Advanced metal casting simulations save time and cost

Over recent years, software for use with metal casting processes has made enormous progress. In this article Marco Aloe and Marco Gremaud of the ESI Group in Switzerland describe in detail some of the latest advances made in software technology developed to take time consuming guesswork out of foundry operation.

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? Can porosity be compensated by graphite expansion? 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?

With the generalisation of CAD 3D design, the increase of computing performance and now almost 20 years of experience in casting modelling, foundry simulation software has reached a state where a relevant input for the design of a die or a mould can be given to the process engineers. Gating systems, overflows, venting channels, risers can be optimised using numerical simulation. Solidification related defects like hot spots can also be predicted taking into account chills or 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. However, the foundry industry wants to focus on more advanced predictions such as stress and deformation, microstructure determination, as-cast mechanical properties and microporosity indication.

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 prediction. 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.

To simulate accurately the stress behaviour, the full coupling between thermal, fluid flow and stress analysis of all the relevant materials, including casting, cores and dies should be considered. 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 solidifying casting must be taken into account. Indeed, this phenomenon also controls the heat transfer at 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 an H13 mould is simulated, as shown in Fig 1. Only the right part of the casting is shown. The left edge of the figure does correspond to mirror symmetry. During solidification the casting contracts, forming a gap between the mould and its extreme right surface while contact pressure increases in the left part of the T shape. The effective interface heat transfer coefficient at two different points on the casting is plotted in Fig 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 Fig 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 Fig 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.

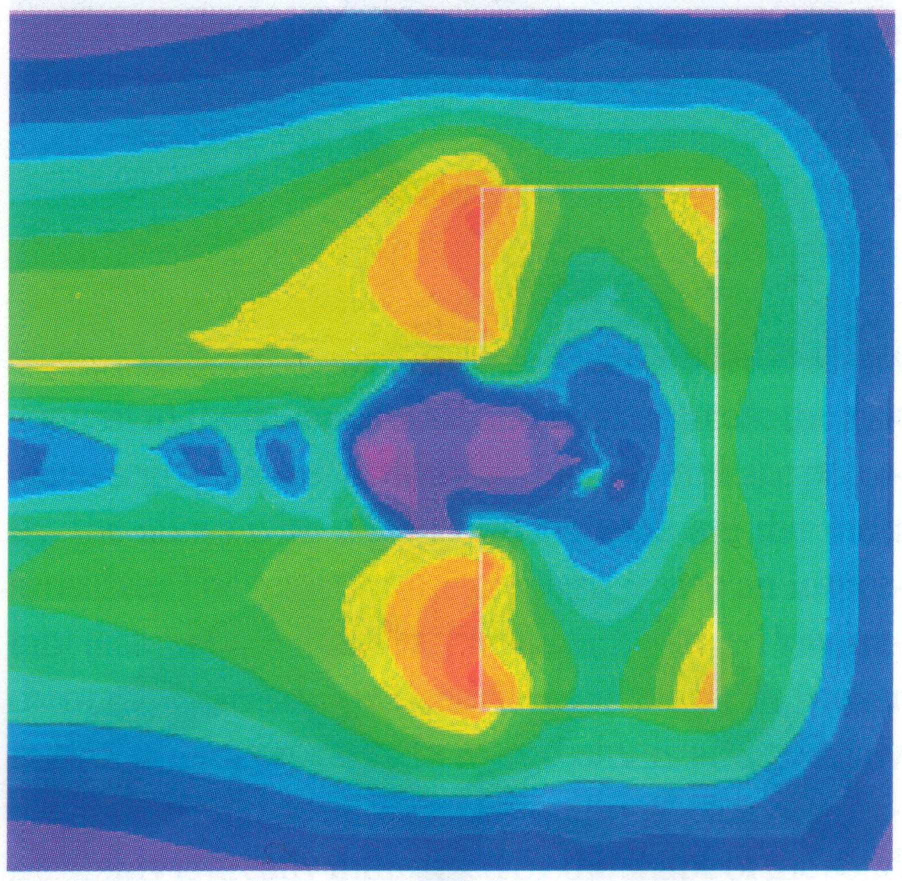


Fig 1: Heat Flux Contours influenced by the gap formations (ProCAST)

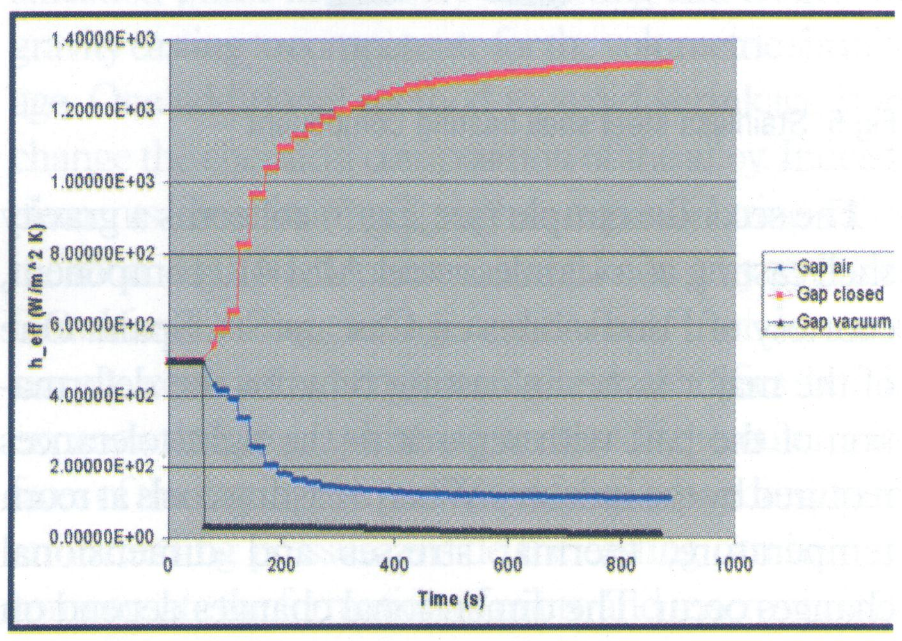


Fig 2: Interface heat transfer coefficients taking into account the mechanical contact

