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Formation of Porosity in Al-Si Alloys

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Abstract

Porosity is one of the major defects in aluminum castings and results in a decrease of the mechanical properties of Al-Si alloys. It is induced by two mechanisms: solidification shrinkage and gas segregation. One of the methods for complex evaluation of macro and micro porosity in Al-Si alloys is using the Tatur test technique. This article deals with the evaluation of porosity with the help of Tatur tests for selected Al-Si alloys. These results will be compared with results obtained from the ProCAST simulation software.

Keywords: Porosity, Aluminum alloy, Simulation, Mushy zone, Tatur test

1. Introduction

Porosity is one of the major defects in castings and results in a decrease of the mechanical properties of Al-Si alloys , in particular the fatigue and ultimate tensile strengths. It is induced by two mechanisms, solidification shrinkage (Fig. 1.) and gas segregation (Fig. 2.), which occur concomitantly but with different intensities. Solidification shrinkage, which induces a negative volume variation during the phase transformation of most alloys, has to be compensated for by interdenritic liquid flow (feeding) to avoid porosity. Feeding induces a pressure decrease in the mushy zone, which combined with a decrease in the temperature, lowers the limit of solubility of dissolved gases in the liquid.

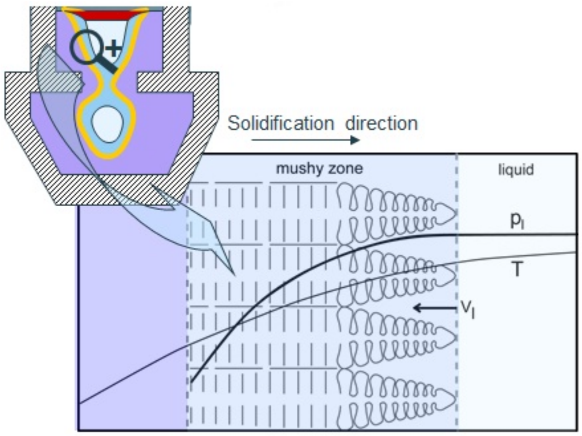

Fig. 1. Solidification shrinkage – liquid suction – liquid pressure drop in the permeable mushy zone

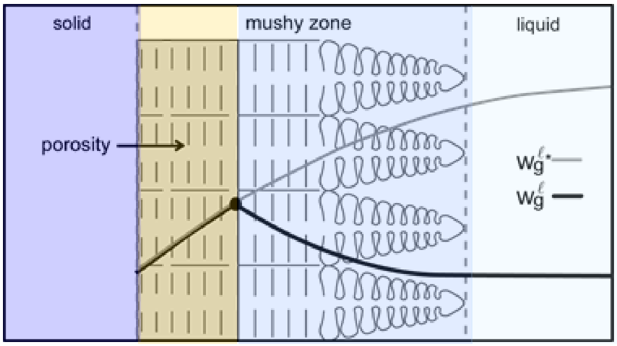

Fig. 2. Gas segregation in the liquid phase – gas solubility limit decreases with liquid pressure and temperature

In addition, during solidification, the gas rejection at the solid/liquid interface leads to an increased gas concentration in the liquid. If this concentration reaches a critical value, based on the limit of solubility of gas in the liquid, then pores can nucleate and grow. Quantitative information on the development of porosity as a function of alloy variables and casting parameters is particularly important for the foundryman in order to control and limit the formation of such defects. Detailed modeling of microporosity formation has been developed mainly in one-dimensional geometry, occasionally in two dimensions, but rarely in three dimensions. It is also necessary to say that pipe shrinkage, i.e. solidification shrinkage appearing at the free surface and macroporosity, i.e., solidification shrinkage appearing in a closed-liquid pocket, can be predicted by most commercial casting software but with information obtained mainly from the thermal field. Up to now, such calculations have never been coupled with microporosity predictions in a consistent way. Moreover, the transition between open regions of liquid and closed regions has never been taken into account. At some stage, a liquid region may become totally surrounded by the mushy zone but not by the solid. In such a partially closed liquid pocket, feeding can still occur via the mushy zone.

