ADVANCED CASTING SIMULATIONS

Marco Aloe, Dominique Lefebvre, Alfons Mackenbrock – ESI Group, France
Adi Sholapurwalla, Sam Scott - ESI NA, USA

ABSTRACT

Beyond simply identifying shrinkage porosity and filling problems, numerical tools have been further developed to predict stresses, microstructures, defects and to model specific processes that can be used effectively by the foundry engineer early in the manufacturing process to save significant time and cost. More specifically this paper will address the following topics:

- Stress and deformation - what is the final shape of the cast component? What about fatigue life of the die? Can heat transfer variation due to gap formation between the casting and the die be taken into account? Can hot tears defects be predicted?
- Micro and gas porosity - what about the integrity of the part? What about the initial gas content in the liquid?
- As-cast mechanical properties - can local mechanical properties be predicted such as yield strength and hardness?
- Core blowing - can core defects be simulated?

The author will discuss the above subjects and will show how international research projects and industrially leaded projects are essential to improve casting simulation capacities.

KEYWORDS

FEM, casting simulation, stress, deformation, gas porosity, microstructure, mechanical properties, core blowing, ProCAST, PAM-QUIKCAST.

INTRODUCTION

With the generalization of CAD 3D modelling and the increase of computing performance, casting simulation software has reached a state where a relevant input for the design of a die can be given to the process engineers. Gating systems, overflows, venting channels can be optimized using numerical simulation. Solidification related defects like hot spots can also be predicted taking into account cooling channels and die cycling so as to accurately reproduce production conditions.

Today, most of the casting simulation packages in the market can handle solidification and fluid flow in the casting with satisfactory accuracy. Now, the foundry industry wants to focus on more advanced predictions such as stress and deformation, microstructure determination, as-cast mechanical properties, microporosity indication and core blowing defects.

STRESS AND DEFORMATION

Besides the defects related to filling and solidification, there are a number of stress related issues which can affect the final integrity of the cast component as well as result in die failure. One of the main goals of the casting process still remains to approach and achieve net shape. Indeed, large deformation or distortion in the part requires more rework, like hot pressing, even after a heat treatment operation.

Factors which influence the stress behaviour and fatigue life of the die include geometry, thermal history (metal temperature, gap formation, die spraying, cooling/heating channel…), material properties of the die and the casting, external forces and pressures.

In order to accurately simulate the stress behaviour, one should consider the full coupling between thermal, fluid flow and stress analysis of all the relevant materials, including casting, cores and dies. Some of the considerations to be addressed when translating this concept into a commercial code include appropriate material models, appropriate thermal/mechanical contact algorithms, hot tearing, cracking and die fatigue predictions, among others.

Gap Formation

The main reasons for stress formation are mechanical resistance of the mould and non-homogeneous temperature gradients. Therefore, the influence of an air gap formation or inversely contact pressures between the mould and the solidified casting must be taken into account. Indeed, this phenomenon also controls the heat transfer of the casting/mould interface and consequently greatly influences the above listed defects prediction. This requires a coupled thermal and stress analysis possible only with the FEM technique.[1]

For demonstration purposes, a simple T shaped casting of A356 in a H13 mould is simulated, as shown in Figure 1. The effective interface heat transfer coefficient at two different points on the casting is plotted in Figure 2. The top curve is from a point experiencing increasing contact pressure as the casting contracts. The middle curve is from a point where a gap is opening up between casting and mould, assuming the presence of air. The bottom curve is from that same point, but assuming a vacuum. The large variation in the coefficient illustrates the importance of accounting for local conditions by coupling thermal and mechanical calculations. In addition, this example illustrates the value of the reverse coupling of the mechanical deformations with the energy solution. This effect can be seen in Figure 1 where the heat flux contours are plotted. The heat flux is greatest where the contact pressure is highest.

This phenomenon will result in a different solidification path between a coupled and uncoupled calculation which could greatly influence the prediction of defects such as hot tearing as shown in Figure 3. Indeed, whether or not hot tearing occurs depends on the mechanical loads that develop due to thermal contraction and the contact constraints of the die wall.

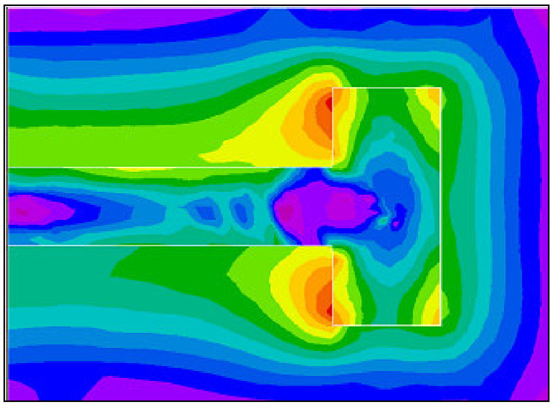


Figure 1: Heat Flux Contours influenced by the gap formations. (ProCAST)

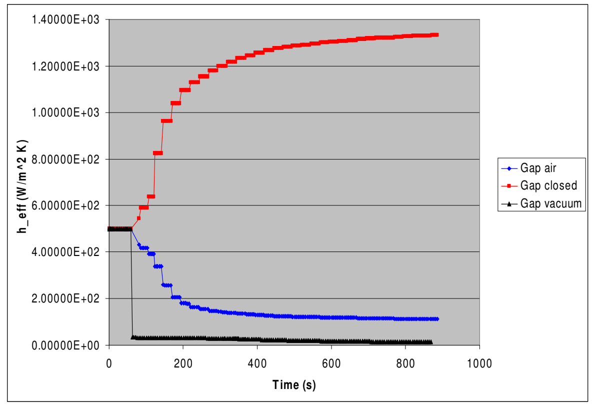


Figure 2: Interface heat transfer coefficients taking into account the mechanical contact.

