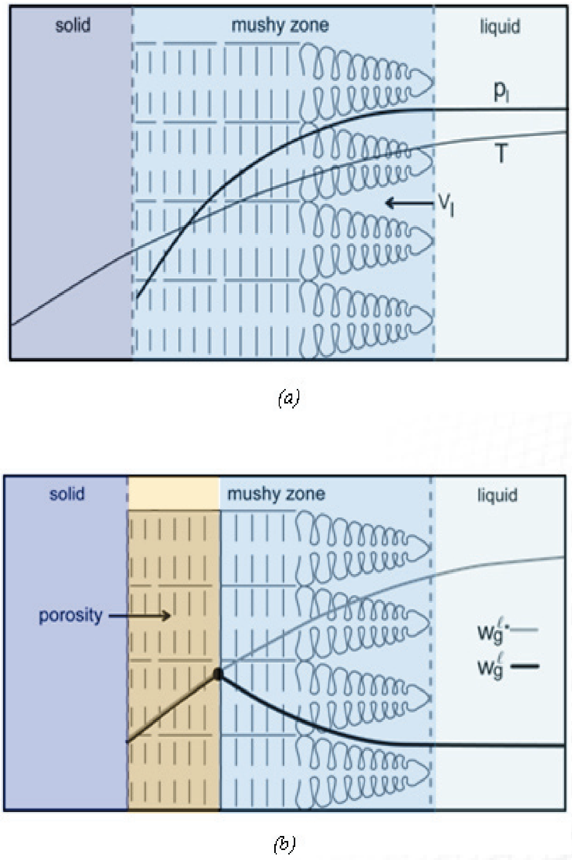
Influences of Solidification Length and Pressure Intensification on Gas Shrinkage Microporosity in Casting Components

CASTING E-TIP 32

Introduction

Porosity in castings is a major defect since it affects the mechanical properties. In particular porosities are sites for the initiation of fatigue cracks. Therefore, the reduction of porosity fraction and size, the control of porosity distribution and morphology are crucial for the optimization of mechanical resistance of as cast components.



(a)

(b)

Figure 1. Concomitant mechanisms responsible for microporosity formation.

As depicted in figures 1.a and 1.b, in general microporosity is the result of two concomitant mechanisms: (a) solidification shrinkage induces a suction and thus a liquid pressure drop (p_l curve) 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 (thick curve) in the remaining liquid part. If the gas concentration in the liquid phase reaches the gas solubility limit decreasing with liquid pressure and temperature (thin curve), some micropores 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 softwares 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).

New model

As a consequence, the prediction of porosity is not straightforward in general. This is the reason that conducted CALCOM-ESI and the Swiss Federal Institute of Technology in Lausanne (EPFL) (in collaboration with several leading casting industries) to the development of a microporosity numerical model based on the previously described mechanisms (see the original scientific paper[1]). This model has been recently extended to all kind of industrial alloys (Al, Fe, Cu, Mg, Ni, Ti base alloys. See scientific paper[2]) in order to predict all porosity families in complex geometrical situations:

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

This work leads to a software customized for all casting processes:

- gravity casting,
- high pressure die casting,
- investment casting,
- continuous casting,
- …

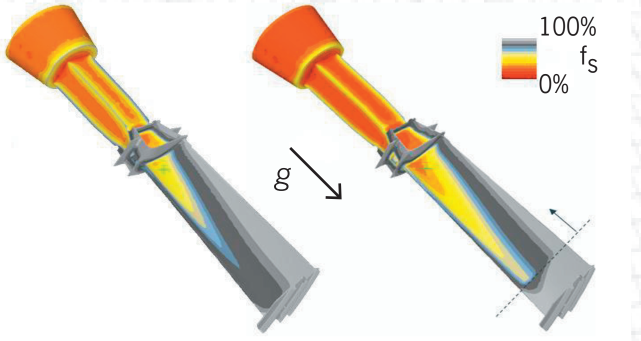
This Advanced Porosity Module (APM) can predict the influence of various parameters on the location and amount of porosity:

- 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),
- intensification pressure (third phase),
- …

This e-tip is the opportunity to illustrate the APM capabilities in term of prediction of gas-shrinkage microporosity. The influences of two previously mentioned parameters are shown in the next two sections. In a first section, the effect of the mushy zone length is studied in a real turbine blade geometry (courtesy of SALUT, Russia). In a second section the effect of the applied pressure on gas shrinkage microporosity is illustrated in an HPDC industrial component (courtesy of INJECTA Druckguss, Switzerland).