2. New model

In order to be able to control and limit the formation of porosity defects, quantitative information on the distribution, quantity and morphology of pores as a function of alloy properties and of process parameters is essential. A Finite Volume model, coupled with FE heat/flow calculations, has been developed to predict microporosity, macroporosity, and pipe shrinkage formation during the solidification of alloys for arbitrary 2D (cartesian and axisymmetric) and 3D geometries. The microporosity model, built upon a Darcy flow approach, includes al1 the basic physical phenomena, which are at the origin of microporosity formation. In particular, the pressure drop in the mushy zone, gas segregation, the equilibrium between gas bubbles and solid-liquid phases, and nucleation and the growth of pores are taken into consideration.

In order to accurately calculate the pressure drop within the mushy zone, a dynamic refinement technique was implemented: a fine and regular Finite Volume (FV) grid is superimposed onto the Finite Element (FE) mesh used for the heat flow calculations.

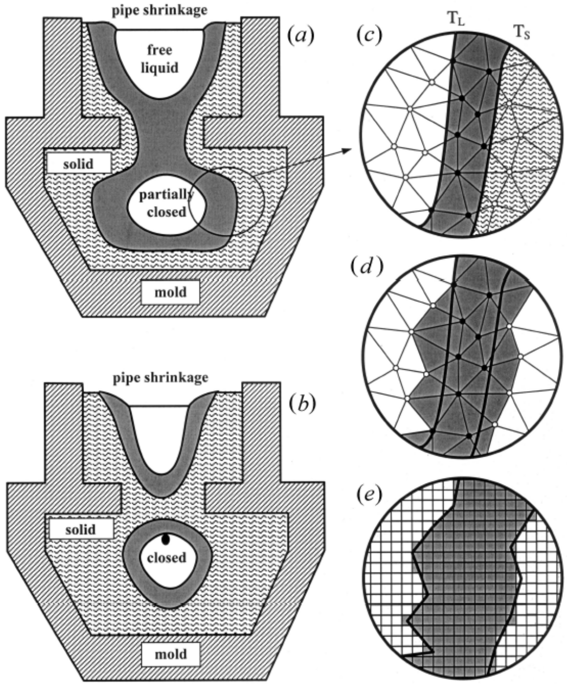

Fig. 3. (*a*) Schematic representation of pipe shrinkage at a top free surface and of a partially closed liquid pocket. (*b*) A macropore, which might start to form in a partially closed liquid region when this liquid region is closed. (*c*) A magnified view of the mushy zone shows that only a few FE nodes fall within its thickness (filled circles). (*e*) The FE elements are refined into small regular squares or cells (*a*), and those falling within mushy elements (gray elements in (*d*)) are activated.

For each time step, the cells which fall into the mushy zone, are activated and the governing equations of microporosity formation are solved only within this restricted domain with the appropriate boundary conditions. For this purpose, liquid regions which may appear during solidification are automatically detected and classified according to three categories. Figures 4 and 5 show schematics of a simplified casting. Solidification induces three types of voids: (1) at a free surface (e.g., of risers), the level of liquid decreases as solidification proceeds (piping); (2) within closed liquid pockets (hot spots), a macropore surrounded by microporosity will be present; (3) microporosity is finally dispersed within the mushy zone and might finally appear at an early stage of solidification (gas porosity) or deep in the mushy zone, especially when a dense interdendritic phase forms (shrinkage porosity). An open region of liquid has at least one surface in contact with a gas of known pressure. A closed liquid pocket is totally surrounded by the solid or mold. Before it becomes closed it can be partially closed, i.e., it is still connected to an open region of liquid through the mushy zone.