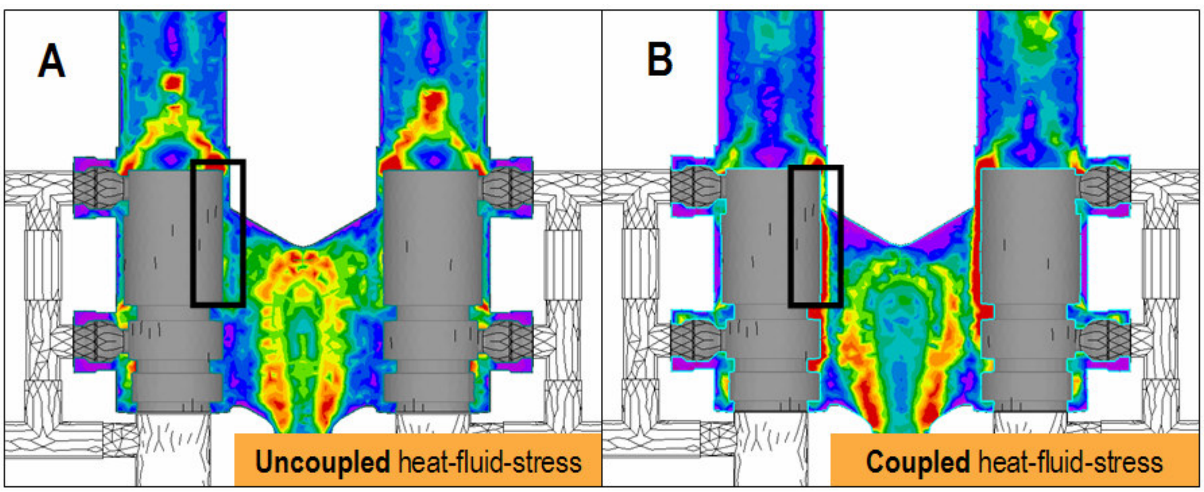
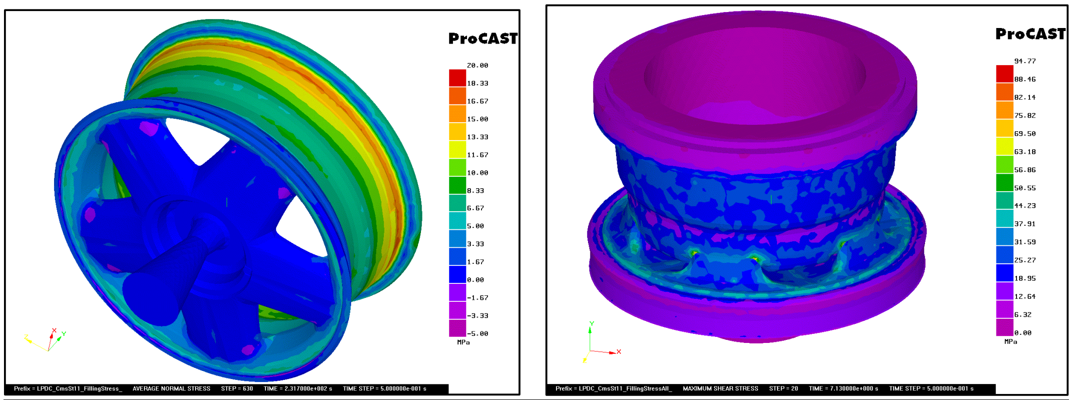


Figure 3: Hot tearing indicator showing different sensitivity and location between a coupled and uncoupled calculation. (ProCAST, Low Pressure Die Casting of Brass component, courtesy of KWC Engineering AG, Switzerland)

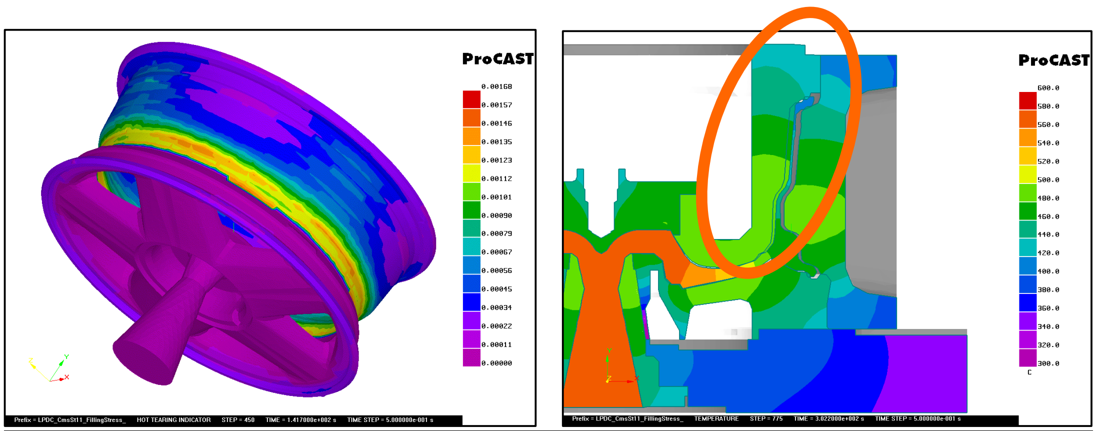
Industrial Example-Quality Map

ProCAST [2] provides a unique solution based on a fully coupled thermal, flow and stress model in order to have accurate prediction of hot tearing, cracking, part distortion as well as die distortion and die fatigue life.

The first example concerns a low pressure die casting of an aluminium automotive wheel, courtesy of C.M.S. Jant Ve Makina San A.S. in Turkey. The plots in figure 4, showing residual stresses, hot tearing sensitivity and deformations, indicate where the integrity of the casting and the die is of particular importance thereby acting as a component ‘Quality map’ to the foundry man.



Residual stresses in the casting
Shear stresses in the mould



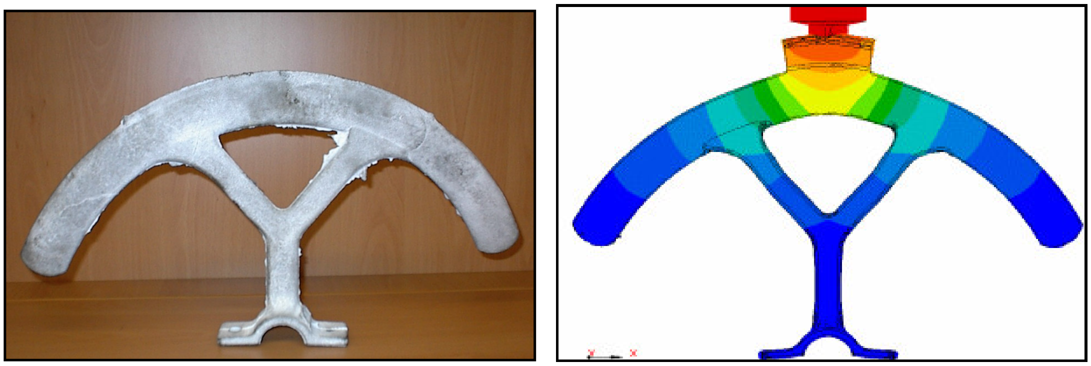
Hot tearing prediction
Enlarged deformation observed during cooling