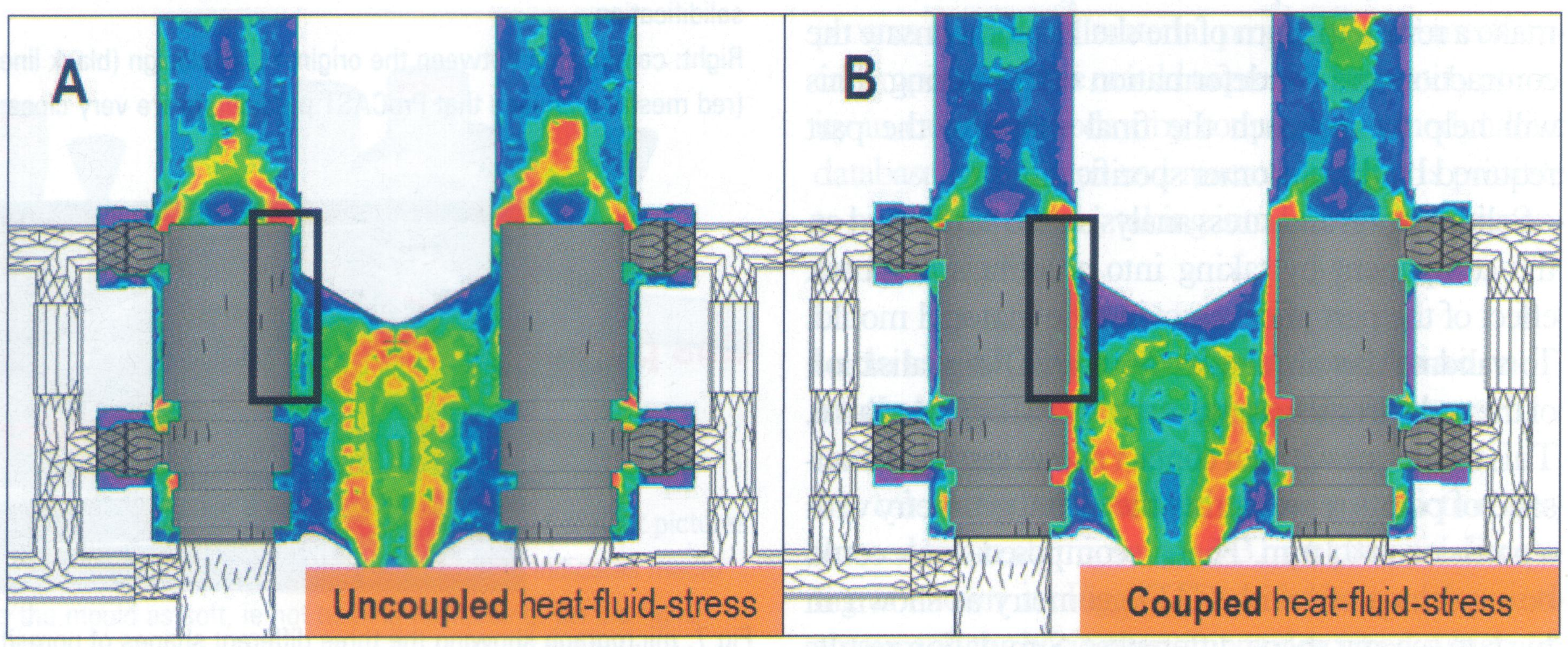
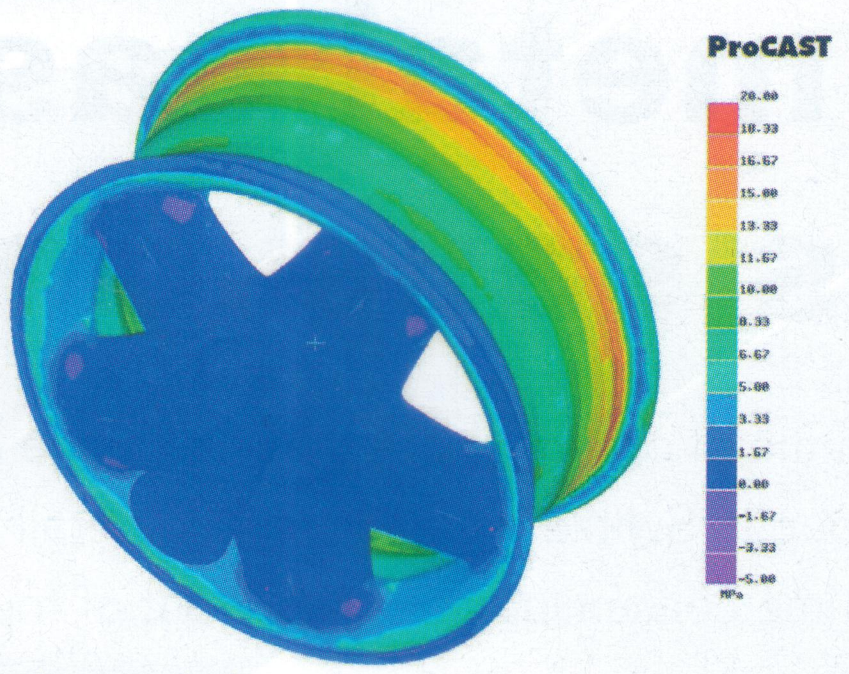


