MODELING MICROSTRUCTURE, MECHANICAL PROPERTIES AND DENSITY VARIATION OF CAST IRON

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ABSTRACT

Cast irons are important industrial materials offering to the design engineer unique combination of high strength, wear resistance, ductility and toughness material properties. In foundries, cast irons could suffer as all metal alloys from shrinkage porosity formation during solidification. In order to reduce shrinkage formation, feeders are normally used in the process design, which reduces porosity level but leads to a low yield. Cast irons could exhibit a wide range of properties obtained through the microstructure control. Then, in order to better understand the shrinkage behavior of cast iron during solidification, a micromodel [1] was developed to simulate the microstructure formation. The density change during solidification and the ambient temperature mechanical properties can be calculated based on the microstructure. The scope of this article is to discuss microstructure and resulting mechanical properties as wells as to describe the mechanism behind shrinkage porosity in cast iron. The simulations have been compared with industrial cases.

KEYWORDS

Casting simulation, microstructure, mechanical properties, graphite expansion, shrinkage porosity, ProCAST^{TM} [2].

INTRODUCTION

Shrinkage porosity is the most common solidification defects. The main reason of shrinkage formation is that all metal alloys contract when it cools from the pouring temperature to the solidus. If the contraction is not compensated by supplying feed metal from the risers or the gating system, a pore will occur. Feeding system is efficient until the amount of solid phase reaches a certain level.

Cast iron alloys which solidify with a precipitation of graphite represent a more complex behavior, the reason being that the dissolved carbon partly precipitates as graphite with a lower density than the base iron. Based on the shape of graphite, cast iron can be lamellar (flake) graphite iron or spheroidal (nodular-ductile) graphite iron. The graphite formation is thus associated with a volume increase. This expansion could compensate under certain circumstances the contraction of the metal to avoid or reduce shrinkage. Thus, the generation of shrinkage cavity in cast irons is closely related to the density change on solidification. The expansion and shrinkage behavior is affected by alloy composition, cooling rate and thus microstructure, process conditions, nucleation, fading, shape and material of the mould.

Today, advanced simulation could be used to understand and control such a complex behavior. Indeed, heat flow, solidification, fading effect, graphite/austenite eutectic transformation, ledeburite eutectic transformation, graphite growth in the austenite regime, and the eutectoid transformation could all be modeled. In ProCAST™, a comprehensive micromodel was developed which can give accurate microstructural information as well as the mechanical properties, such as yield strength, tensile strength, elongation and hardness. The fractions of austenite, ferrite, pearlite, graphite, liquid, and ledeburite are all calculated. The micromodel together with thermodynamic database has been coupled with the porosity model allowing an accurate shrinkage prediction by taking into account the complex phenomenon of graphite expansion. The predictions have been compared with experimental results.

MICROSTRUCTURE AND MECHANICAL PROPERTIES

Microstructure formation during the solidification of alloys is a very important factor for the control of the properties and the quality of casting products. There are different types of microstructures for different alloys. The types of phases present, the volume fraction of the phases, the grain size, and grain shape determine the properties, which in turn govern the appropriate application of the alloy.

To obtain microstructure predictions, ProCAST™ couples thermodynamic calculations (from CompuTherm® LLC databases) with microstructure models and the macro-scale thermal and fluid flow calculations. Depending upon the chemical composition, the microstructure module automatically detects the phases which will appear and the type of microstructure which should be computed (dendritic, eutectic, nodular ...). Depending on the alloy type and composition, additional information will be available, for instance nodule counts, austenite radius, pearlite and ferrite fractions for nodular cast iron (see Figures 1&2).

In the below industrial example, a manifold is poured in a hypo-eutectic nodular cast iron Ni RCT (courtesy of Fonderia CASATI SpA, Italy). With the presence of magnesium element in the composition, there is nodular graphite precipitation after solid phase transformation as well as ferrite and pearlite phases (see Figure 2). The metastable pearlite structure is composed by ferrite and cementite and can decompose upon process conditions to ferrite and graphite. The final amount of decomposed pearlite depends on carbon equivalent content and cooling rates.