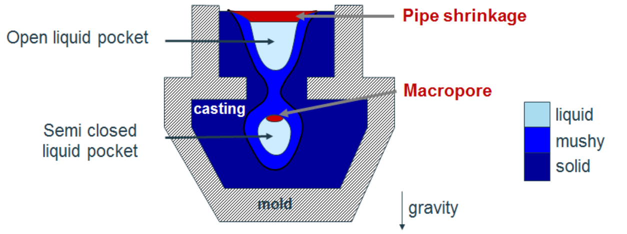

Fig. 4. Schematic illustration of a solidifying casted component

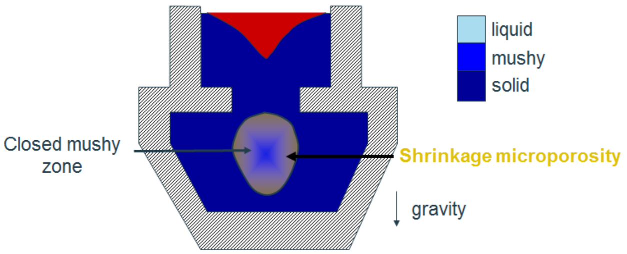

Fig. 5. Schematic illustration of a solidifying casted component with closed liquid pocket

Since microporosity develops within the mushy zone, calculations must be performed for the solid-liquid two-phase region only. For that purpose, a dynamic "mushy-zone tracking" procedure was developed. Using a fixed finite element (FEM) unstructured mesh, heat and fluid flow computations are performed at the scale of the whole casting + mold. At each time step, the position of the mushy zone and thus the "mushy elements" are known. For these elements, volume elements of a structured grid are activated for the calculation of the pressure drop.

3. Macroporosity

Macroporosity appears in a partially closed liquid region, when the pressure in this cavity falls below the cavitation pressure. It also forms in a closed liquid region, i.e, in a closed system where feeding is impossible since the solidification shrinkage can be only compensated for by porosity formation. The volume of macroporosity is obtained by integrating the liquid velocity over the boundary of the liquid pocket. Pipe shrinkage, i.e., shrinkage appearing at a free surface, is obtained by integration of the calculated interdendritic: fluid flow over the open region boundary, thus ensuring that the total shrinkage (microporosity plus macroporosity and pipe shrinkage) respects the overall mass balance. This very general approach is applied to Al-Cu and A1-Si alloys. The sensitivity of the model to various parameters such as gas content, alloy concentration or cooling conditions is pointed out through 2D and 3D examples. Mode1 predictions appear to be in good agreement with general observations in normal casting practice and results presented in the literature. Comparisons with experimental work are also carried out and demonstrate the significance of the model.

Microporosity

As depicted in figures 1 and 2, in general, microporosity is the result of two concomitant mechanisms: (a) solidification shrinkage induces a suction and thus a liquid pressure drop in the permeable mushy zone (Darcy's law), (b) trace gaseous elements in the liquid being generally less soluble in the solid phase, solidification induces gas microsegregation in the remaining liquid part. If the gas concentration in the liquid phase reaches the gas solubility limit decreasing with liquid pressure and temperature, micropores will nucleate deeply in the mushy zone. If the situation is such that all these mechanisms are involved, the microporosity is called gas shrinkage microporosity. Gas shrinkage microporosity can not be modelled with the traditional approaches used in commercial software to calculate the fraction of pure shrinkage microporosity encountered in closed mushy zones. For this last porosity family, the final porosity fraction is locally simply equal to the solidification shrinkage volume, because no liquid flux can partially compensate the shrinkage (closed system).

4. Advanced porosity module

As a consequence of previous texts, predicting porosity is not so straightforward. This is the reason that CALCOM-ESI and the Swiss Federal Institute of Technology in Lausanne (EPFL) (in collaboration with several leading casting industries) developed a microporosity numerical model based on the previosly described mechanisms. This model has been recently extended to all kinds of industrial alloys (Al, Fe, Cu, Mg, Ni, Ti base alloys) in order to predict all porosity families in complex geometrical situations:

- gas-shrinkage microporosity,
- pure-shrinkage microporosity,
- macroporosity,
- pipe-shrinkage.