Fig 3: Hot tearing indicator showing different sensitivity and location between a coupled and uncoupled calculation. (ProCAST, Low pressure diecasting of brass component, courtesy of KWC Engineering AG, Switzerland)

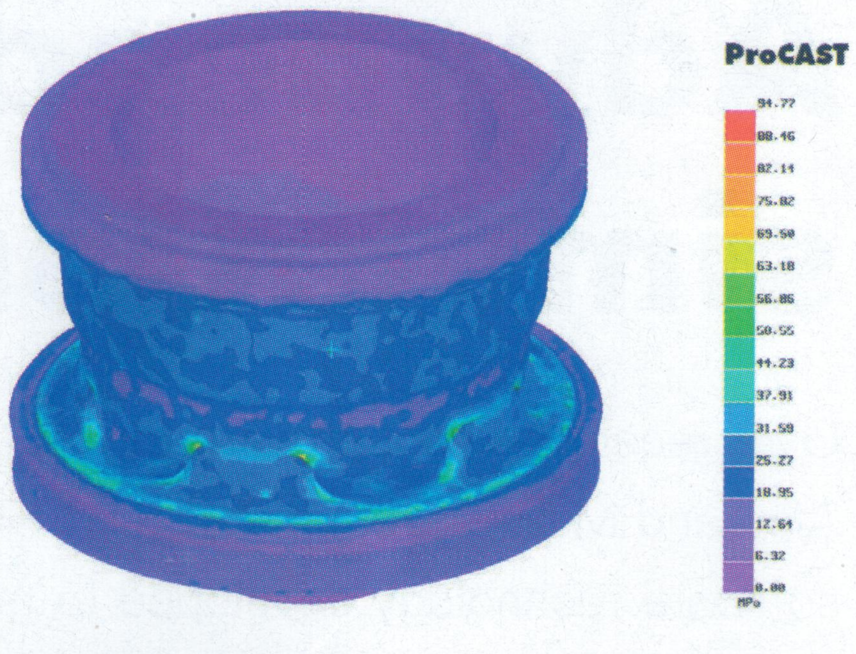
Industrial Example-Quality Map

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.

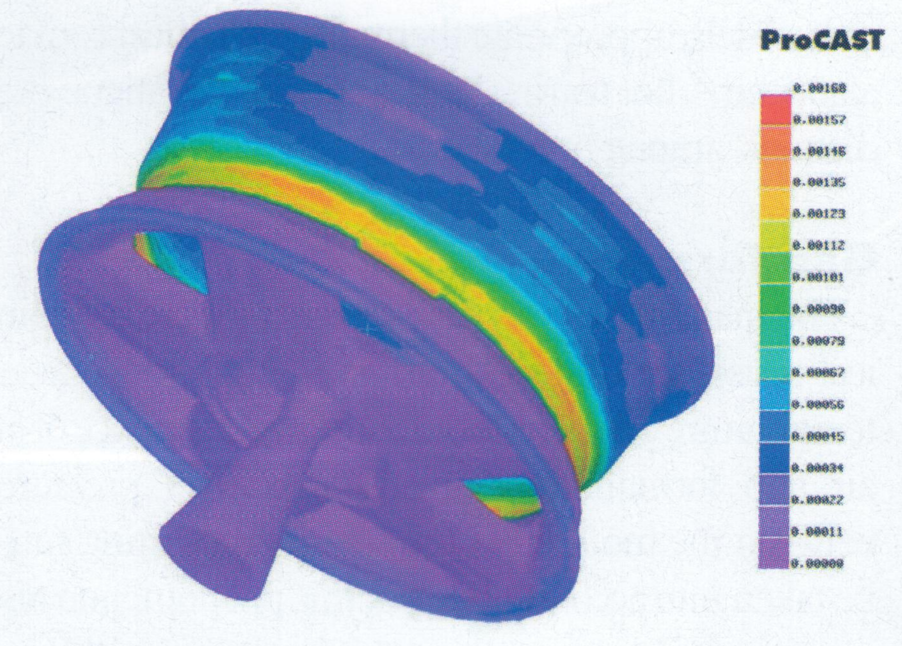
A first example concerning a low pressure diecasting of an aluminium automotive wheel, courtesy of CMS Jant Ve Makina San AS in Turkey will be discussed below. The plots in Fig 4, showing residual stresses, hot tearing sensitivity and deformations, indicate where the integrity of the casting and the die is of particular importance thereby acting as a component ' Quality map' to the foundryman.