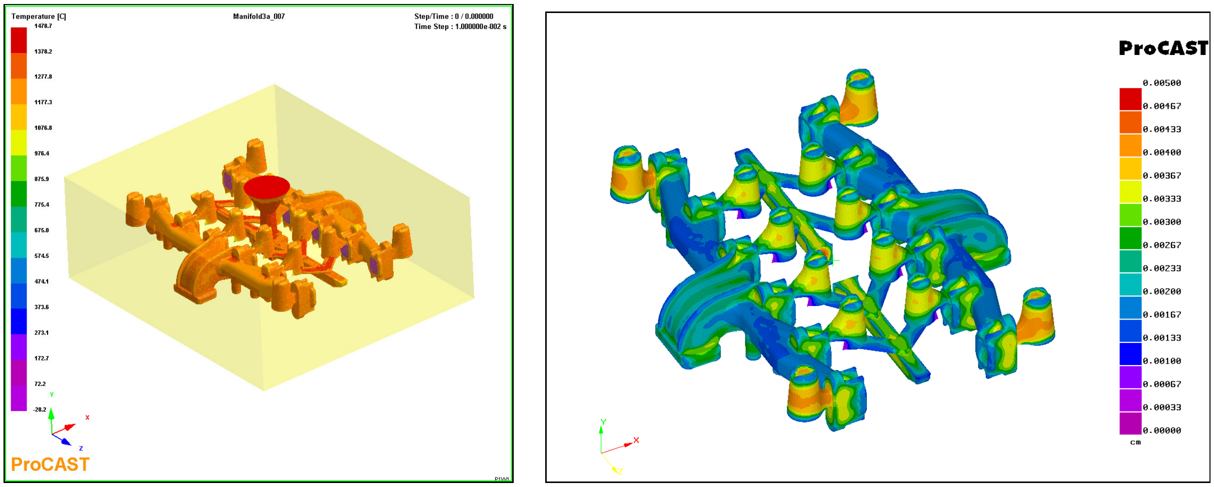

Figure 1: The chemical composition can be varied to identify the optimum mechanical properties configuration (SDAS results of ProCAST™ on the right and geometry with the gating, risering and sand mould on the left).

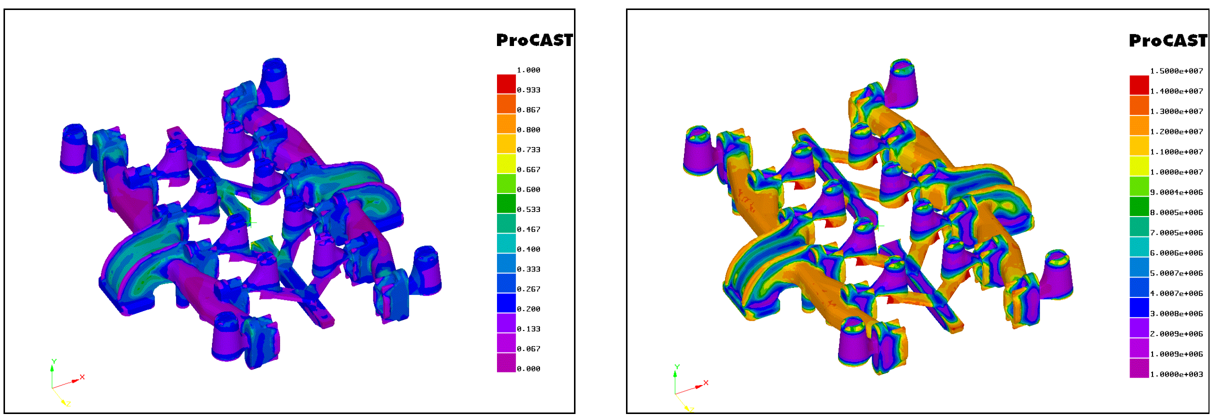

Figure 2: Fraction of ferrite (left), and nodule count (right), provide insight into the mechanical state of the as-cast part.

As cast material properties

Microstructure calculations can finally be used to predict the final mechanical properties for some alloy systems. For instance, yield and tensile strengths as well as hardness and elongation can be obtained for different kind of alloys. In cast iron, the type, amount and morphology of the eutectic will determine the desired mechanical properties. The structure of the matrix is essentially determined by the cooling rate through the eutectoid temperature range (between 700 and 900°C). Slow cooling rates promote the transformation of ferrite, thus lower tensile strength.