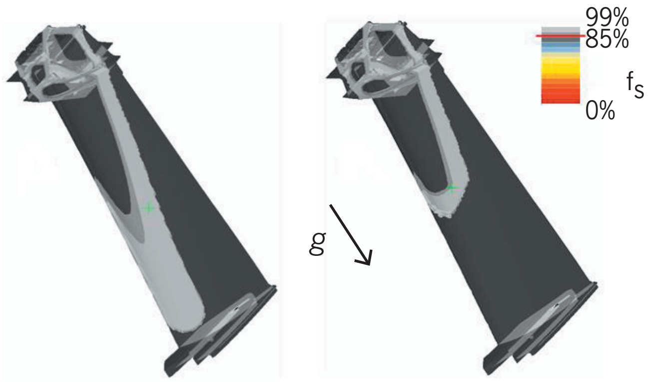
Solidification Length Investment Casting

In the first example, a 35cm Ni base turbine blade is solidified. In the reference case the cooling is homogeneous or uniform around the part. In the second case, an optimized directional cooling condition has been applied in order to decrease the mushy zone length (see figure 2-3)



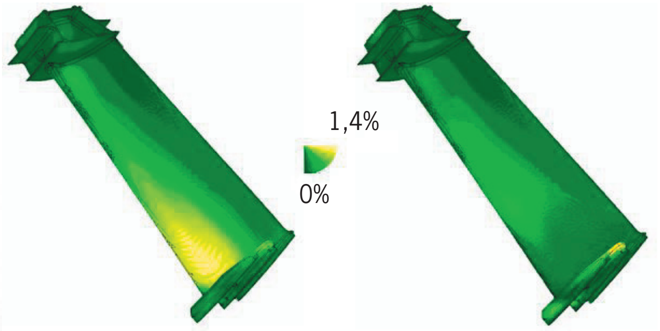
Uniform cooling Directional cooling

Figure 2. Simulation of a solidification turbine blade (courtesy of SALUT). In the left figure, the cooling is uniform, whereas in the right figure, a controlled directional solidification is employed.



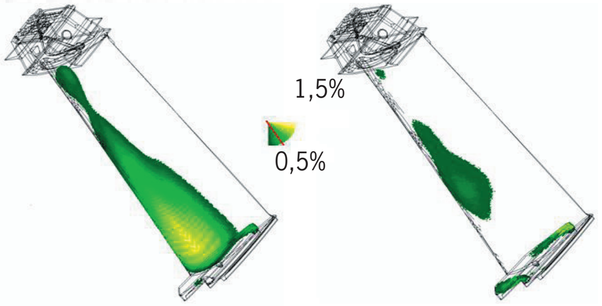
Uniform cooling Directional cooling

Figure 3. Snapshot of the simulation of a solidifying blade (courtesy of SALUT). Only solid fraction inbetween 85% and 99% is represented. In the left figure, the cooling is uniform, whereas in the right figure, a controlled solidification is employed.



Uniform cooling
(a)

Directional cooling
(b)



Uniform cooling
(c)

Directional cooling
(d)

Figure 4. Final porosity fraction in a turbine blade calculated by the Advanced Porosity Module. In the left figures the cooling is uniform, whereas in the right figures a controlled directional solidification is employed. The porosity is represented at the surface of the casting (a, b) and then with a cut off value showing the porosity above 0.5% (c, d).

The solidification length is revealed in figure 3 for both cooling configurations. The pressure drop is really significant for high solid fractions; this is the reason why only solid fraction exceeding 85% is displayed in figure 3. The Darcy's law is a linear relationship between the liquid velocity and the liquid pressure gradient locally in the semi solid part. The integration of the alloy mass balance coupled to the Darcy's law along the mushy zone makes the liquid pressure at the root of the partially solidified zone decrease in a parabolic way with an increasing solidification length for a given cooling rate. A large amount of gas shrinkage microporosity is thus expected for long mushy zones. As observed in figure 4, it is exactly what is predicted with the Advanced Porosity Module: in the absence of directional cooling condition (left figures), as the mushy zone is long the porosity fraction is high at the extremity of the turbine blade (1.4%), whereas the directional solidification solution (right figures) drastically reduces the porosity fraction because the solidification length is limited.

Third Phase Effect High Pressure Die Casting

In the second example, the effect of the pressure intensification during the third stage on the final porosity fraction and location in an HPDC part is illustrated. The geometry of the component in the mold is represented in figure 5.