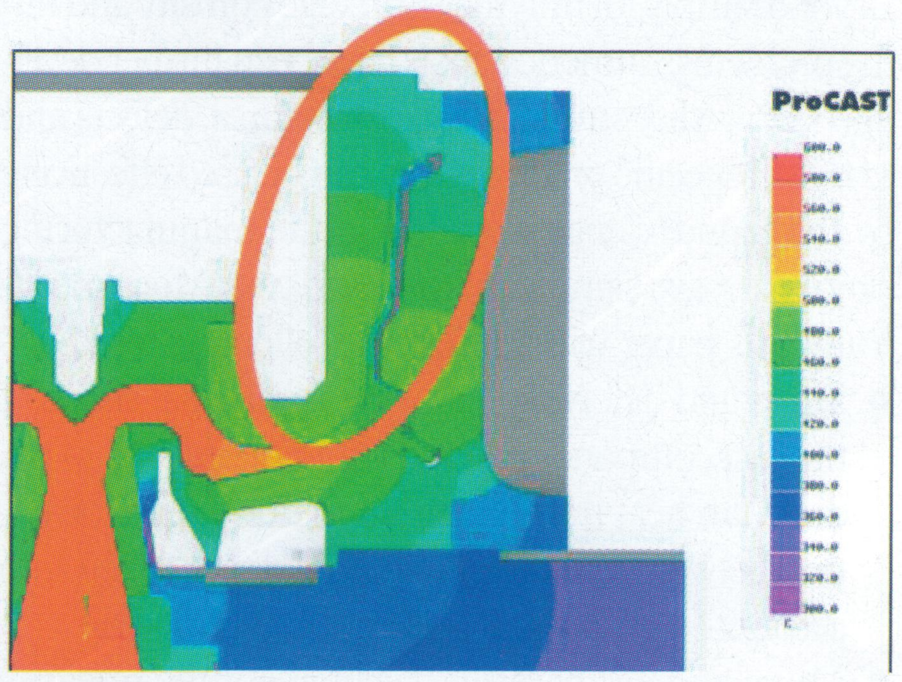
Residual stresses in the casting



Shear stresses in the mould



Hot tearing prediction



Gap formation observed during cooling

Fig 4: Stress modelling (ProCAST)