Figure 4: Stress modelling. (ProCAST)

Industrial Example-Shape Prediction

The second example (see Figure 5) concerns a gravity shell casting of a stainless steel AISI 410 component, courtesy of Fundiciones en Cascara S.A., in Spain. One of the major issues in casting remains the deformation of the part with regards to the tight tolerances required by the industry. When a casting cools at room temperature, thermal stresses and dimensional changes occur. The dimensional changes depend on the casting's geometry, temperature and material properties. The scope of this calculation is to accurately predict the final shape of the component in order to make a reverse pattern of the shell to compensate the contraction and the deformation of the casting. This will help to approach the final shape of the part required by the customer specifications.

Solidification and stress analysis were performed on the component by taking into account springback effect of the part after removing the material mould. To validate the simulation results, 3D digitalization of the real part was carried out with a SIDIO machine. This technique without contact allows getting a thousand of points representing the actual geometry with a precision of 0.1mm. Then, recomposed shape could be superimposed with CAD geometry as shown in figure 6 to see any shape differences. Simulation results showed good correlations with the final shape of the part in terms of tendencies and absolute displacements.



Production part Simulated results (temperature field, ProCAST)

Figure 5: Stainless steel shell casting component.

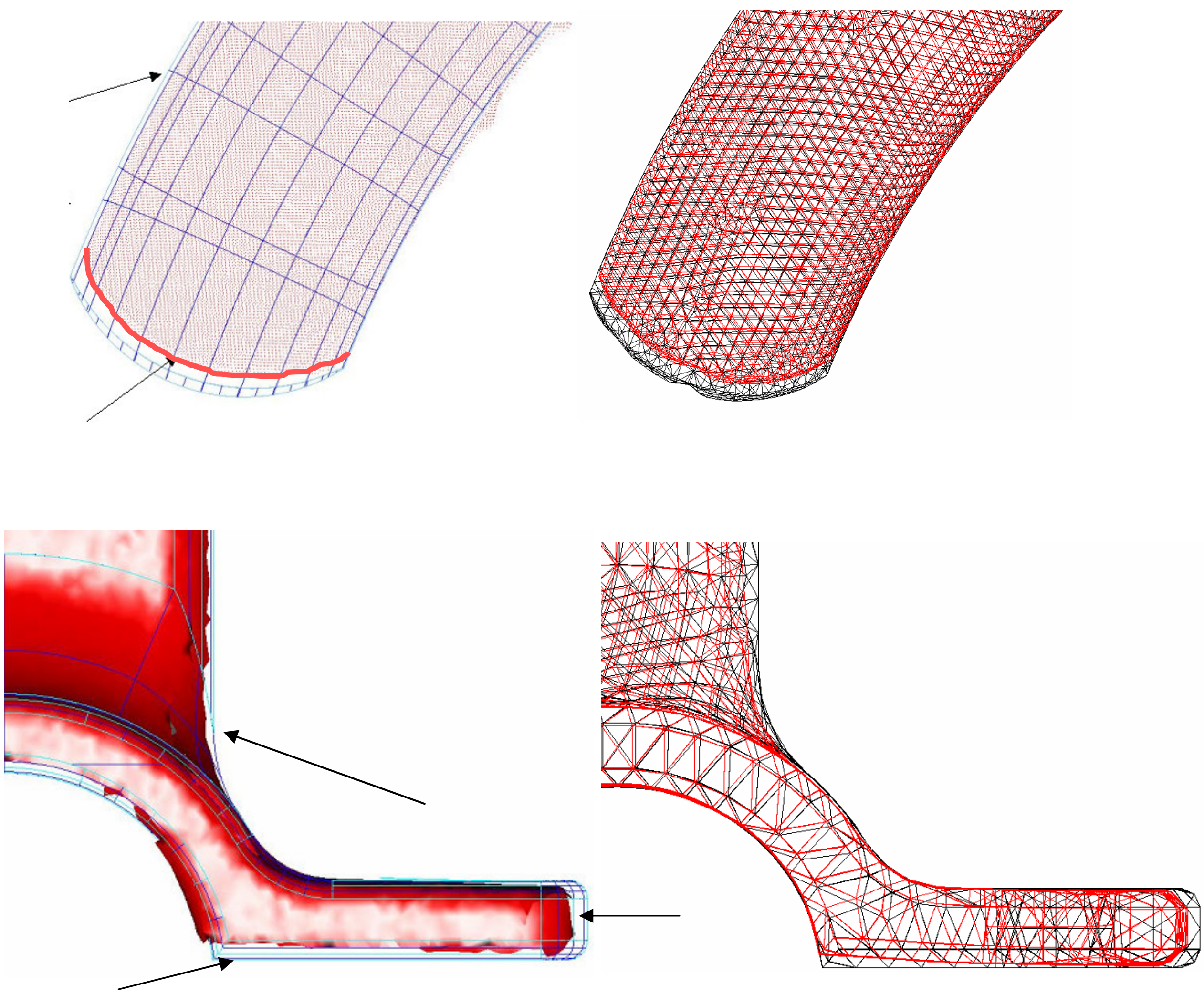


Figure 6: Comparison between the actual digitized geometry (red points or contours on the left) and computed results by ProCAST (red tetrahedral mesh on the right) and the original CAD/Mesh geometry in black or blue (on both sides) is shown.