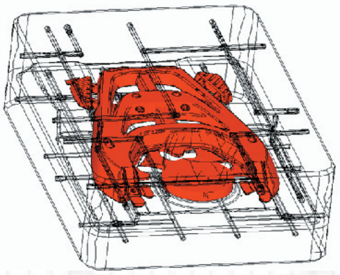


Figure 5. HPDC component in its mold (Courtesy of INJECTA).

As the gas solubility limit increases with the liquid pressure, it is expected a decrease of the gas shrinkage microporosity fraction when the applied pressure is raised. As observed in figure 6, this effect is perfectly reproduced by the APM: the gas shrinkage microporosity has totally disappeared at 400 bar. In the 400 bar case, the remaining porosity is pure shrinkage microporosity appearing in closed mushy zones. An increase of the applied pressure will not reduce the pure shrinkage microporosity, because closed mushy zones can not anymore be feed by liquid. The correlation between closed mushy zones and pure shrinkage microporosity is represented in figure 7. In order to remove these remaining shrinkage microporosities, it would be necessary to modify the cooling conditions and/or to use pin squeeze.

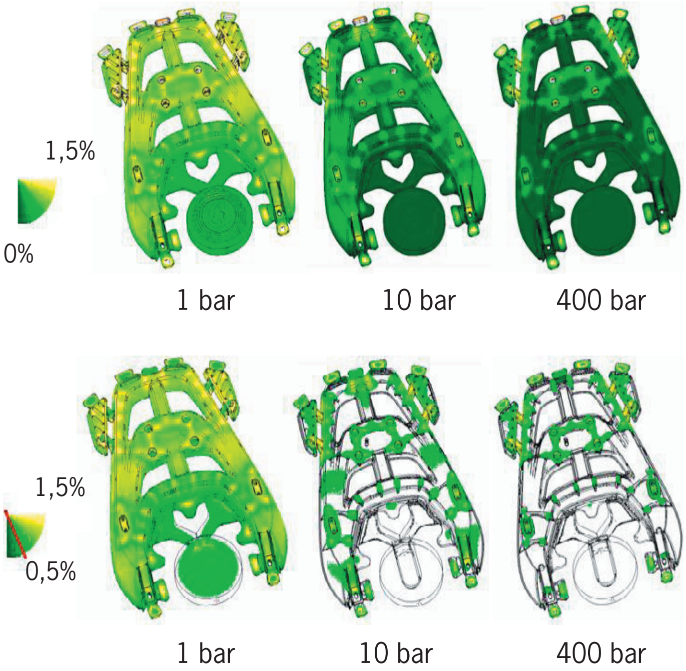


Figure 6. Final microporosity fraction in the component for different third stage applied pressures. The porosity is represented at the surface of the casting (upper figures) and then with a cut off value showing the porosity above 0.5% (lower figures).

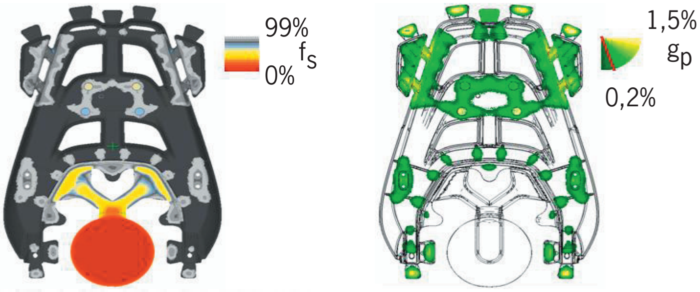


Figure 7. Correlation between closed mushy zones (left) and pure shrinkage microporosity (right) in the 400 bar case.

Conclusion

A model taking into account all the physics and thermodynamics of porosity formation in castings has been developed. These developments lead to a new module in the ProCAST software: The Advanced Porosity Module (APM). In particular, this module allows the prediction of the gas shrinkage microporosity that can not be modelled with traditional shrinkage approaches.

[1] Ch. Pequet, M. Gremaud, and M. Rappaz, "Modelling of microporosity, macroporosity, and pipe-phrinkage formation during the solidification of alloys using a mushy-zone refinement method: applications to aluminium alloys", Met. Mater. Trans., 33A (2002) 2095.
[2] G. Couturier, M. Rappaz. "Modeling of porosity formation in multicomponent alloys in the presence of several dissolved gases and volatile solute elements", TMS, Symposium on Simulation of Aluminium Shape Casting Processing (2006).