Industrial example-shape prediction

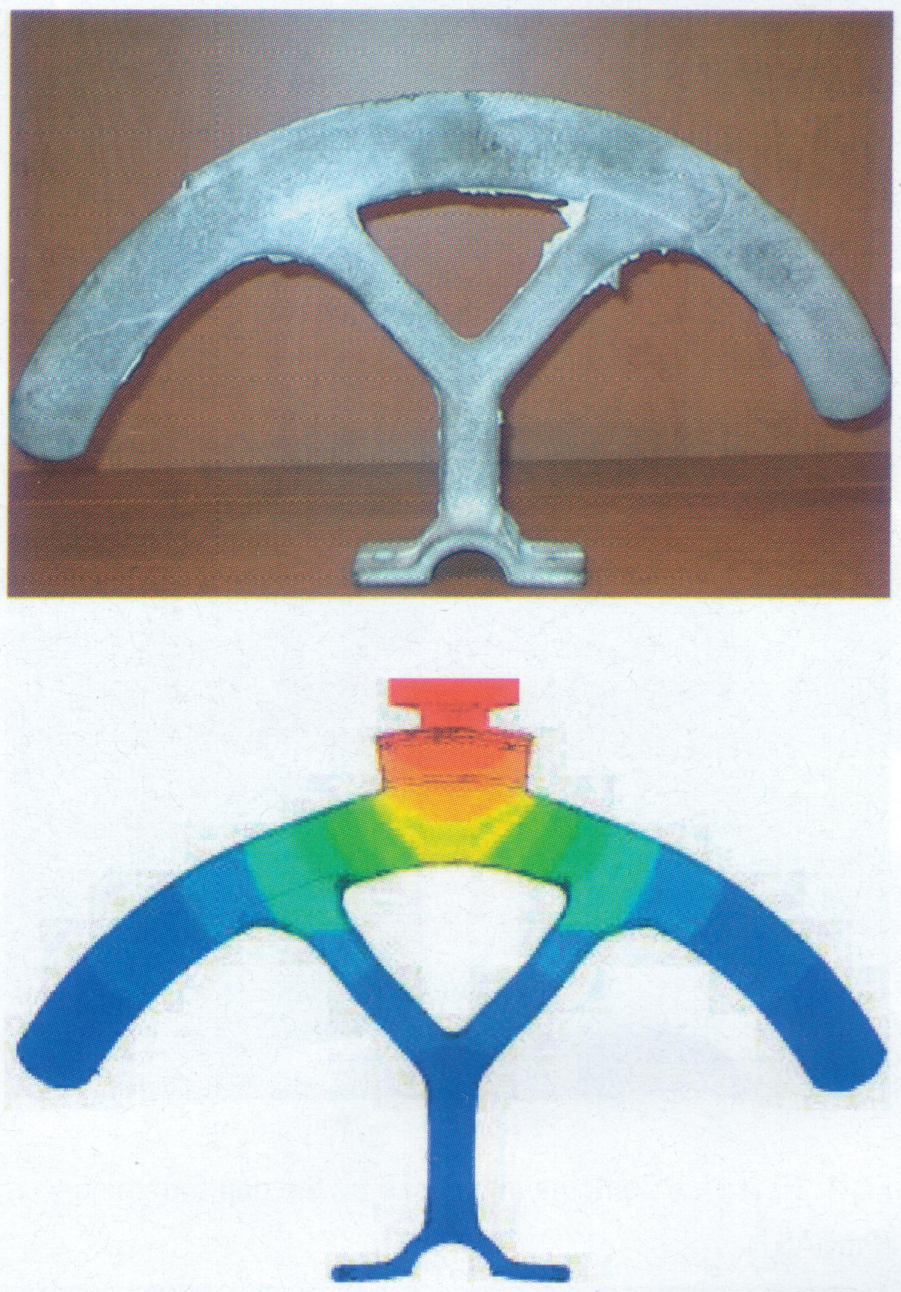


Fig 5: Stainless steel shell casting component

The second example (see Fig 5) concerns a gravity shell casting of a stainless steel AISI 410 component, courtesy of Fundiciones en Cascara SA, 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 geometry, temperature and material properties. The scope of this calculation is to predict accurately 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 digitalisation 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 Fig 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

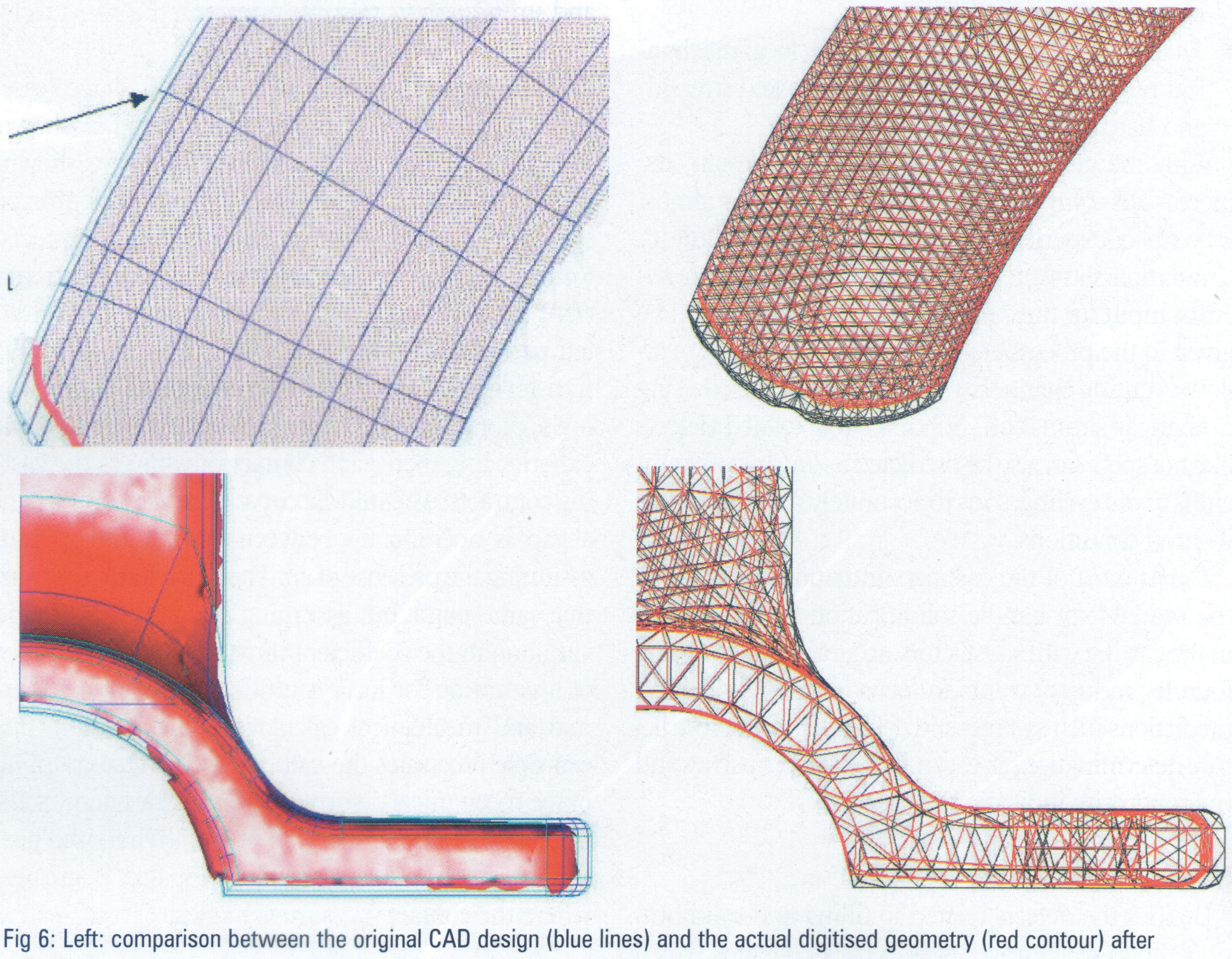


Fig 6: Left: comparison between the original CAD design (blue lines) and the actual digitised geometry (red contour) after solidification.
Right: comparison between the original CAD design (black lines) and the actual shape as predicted by ProCAST after simulation (red mesh). It is seen that ProCAST predictions are very close with experimental measured shape.

Fig 7: micrograph showing the three different shapes of porosity (a) Gas pore with a regular and round shape as well as a smooth skin, (b) Micro-shrinkage porosity with an irregular and interdentritic form (c) Macro-Shrinkage porosity with an irregular and rough skin (Picture courtesy of Alcan Technology & Management SA, Neuhausen, Switzerland).