To illustrate these capabilities, a sample plate was cooled in a mould to room temperature, whereas the exact same model was cooled quicker (shakeout occurring just after solidification, but before the solid state temperature was achieve) (see Figure 3). As a result, these different cooling conditions create different microstructural evolution conditions (see Figure 4). The slowly cooled plate developed a much lower tensile strength than that of the quickly cooled plate, which corresponds with experimental results [3].

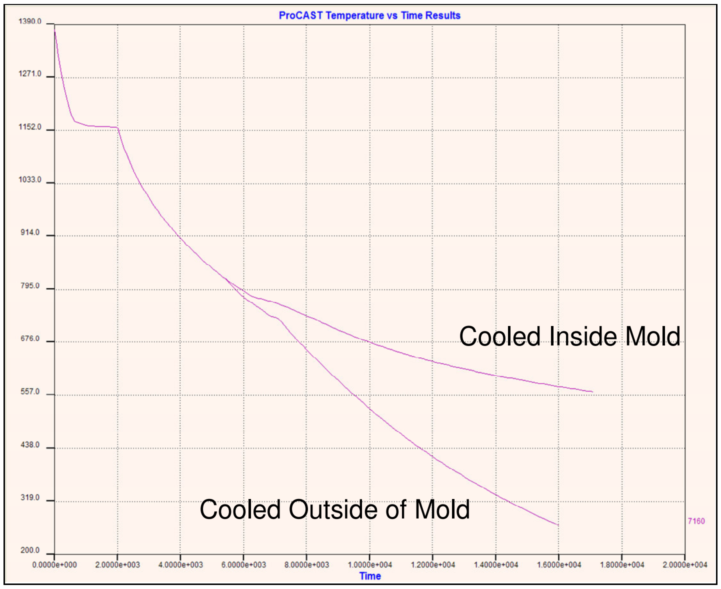

Figure 3: Cooling curves at the same location indicate the cooling rate differences when the part is cooled inside the mold versus when the part is shaken out while still above the solid state temperature.

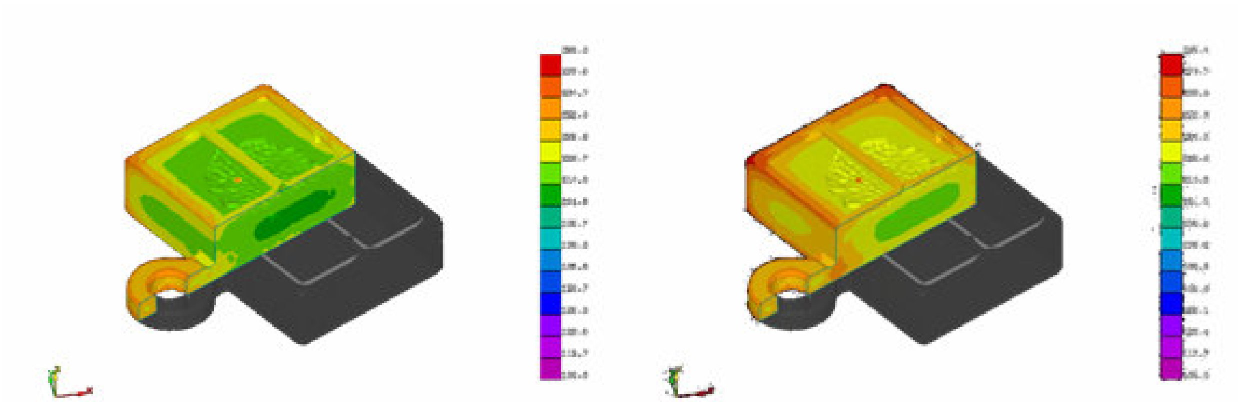

Figure 4: Tensile Strength plots display material property differences between a part that is shaken out after (left) versus before (right) solid state temperature is reached (ProCAST) (Pictures courtesy of Caterpillar, Inc., USA).

POROSITY PREDICTION

The final integrity of a casting, e.g. mechanical properties and surface finish, is greatly influenced by the presence of porosity [4]. Three basic type of porosity (piping, macro/micro-shrinkage porosity and gas porosity) are encountered by foundries. However, in most of simulation software today, porosity prediction is limited to macro-shrinkage porosity corresponding to the sole contraction of the metal during solidification at a free surface (piping) or within a pocket of liquid surrounded by solid (macropores). Macropores are usually found at the last area of solidification.