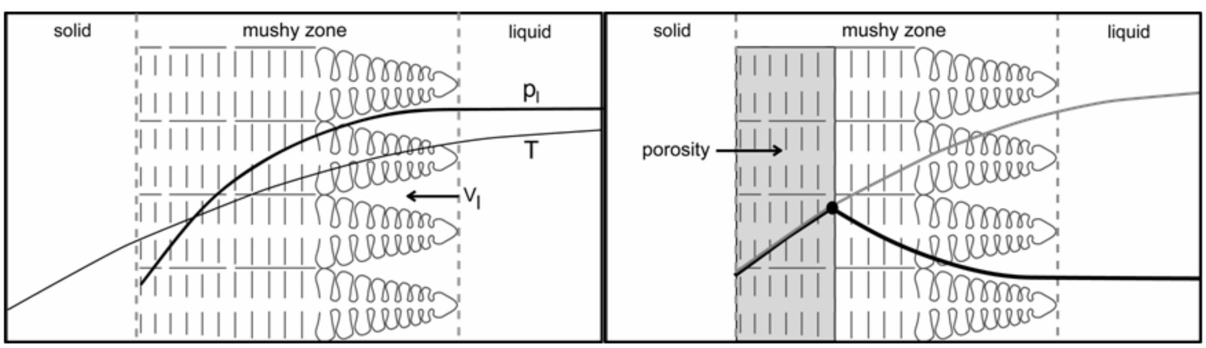
IMPRESS Project

ESI Group, editor of ProCAST and PAM-QUIKCAST products contributes to the IMPRESS[1] project with the development of its simulation software on (i) coupling casting and heat treatment simulation, (ii) assessment of solid state transformations during heat treatment of TiAl intermetallic alloys, and (iii) prediction of material properties as a function of microstructures and porosity.

MICRO AND GAS POROSITY [3]

This section is a summary of the paper published by G. Couturier and M. Rappaz, "Modeling of Porosity Formation in Multicomponent Alloys in the presence of several dissolved Gases and Volatile Solute Elements", *Symposium on Simulation of Aluminum Shape Casting Processing,* Edited by Qigui Wang (TMS, 2006).

The final integrity of a casting, e.g. mechanical properties and surface finish, is greatly influenced by the presence of porosity.[4] In most of simulation software today, porosity prediction is limited to macro-shrinkage porosity which corresponds to the contraction of the metal during solidification. This approach does not take into account for gas and interdendritic shrinkage porosity. Gas porosity in aluminium alloy is due to the segregation of hydrogen dissolved in the molten metal as it has almost no solubility in the solid phase. Therefore, as shown in figure 7, porosity is the result of the combination of solidification shrinkage and segregation of gases. The liquid permeability is reduced in the solid dendritic area hindering efficient metal feeding and decreasing the pressure in the liquid. Simultaneously, gas concentration is locally increased due to segregation. Consequently, if the gas exceeds the effective solubility limit, nucleation and then growth of pores has to be considered.



(a) (b)

Figure 7: Schematic representation of (a) the liquid pressure drop in the mushy zone due to solidification shrinkage and (b) the increase of gas concentration, in the mushy zone due to gas microsegregation (thick line) and the decrease of the solubility limit (thin line). At equilibrium, cavitation occurs at the crossing point of these two curves.

General Theoretical Framework

Figure 8 shows schematics of a simplified casting. Solidification induces three types of voids: (i) at a free surface (e.g., of risers), the level of liquid decreases as solidification proceeds (piping); (ii) within closed liquid pockets (hot spots), a macropore surrounded by microporosity will be present;

---

[1] The IMPRESS Integrated Project is a large pan-European "flagship" project in the field of applied material science. IMPRESS is an acronym for Intermetallic Materials Processing in Relation to Earth and Space Solidification. The project is managed by the European Space Agency and is co-funded by the European Commission in the 6th Framework Programme. IMPRESS comprises a large multi-disciplinary consortium of 42 research groups and companies, with a total 5-year budget of 41 million Euros.

(iii) microporosity finally dispersed within the mushy zone 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.

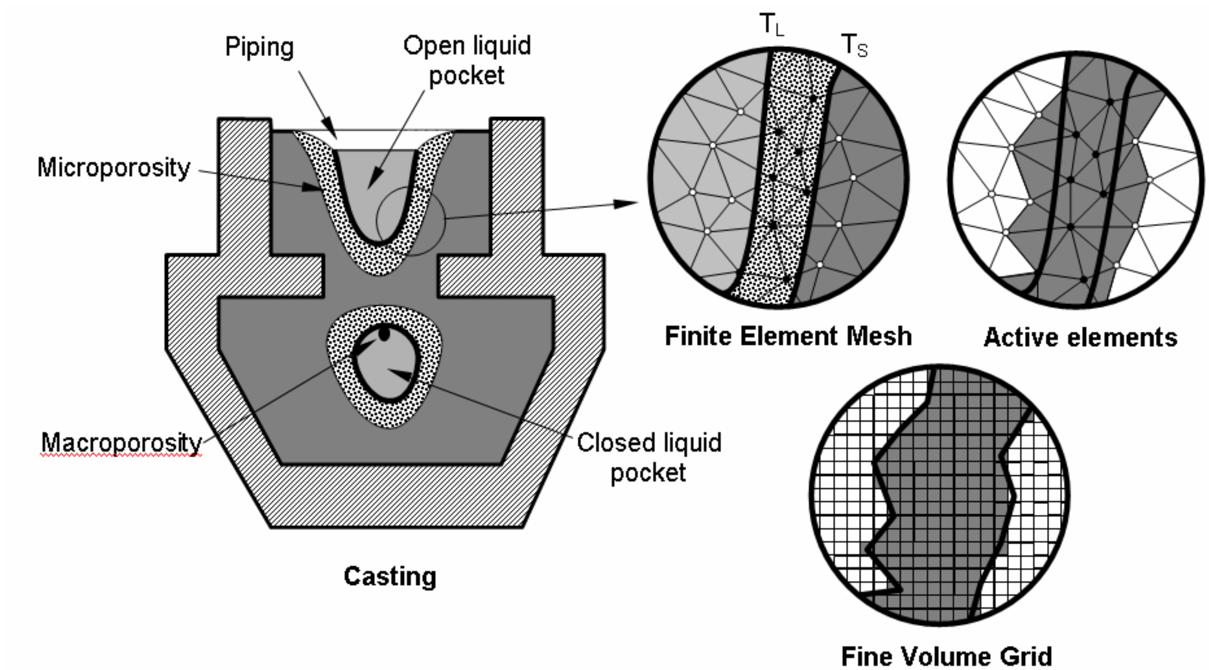


Figure 8: Schematics of a casting showing piping at a free surface and macroporosity formation in a closed liquid pocket. A zoom of the unstructured FEM mesh and structured fine volume grid are shown on the right (see text).

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 has been 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 such elements, volume elements of a structured grid are activated for the calculation of the pressure drop.

