scale (0.25m), Δx being the REV scale (10^{-3}m) and d the dendritic scale (5.10^{-5}m). This sets the time stepping important in front of 4.10^{-2} seconds, and validates the proposed mesh ($\Delta x = 10^{-3}$ m).
- The assumption of semi solid domain homogenization is proposed.
- Finally, the observation referential is based upon the solid phase. In other words, in the chosen referential we can put the solid velocity to zero $\mathbf{u}_s = 0$.

Energy balance: Thermal transfer simulation, with change of phase, is based on an enthalpic formulation where enthalpies are defined by:

$$H_1 = g_l \rho_l H_{ls} + \int_0^{T_1} (g_l \rho_l Cp_l) dT + \int_0^{T_1} (g_s \rho_s Cp_s) dT$$

$$H_2 = \int_0^{T_2} (g_s \rho_s Cp_s) dT$$

Where H and T represent respectively the enthalpy and the temperature ($_1$ for cast part alloy, $_2$ for mold).

Energy balance equations

$$x \in V_1 : \frac{\partial H_1(x,t)}{\partial t} = \nabla.(D_1(H_1)\nabla(H_1(x,t))$$

$$x \in V_2 : \frac{\partial H_2(x,t)}{\partial t} = \nabla.(D_2\nabla(H_2(x,t))$$

where V_1 is the part geometry and V_2 the mold geometry.

Boundaries conditions for $t > 0$

$$x \in S_1 : -k_1\nabla(T_1(x,t)) = \varepsilon_1\sigma(T_1^4 - T_\infty)$$

$$x \in S_2 : -k_1\nabla(T_1(x,t)) = \frac{T_2(x,t) - T_1(x,t)}{R} = k_2\nabla(T_2(x,t))$$

$$x \in S_3 : -k_2\nabla(T_2(x,t)) = \varepsilon_2\sigma(T_2^4 - T_\infty)$$

S_2 is the boundary between the cast part and the mold. R represents the interface thermal resistance. Other surfaces are in contact with the air.

Initials conditions

$$x \in V_1 : H_1(x,0) = H_{1\_initial}$$

$$x \in V_2 : H_2(x,0) = H_{2\_initial}$$

Mass balance: Writing mass balance requires considering the liquid speed. The liquid movement appears through the action of the pressure variation of gradient Δp_R. This last parameter is the result of volumic contraction caused by the volume solidification Δv on the remaining liquid v. This is why we will use the bulk's modulus of aluminium M. To express this pressure variation, caused by the volume solidification.

$$\Delta p_R = -M \frac{\Delta v}{v}$$

Darcy law uses the ratio between the semi solid zone permeability K and the liquid aluminium

dynamic viscosity μ_L. From this ratio we can write the liquid phase speed in the considered referential.

$$\mathbf{u_l} = \frac{-K}{g_l \mu_l}(\nabla p_R - \rho_l \mathbf{g})$$

From the anterior simulations, we saw that the Kozeny-Carman law is the most adapted to describe the media permeability variation related to the solidified fraction.

$$K = \alpha \frac{g_l^3}{g_s^2}$$

Integrating these two relations in the mass conservation equation, we get the equation volumic fraction defaults evolution.

$$\frac{\partial g_p}{\partial t} = -\beta \frac{\partial g_l}{\partial t} + \frac{\rho_l}{\rho_s} \nabla.(g_l \mathbf{u_l})$$

The product of these parameters α, M and μ_l define one only parameter. Consequently we will have only this parameter to describe in order to write correctly the occurrence of micro-porosity. This characteristic gives us a parsimonious model.

Theses conservation equations are implicitly coupled. On an industrial geometry we solve this system. The heat balance equations is solved on the part (V_1 see figure 3) and mold (V_2) geometry. We use two diffusion equations.

The mass balance équation is solved on the part geomertry as a simple time integration.

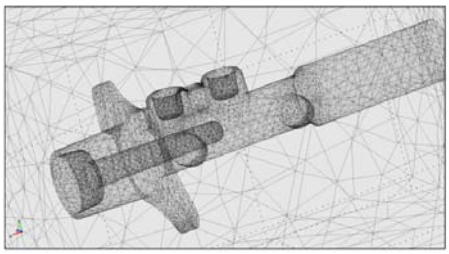

Figure 3: mesh of the subdomains

We use the UMFPACK of FEMlab 3.1 to solve this problem.

3 Experimentations

We use an industrial mold within we poured industrial alloy quality. We then proceed to a rocked pouring in order to prevent turbulence, which could imprison air within the liquid.