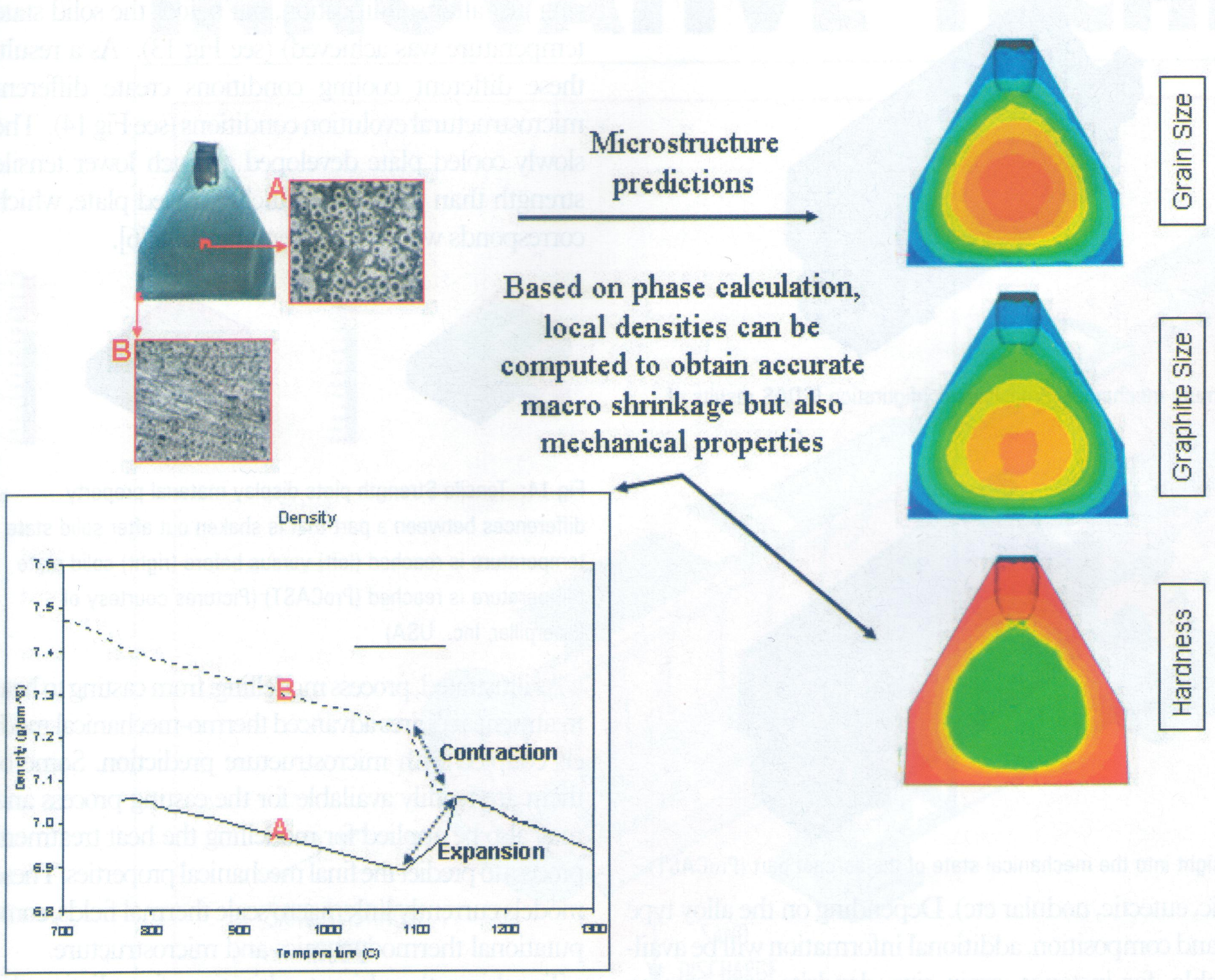


Fig 8: Picture (top-left) shows microstructural results of a nodular cast iron in a simple test. Two different microstructures are shown at two different locations. (A) does correspond to a low cooling rate structure allowing graphite precipitation to occur in a round shape due the presence of Mg. (B) 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)