Industrial Case Study

A calculation of advanced porosity prediction performed for an aluminium A383 high pressure die casting is shown in Figure 9. This calculation takes into account all basic phenomena described above, which are at the origin of micro and macro porosity. The geometry is shown on the left. Applying a pressure of only 1 bar (central figure), the amount of porosity which is shown with various green levels is quite high. Macropores are even present at some locations (e.g., red zone at the centre of the zoomed region). The application of a pressure of 100 bars during solidification (figure on the right) allows to completely eliminate these macropores as well as the microporosity generated by gas segregation and pressure drop. However, with the given cooling conditions, the previous hot spots remain now as isolated mushy pockets for which the application of a high pressure has no effect. There are no longer holes in these regions, but a high level of microporosity due to uncompensated solidification shrinkage.

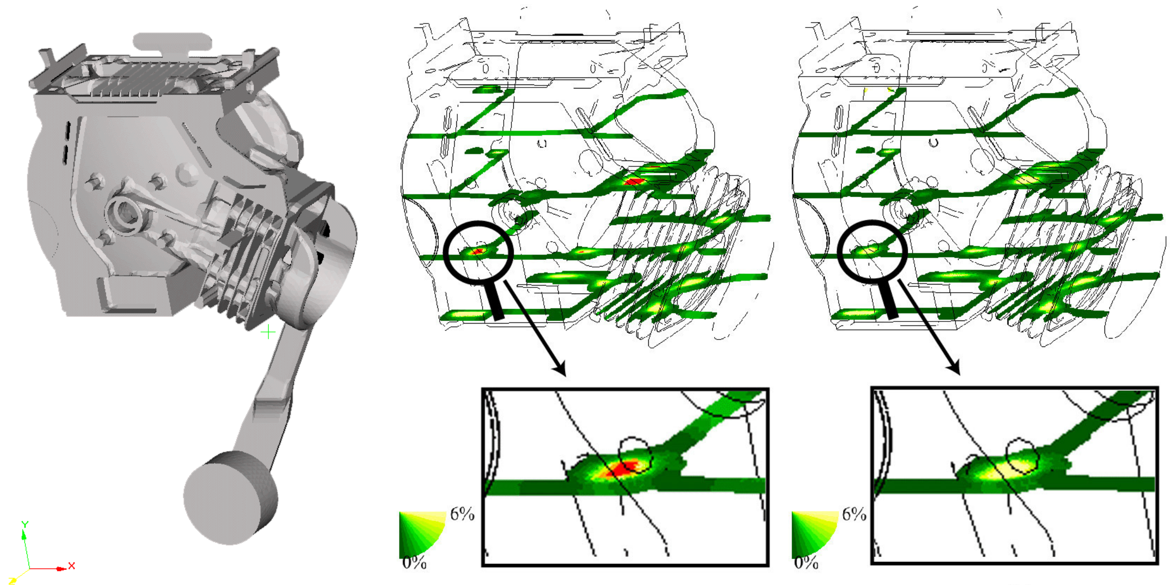


Figure 9: Example of the type of porosity calculation that can be carried out for a complex shape A383 casting. The geometry is shown on the left, while the calculated porosity fraction is displayed with various green/red levels for a few sections when the applied pressure is 1 bar (center) and 100 bars (right).

Mechanical properties of cast aluminium alloys, in particular fatigue resistance and toughness, are affected by the presence of microporosity. Thus, next generation of ESI casting solutions will allow the transfer in STL format of porosity predictions in any FEA code. This information can then be used to better predict admissible designs.

POST Project

Within the MOS project terminated in 2001, a unique porosity module has been developed for the calculation of microporosity formation in binary alloys in the presence of one gas content.[5] This module considers solidification shrinkage and variations of the specific masses, interdendritic fluid flow, segregation of gas, nucleation-growth of pores using a dynamic and evolving refinement of the mushy zone. One of the goals of the on-going POST[2] project is to extend this model for multi-component and multi-gas systems. For instance, the contribution to porosity formation of volatile solute elements such as zinc has been considered in [6].

MICROSTRUCTURE AND MECHANICAL PROPERTIES PREDICTION [7]

Cost savings in castings are achieved by producing the lightest part possible to perform the job to be done. Today there is an increasing trend in the industry towards alloys that provide increased strength over traditional alloys. In order to determine whether the casting process produces a part with proper as-cast mechanical properties, microstructure prediction is required. Slight variances in elemental composition can be evaluated to determine if the change has a significant affect on final mechanical strength. Additionally, cooling rates, including those after shakeout or die ejection, can be optimized to produce desired mechanical properties in as-cast parts, thus allowing the foundry engineer to produce castings that may not require a heat treatment operation.

[2] POST is an acronym for POrosity and STress modelling. The project is coordinated by Calcom ESI and EPFL and comprises industrial partners such as Alcan, GM, Hydro and Umicore.

By understanding the relationship among material composition, process conditions and the microstructural evolution of mechanical properties, the foundry engineer and part designer can consolidate efforts to produce the best part for the job. If more strength is needed and is developed during the process, then design allowances such as larger thicknesses, more mass, larger fillets may not be needed, leading to more efficient part design, and cost-savings for the foundry. Additionally, these analysis-derived mechanical properties can be fed back into the structural analysis to understand how the as-cast part will perform.

Microstructure

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 grain size, dendrite arm spacing or eutectic fractions for aluminium and nodule counts, austenite radius, pearlite and ferrite fractions for nodular cast iron.

In the below industrial example (see Figure 10; courtesy of Combi Wear Parts in the Netherlands), as the carbon equivalent equal to 0.767, there is no peritectic reaction. The peritectic occurs when 0.09% < CE <0.53%. There is only the primary phase, which is austenite forming during solidification. Larger dendritic radius is located in the lower cooling rate areas of the casting. The primary solid fraction corresponds to the fraction of primary phase, i.e. austenite. “Secondary Dendrite Arm Spacing" refers to the distance between the secondary dendrite arms of the primary phase (see Figure 11).