Temperature measurements: The 15 used thermocouples are of type K (~41.10-3 $V.K^{-1}$), diameter of 0.5mm. They are introduced in a girdle of exterior diameter of 0.9mm. The thermocouples are homogeneously put on the part height. The amplification was realised with chip AD595CQ dedicated to each of the thermocouples. Acquisition was realised with NI® PCMCIA card. The frequency of the sampling is 25 points per second per thermocouples. The alloy is poured at 650°C. The initial temperature of the chill is 100°C (measured by IR pyrometry). The complete solidification of the cast part takes 1500 seconds.

Position measurement of thermocouples: Considering thermocouples can slightly move during the pouring, the exact position of the thermocouples is made with RX radiography. Photos are taken in three orthogonal directions.

Porosity measurement: A section of the part is carried out in his axe direction, the surface is polished. The micro-porosity measurement is performed with an optical microscope. An automatically controlled stage allows screening the whole surface. A photo is automatically taken and treated for each position of the surface.

Each default is recorded, positioned and measured. We finally get a porosity mapping.

4 Results

The first results came to validate the energy balance simulation.

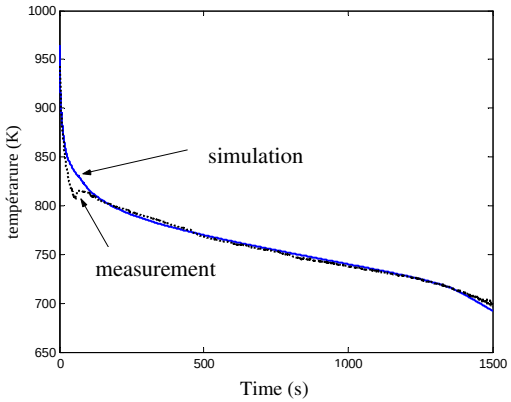

Figure 4: temperature evolution

Using inverse method, we have identified the value of the product $\alpha M \mu_l^{-1}$ on a simple géometry. From the micro-porosity measurements, we have optimized the value of this product, in order to minimize the difference between the measured and the simulated micro-porosity. This method is adequate for indirect measurement of the semi solid permeability. The result of this study proposes a value for $\alpha M \mu_l^{-1}$. This value is used on the industrial geometry presented on the figure 3.

5 Discussion

So far, permeability measurement was studied by two different methods: experiments and simulations.

Experimental methods ([2], [3] and [4]) allow measurement of permeability, for different solid

fractions. But experiments are limited to solid fractions and betters experiments are limited to solid fractions around gs=0.9 (micro-porosity appears precisely from gs>0.96).

Other numerical studies try to simulate permeability, but the dendritic and eutectic morphology isn't often taken into account ([5] and [6]).

If estimate liquid aluminium dynamic viscosity and appearing liquid aluminium compressibility then get a value of 1.3 10^{-11} m^2 for α . Which means a permeability, of 10^{-14} at gs=0.9.

It looks like this method under estimates permeability compared to experimental methods with same solid fractions (around 10^{-12}). This is due to the tortuosity of the media. Actually, a study is conducted to be able to estimate the tortuosity at high solid fraction on a semi solid configuration (figure5). Actually we have put the tortuosity of the media to 9.

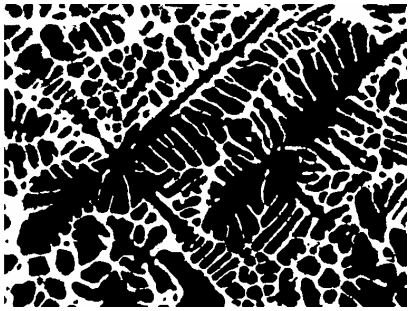

Figure 5: semi solid media

Although this under estimation, the 3D model had a very good correlation with industrial configuration. The localization are correctly predicted.

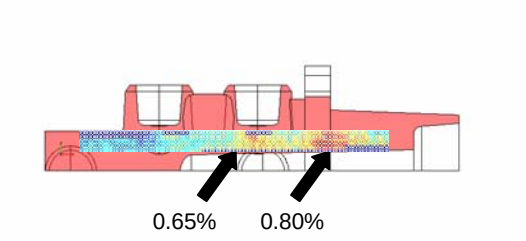

Figure 6: estimated micro-porosity defect

As presented on the figure 6 the micro-defects represent very low volumic fractions (lower than 1%) as measured on industrial production.

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