This Advanced Porosity Module (APM), which is integrated into the ProCAST software, can predict the influence of various parameters regarding the location and amount of porosity:

- alloy composition (gas solubility is influenced by the solute element concentrations).
- process parameters (locations of gatings, risers, cooling channels and chills, thermal properties of the mold etc…).
- alloy thermo-physical properties (thermal properties, liquid viscosity, density).
- gas contents and gas thermodynamic properties in the considered alloy.
- mushy zone microstructure (influenced by some previously mentioned parameters).
- mushy zone – liquid pocket topology and morphology (ex: mushy zone length).

5. Experiment

The main aim of experimental work will be to test the ProCAST APM model. The main focus will be to observewhether or not the model is giving correct results in not only the numerical sphere but also when compared to experimental measurements. Various parameters on microporosity and pipe shrinkage will be tested, such as gas content, alloy concentration, cooling conditions, and gravity. For test purposes a Tatur test mold will be used, which is optimal for assuming complex macro and micro porosity. Experimental samples will be poured and tested. These samples will then be compared to simulation results. Various aluminum alloys will be used, as well as various gas content and cooling conditions.

Tatur test

The Tatur test is a technique used to assess macro and micro porosity in Al-Si alloys. The test uses a copper or graphite permanent mold of standard geometry as shown in Figure 6. Slumping and contraction, macroshrinkage (pipe), and microshrinkage can be assessed by density measurement and very fine sand displacement. These types of shrinkage are affected by many parameters, such as inclusions, gas content, alloying elements, grain refinement, modification and cooling rate.

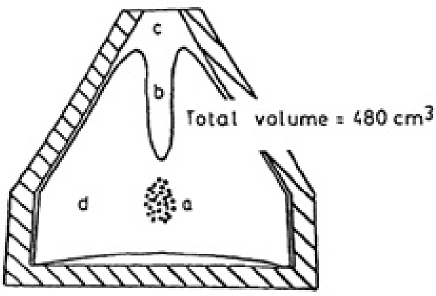

Fig. 6. a) microporosity, b) pipe volume, c) slumping and contraction volume, d) actual casting volume

The test uses a graphite or copper mold whose dimensions are shown in Figure 7.

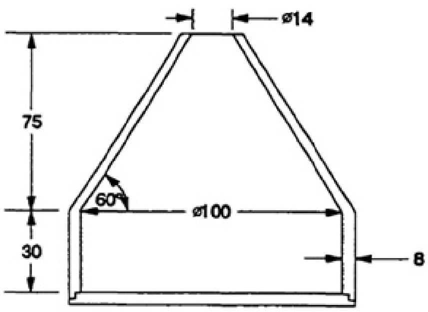

Fig. 7. Dimenions of tatur test (mm)

The bottom plate of the mold will be preheated on a hot plate to 175 *°C* prior to casting. The volume of the ladle will be the same as that of the Tatur mold. The ladle will be preheated to around the melt temperature *(725 °C)* prior to transferring the melt from the furnace to the mold. The ladle and the mold will be coated with a boron nitride aerosol spray. Surfaces to be sprayed will be cleaned and degreased, and then a thin uniform coating will be applied.

6. Conclusion

A FV model for the prediction of microporosity, macroporosity, and pipe shrinkage during the solidification of alloys has been recently presented for 2-D and 3-D geometry. It includes all the basic physical phenomena which are at the origin of microporosity. In particular, falling pressure in the mushy zone, gas segregation, equilibrium between gas bubbles and solid-liquid phases, laws of nucleation, and growth of pores are taken into account. Pipe shrinkage and macroporosity are predicted by detecting automatically open, partially closed, and closed liquid regions, and by applying appropriate boundary conditions. The presented model will be tested if it gives correct results in not only the numerical sphere, but also when compared to experimental measurements. Various parameters on microporosity and pipe shrinkage, such as gas content, alloy concentration, cooling conditions, and gravity will be tested.

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