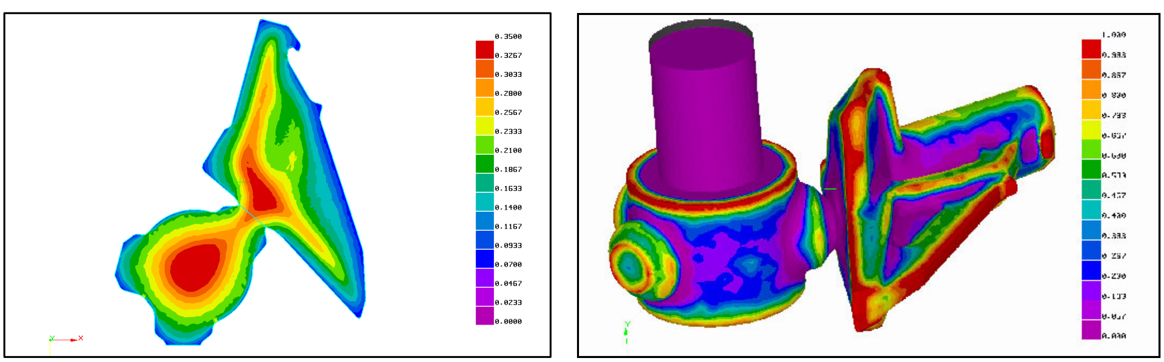


Figure 10: Grain size plot (left), and primary solid fraction (right), provide insight into the mechanical state of the as-cast part. (ProCAST)

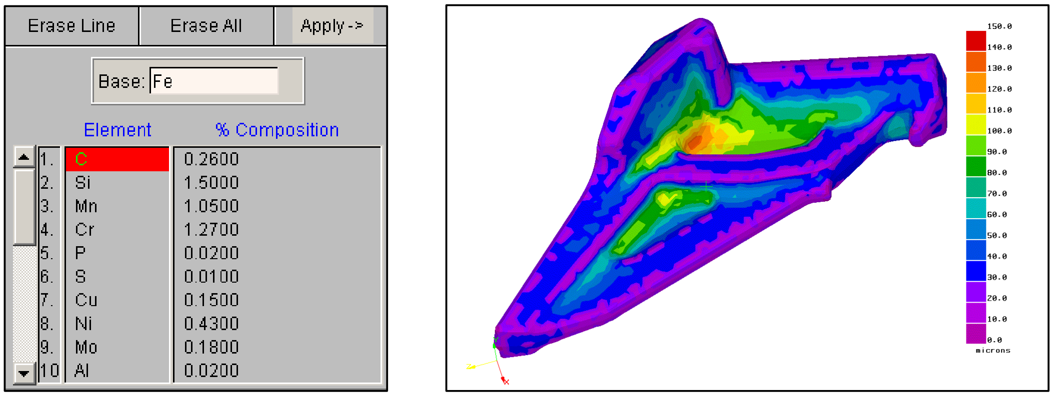


Figure 11: The chemical composition can be varied to identify the optimum strength configuration. (Secondary Dendrite Arm Spacing results of ProCAST on the right)

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 can be obtained for different kind of alloys.

To illustrate these capabilities, a sample plate was cooled in the mold to room temperature, whereas the exact same model was cooled with the variation that shakeout occurred just after solidification, but before the solid state temperature was achieved (see Figure 12). As a result, these different cooling conditions create different microstructural evolution conditions (see Figure 13). The slowly cooled plate developed a much lower tensile strength than that of the quickly cooled plate, which corresponds with experimental results. [8]

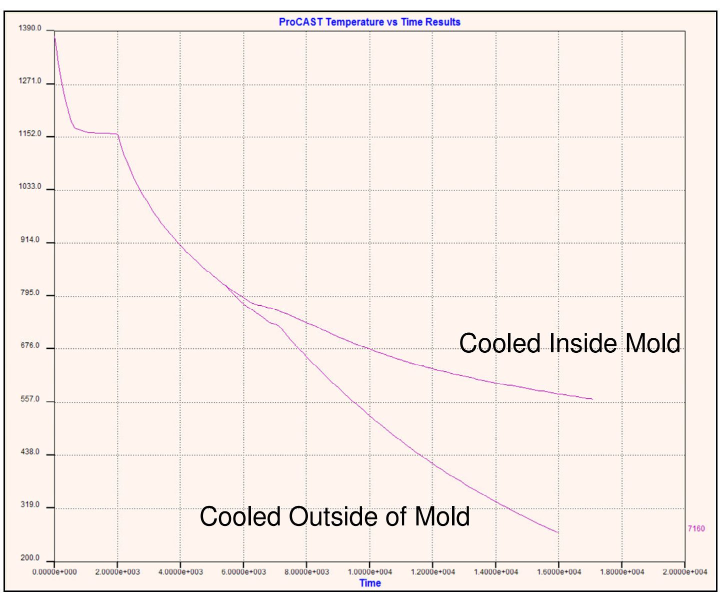


Figure 12: Cooling curves at the same location indicate the cooling rate differences when the part is cooled inside the mold versus when the part is shaken out while still above the solid state temperature.

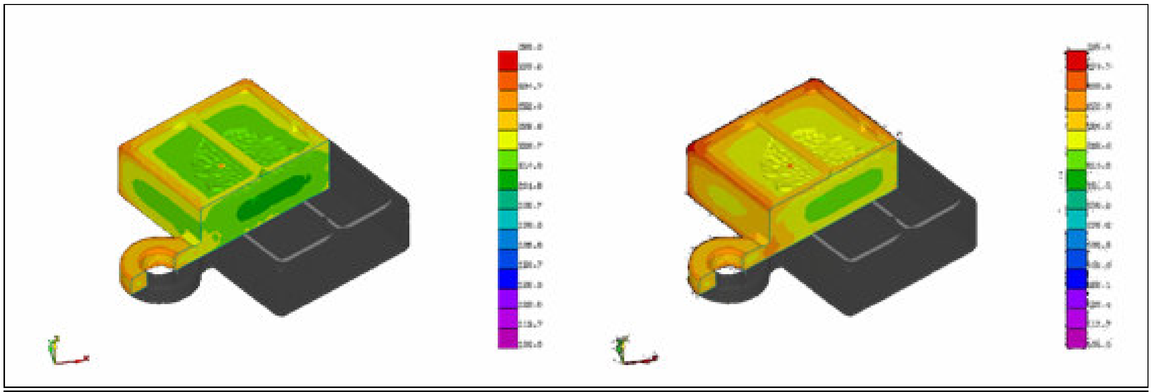


Figure 13: Tensile Strength plots display material property differences between a part that is shaken out after (left) versus before (right) solid state temperature is reached. (ProCAST) (Pictures courtesy of Caterpillar, Inc., USA)

As illustrated, process modelling, from casting to heat treatment, requires advanced thermo-mechanical models coupled with microstructure prediction. Some of them are readily available for the casting process and may also be applied for modelling the heat treatment process to predict the final mechanical properties. These models currently link macro scale thermal fields, computational thermodynamics and microstructure.