Solutions used by foundries to avoid macro-shrinkage porosity are pin squeeze and intensification phase in pressure die casting and feeders in gravity casting to compensate for the volumetric shrinkage. One additional method to avoid shrinkage is to change the chemical composition of the alloy. Indeed, elements like silicon and graphite expand during solidification. This phenomenon is well known by cast iron foundries. During casting, nodular cast iron does not simply contracts when it cools and solidifies but it expands due to graphite expansion. If the outer surface of the casting are preventing from expanding, then an increasing pressure inside the casting can help to compensate the formation of micro and macro shrinkage porosity. As explained in the introduction, this physical phenomenon is not trivial to understand and subsequently very difficult to model. Indeed, it is required to consider microstructure, process conditions, material properties, inoculation, fading, density variation and mechanical properties of the mould to accurately predict shrinkage porosity in cast iron. Today, by coupling thermodynamic database with micro and macro model, it is possible to predict porosity by taking into account alloy expansion (see Figure 5).

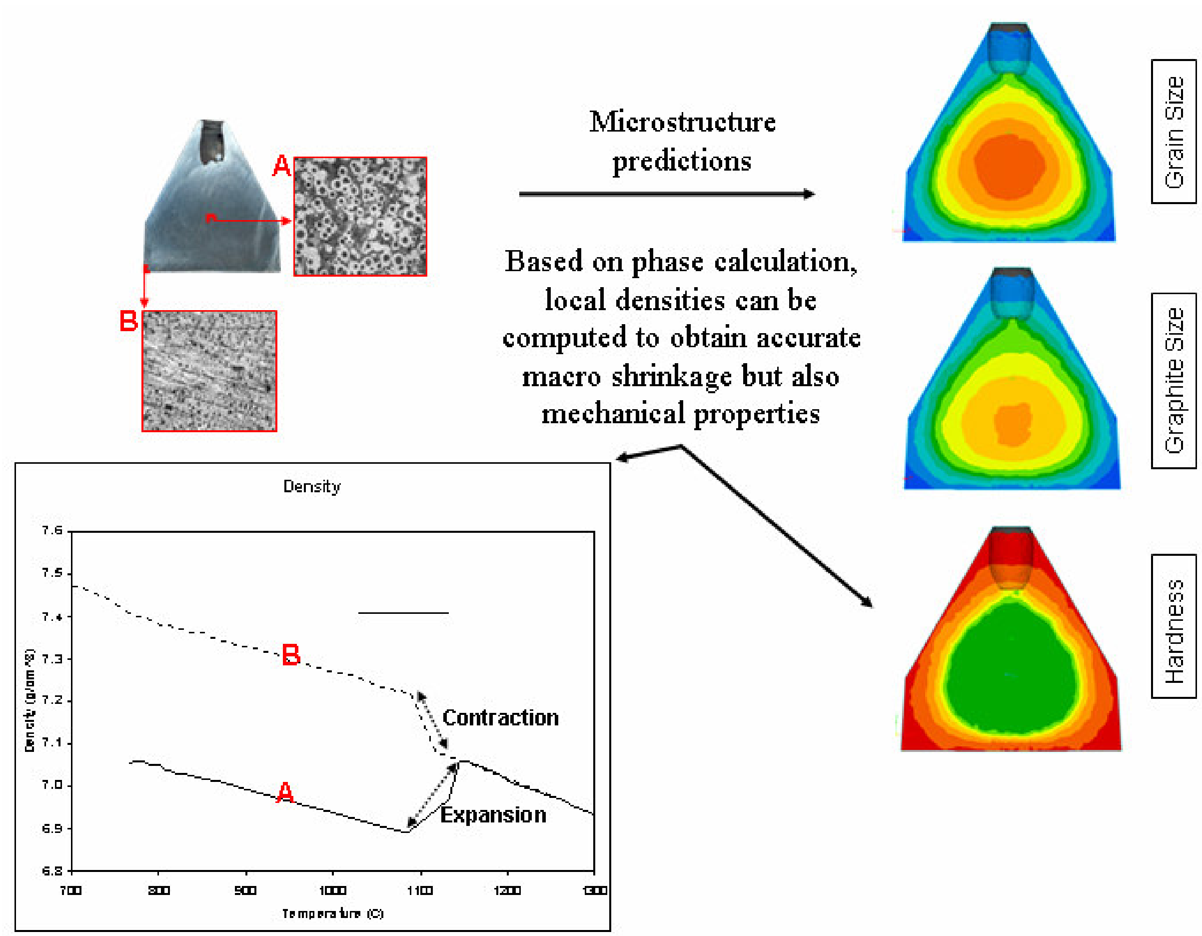

Figure 5: Picture (top-left) shows microstructural results of a nodular cast iron in a simple test. Two different microstructures are shown at two different locations. (A) does correspond to a low cooling rate structure allowing graphite precipitation to occur in a round shape due to the presence of Mg. (B) shows ledeburite structure with no graphite precipitation due to a high cooling rate. This results in two different local densities shown in the graphics (bottom-left) and computed by ProCAST™. Local density for the location (B) shows only contraction whereas location (A) shows expansion due to the presence of nodular graphite. On the right, we have microstructural and mechanical properties predictions (simulation results ProCAST™).