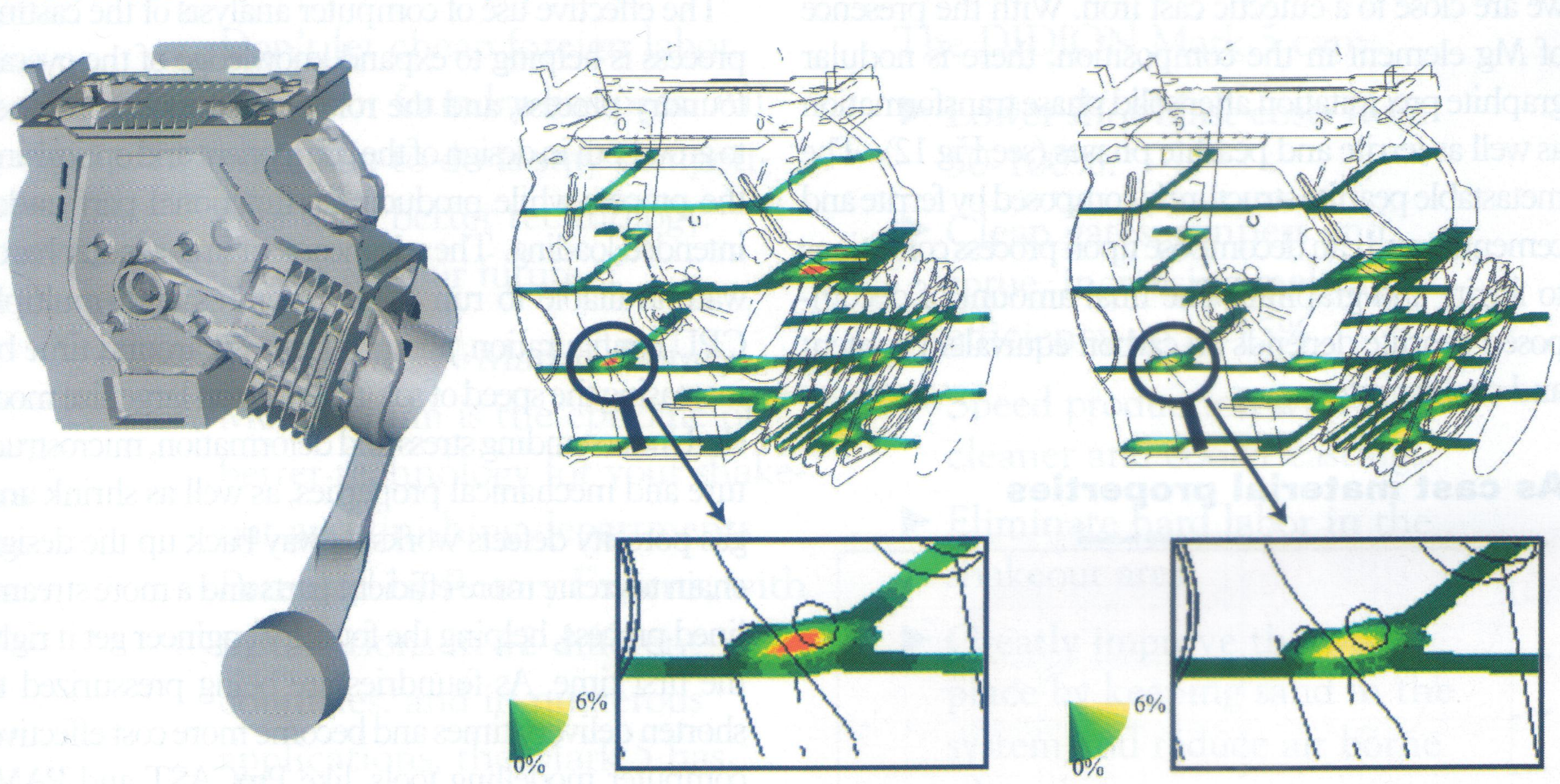


Fig 9: Example of the type of porosity calculation that can be carried out for a complex shape A383 casting. The geometry is shown on the left, while the calculated porosity fraction is displayed with various green/red levels for a few sections when the applied pressure is 1 bar (centre) and 100 bars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

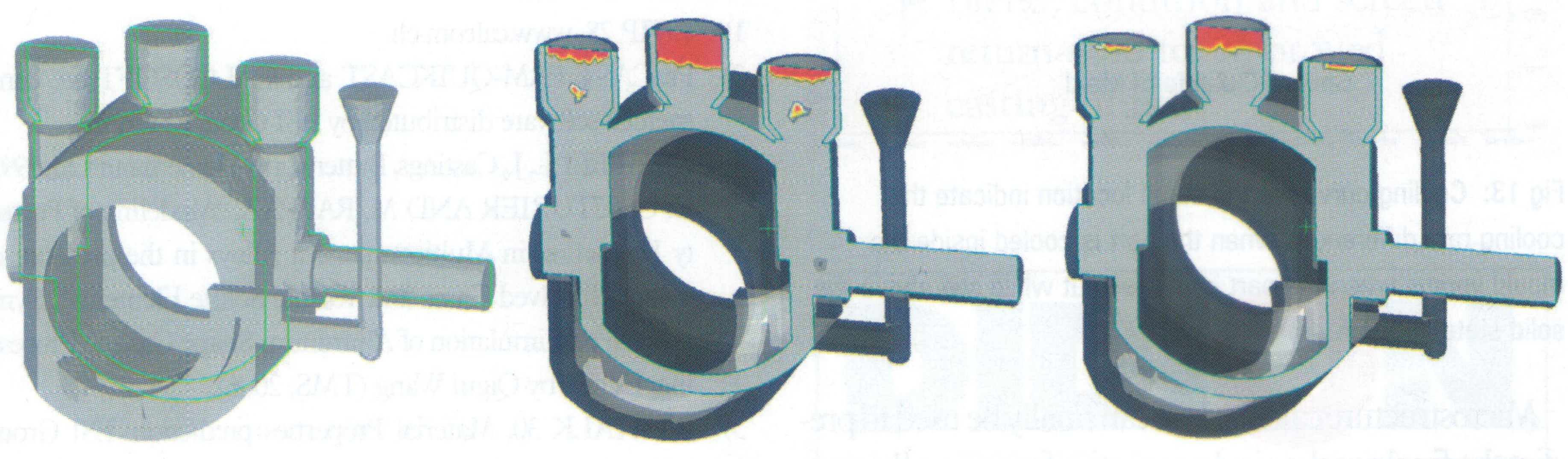


Fig 10: On the left, picture shows the geometry of the casting with a green line indicating the cross-sectional cut of right pictures. In the middle, picture shows cross-section contour plot of shrinkage porosity where yellow (red means empty) indicates macro pores when not considering the graphite expansion and considering the mould as soft, ie not helping for feeding. On the right, shrinkage porosity prediction when considering graphite expansion occurring to only a medium degree and thereby compensating part of the piping but all the shrinkage of the liquid during solidification. The mould is still considered as soft. Results performed with ProCAST