To achieve the ultimate objective of predicting the mechanical properties of the final "as cast" component, it is also necessary to take into account the influence of casting defects such as porosities. Work is currently in progress in the frame of the European IMPRESS project and in other projects under preparation to achieve this goal.

CORE BLOWING [9]

The manufacturing of iron, steel and non-ferrous castings is achieved using different casting processes requiring the use of cores which form the internal shape of the casting. The core is often of complex shape and many cores are required for each casting. For example, in automotive cylinder head castings, cores often form internal passageways for fluid flow in valves, pumps, compressors and manifolds. The manufacturing of sand cores and moulds is commonly made using chemically bonded sands in two distinct stages. First, the sand is blown from a sand magazine into a core box at high speed. The blowing process is driven by the release of a high pressured air cartridge. A catalyst (amine) or hardening (methyl-formate or CO_2) gas is then passed through the core box to harden and cure the sand.
The design and manufacture of core boxes is a complex process and is traditionally achieved through an experienced based custom and practice technique. This long and expensive trial and error development process aims at finding the most appropriate process parameters which include blowing pressures, gassing pressures and times but also the positioning of nozzles and venting channels necessary in the core box to let gases escape. The manufacturing of cores has traditionally suffered from defects arising from poor sand compaction, low strength and poor surface finish. These typical core defects are responsible for a large proportion of scrap rates in the casting industry. With the availability of numerical simulation solutions, core blowing process parameters can be optimised and reliable and cost effective quality core production can be achieved.

Modelling of sand blowing

The implemented model was applied to the simple core geometry and validated against experimental results. As can be seen on figure 14, results agree qualitatively with experiments and the proposed model is able to correctly describe the transient stages of the blowing process. In this example, all the vents on the left were closed which explains the unsymmetrical filling pattern obtained.

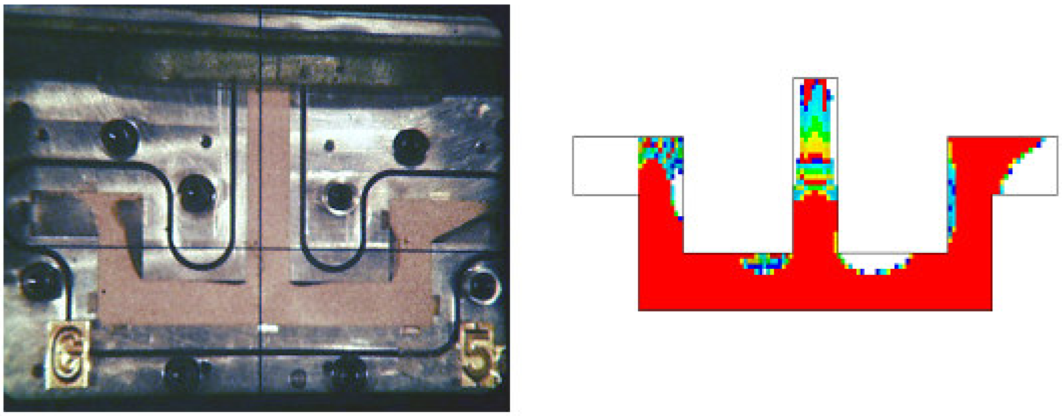


Figure 14: Comparison between experiments and simulations for sand blowing. (PAM-QUIKCAST)

Modelling of gassing

As the sand injected in the mould is first coated with an organic resin, capillarity bridges are formed between sand grains. The consolidation of these bridges is achieved by the supply of a gas mixture containing the right chemical agent to obtain the hardening reaction. Depending on the process, this chemical agent can either take part in the reaction as a co-reactant or just as a catalyst. Once the gassing stage is completed, the core box is finally purged from its remaining active gasses by injecting air in the core box.

The core gassing simulation requires the definition of the gassing pressure applied at the top of the shooting plate and of the initial fraction of active gas. Here again, vents are a key process parameter. They are taken into account as a pressure head loss boundary condition in the same way as for the sand blowing stage. The optimum venting configuration is generally different for blowing and gassing. It is therefore necessary to find the best compromise between the two stages.

Gassing simulations were performed and compared to real time visualisation of the gassing front. In Figure 15, the colour change obtained experimentally with the dies coincides with the arrival of the catalyst gas and can be directly compared with the computed mass fraction of active agent. Simulation results are in good agreement with experiments for the gassing front profile but also for corresponding gassing times.

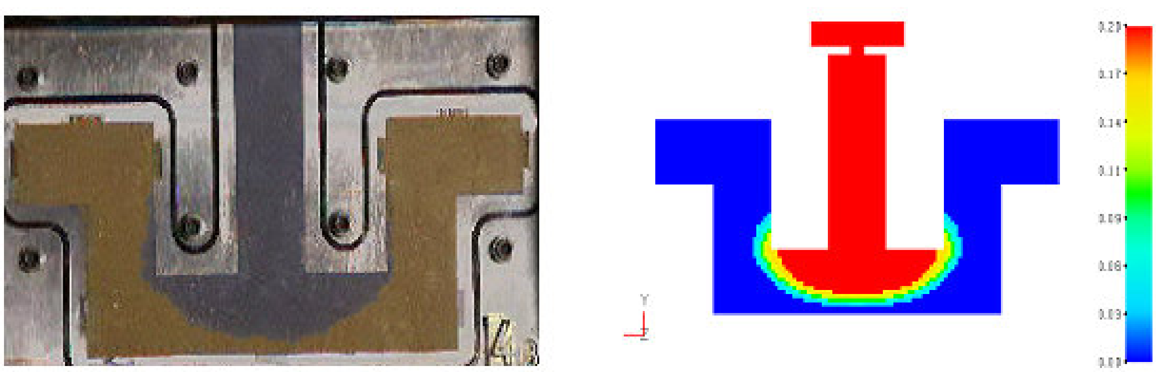


Figure 15: Comparison between experiments and simulations for gassing. (PAM-QUIKCAST)

Industrial Application

An industrial application is used to illustrate the gassing simulation. The core geometry, illustrated on Figure 16 together with the venting arrangement, is used for the manufacturing of aluminium suspension arms by Teksid in Italy. A constant gassing pressure of 2 bars is applied throughout the gassing simulation. An incomplete gassing process was performed experimentally. Upon removal of the core, the remaining sand in the core box corresponds to areas that were not hardened (see Figure 17). These trials can be compared with the predicted gassing front position towards the last stages of the gassing simulation (Figure 17). These results show a good qualitative agreement, the locations of the gassing front indicating the different areas of remaining sand. It should however be noted that, for the simulation, the sand compaction and permeability was assumed constant.