Industrial Case Study - porosity prediction with graphite expansion

Figure 6 illustrates the influence of graphite precipitation on porosity formation. As explained above, graphite nucleation according to inoculation level and process conditions will influence defect prediction. The mould rigidity is also an important factor to be considered. Indeed, the behavior of the mould could significantly influence the pressure in the liquid metal. Using adequate physical model, it is possible today to take into account those phenomena in defects prediction. The automotive part (courtesy of FURESA and AZTERLAN, Spain) poured in cast iron EN-GJS-400-18-LT illustrates this capability.

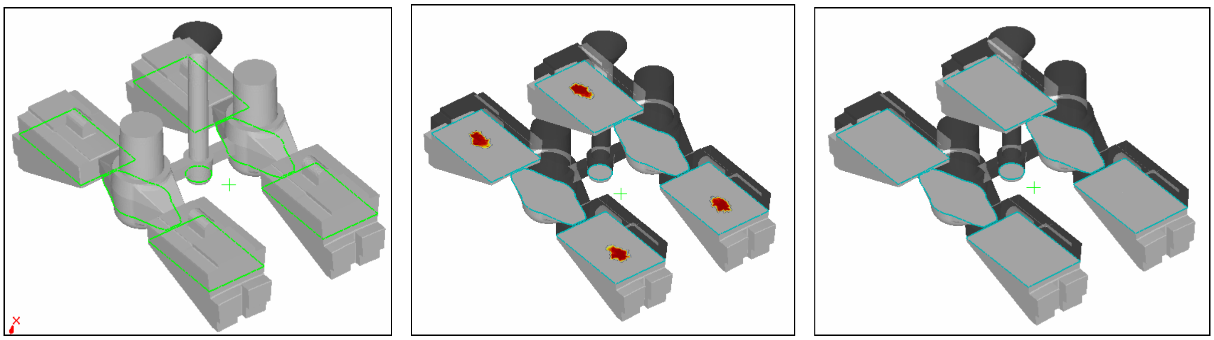

Figure 6: On the left, picture shows the geometry of the casting with a green line indicating the cross-sectional cut of right pictures. In the middle, picture shows cross-section contour plot of shrinkage porosity where yellow (red means empty) indicates macro pores when not considering the graphite expansion and considering the mould as soft, i.e. not helping for feeding. On the right, shrinkage porosity prediction is shown when considering graphite expansion. We then see on this specific industrial case that graphite precipitation and thus expansion can compensate locally all the shrinkage of the liquid during solidification. The result is inline with the reality as the as-cast part is soundness. Results performed with ProCAST.

CONCLUSION

In ProCAST^{TM}, a comprehensive micromodel has been developed to simulate microstructure formation of cast iron. The model can give accurate shrinkage prediction by taking into account density variation through microstructural information as well as the mechanical properties at ambient temperature such as yield strength, tensile strength, elongation and hardness. The predictions have been compared with experimental results and found to be in good agreement.

REFERENCES

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