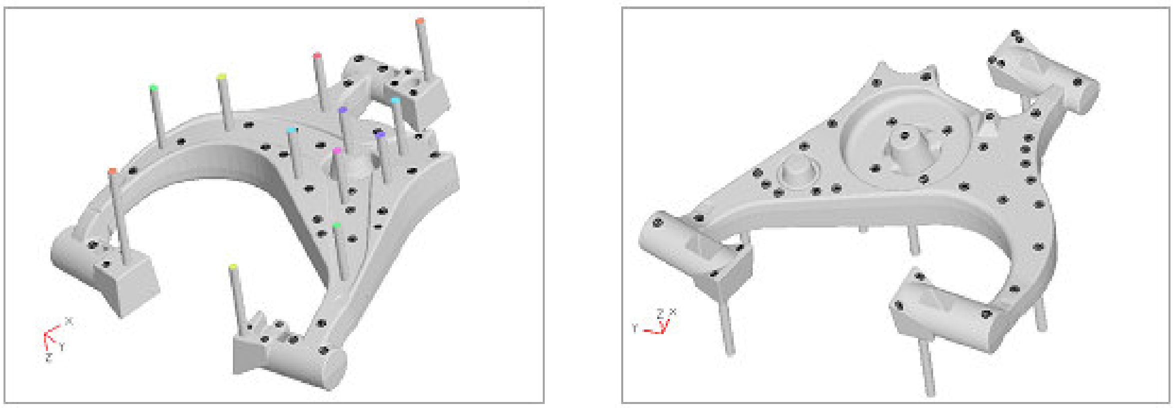


Figure 16: Suspension arm core geometry and vents positioning on upper and lower core box.

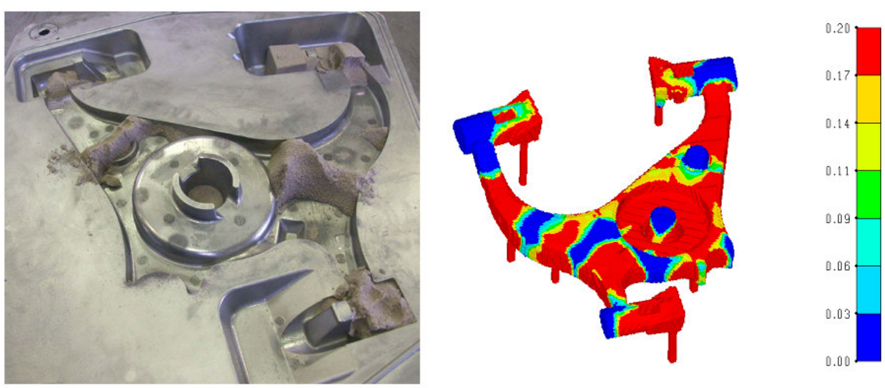


Figure 17: Remaining sand in the core box after an incomplete gassing process. Simulated gas front position towards the end of the gassing (right). (PAM-QUIKCAST - courtesy of CTIF)

OPTIBLOW Project

The present work was conducted within the framework of the OPTIBLOW project funded by the European Commission under the “Competitive and Sustainable Growth” Program (1998-2002) and coordinated by CTI (UK). The contribution of all partners: Ashland (France), CTI (UK), CTIF (France), ESI Group (France), Institut de Mécanique des Fluides de Toulouse (France), Infun (Spain), Laempe (Germany), Teksid (Italy) and Weir Foundries (UK) is gratefully acknowledged.

CONCLUSION

The effective use of computer analysis of the casting process has helped expand knowledge of the overall foundry process, and the role of such tools continues to grow both in design of the component and optimizing the process while producing a functional part under intended loading. The advancement in computer hardware available to run these programs with multiple CPU configuration, allows a fast turn around time by increasing the speed of solution even on large size models. Understanding stress and deformation, microstructure and mechanical properties, shrink and gas porosity as well as core blowing defects works its way back up the design chain to create more efficient parts and a more streamlined process, helping the foundry engineer get it right the first time around. As foundries are being pressurized to shorten delivery times and become more cost effective, computer modeling tools, like ProCAST and PAM-QUIKCAST, which offer these advanced solutions, are becoming more popular in the foundry industry.

REFERENCES

1) E-TIPS 28, www.calcom.ch.
2) ProCAST, PAM-QUIKCAST and CALCOSOFT are commercial software distributed by ESI Group, France.
3) G. COUTURIER AND M. RAPPAZ, “Modeling of Porosity Formation in Multicomponent Alloys in the presence of several dissolved Gases and Volatile Solute Elements”, *Symposium on Simulation of Aluminum Shape Casting Processing,* Edited by Qigui Wang (TMS, 2006).
4) CAMPBELL, J., *Castings*, Butterworth-Heinemann Ltd. , 1993.
5) CH. PÉQUET, M. GREMAUD, AND M. RAPPAZ, “Modeling of Microporosity, Macroporosity and Pipe Shrinkage Formation during the Solidification of Alloys using a Mushy-Zone Refinement Method”, *Met. Mater. Trans.,* 33A (2002) 2095.
6) G. COUTURIER, J.-L. DESBIOLLES, AND M. RAPPAZ, “A Porosity Model for Multi-Gas Systems in Multi-Component Alloys”, *Modeling of Casting, Welding and Advanced Solidification Processes 10*, Eds C.-A. Gandin et al (TMS Publ., Warrendale, USA, 2006).
7) PAMTALK 30, Material Properties prediction.
8) ADI SHOLAPURWALLA, SAM SCOTT, "Integration of Advanced Simulation Techniques with Process Development in the Modern Foundry", AFS Metalcasting Congress 2006, Paper 06-032.
9) DOMINIQUE LEFEBVRE, ALFONS MACKENBROCK, VALÉRIE VIDAL, VINCENT PAVAN, PETER M. HAIGH, "Development and use of simulation in the design of blown cores and moulds", World Foundry Congress 2004, Turkey.