Macro, micro and gas porosity

The final integrity of a casting, eg mechanical properties and surface finish, is greatly influenced by the presence of porosity [3]. Three basic types of porosity (piping, macro/micro-shrinkage porosity and gas porosity) are encountered by foundries (see Fig 7). However, in most of simulation software today, porosity prediction is limited to macro-shrinkage porosity which corresponds to the 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. This approach does not take into account 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 [4]. Therefore, 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 increased locally due to segregation. Consequently, if the gas exceeds the effective solubility limit, nucleation and then growth of pores has to be considered.

Degassing methods are usually used to reduce gas content in the molten metal and then decrease the risk of gas segregation. Concerning micro-shrinkage porosity, the alloys with a large mushy zone are the most sensitive. The temperature gradient is also an important factor in microporosity formation. Indeed low gradient will present long dendrites and therefore higher risk of microporosity. Micro-porosity is also strongly dependent on the alloy dendrite morphology as permeability is greatly influenced by the shape of the solid skeleton. Finally, solutions used by foundries to avoid macro-shrinkage porosity are pin squeeze and intensification phase in pressure diecasting 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 contract when it cools and solidifies but it expands due to graphite expansion. If the outer surfaces of the casting are prevented from expanding, then an increasing pressure inside the casting can help to compensate the formation of micro and macro shrinkage porosity. This physical phenomena is not trivial to understand and subsequently very difficult to model. Indeed, it is required to consider microstructure, process conditions, material properties and mechanical properties of the mould to predict accurately 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 Fig 8)

Industrial case study- micro/macro shrinkage and gas porosity modelling

A calculation of advanced porosity prediction performed for an aluminium A383 high pressure diecasting is shown in Fig 9. This calculation takes into account all the basic phenomena described, which are at the origin of micro and macro porosity. Applying a pressure of only 1 bar (central figure), the amount of

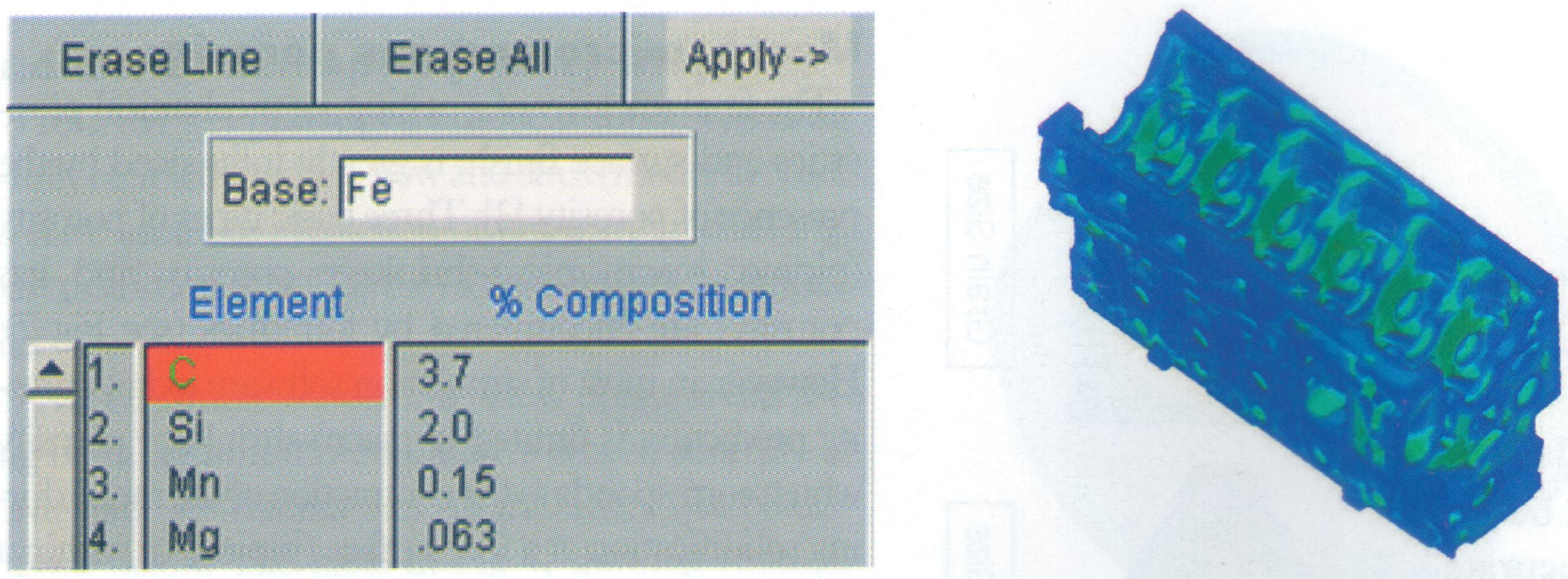


Fig 11: The chemical composition can be varied to identify the optimum mechanical properties configuration (SDAS results of ProCAST on the right).

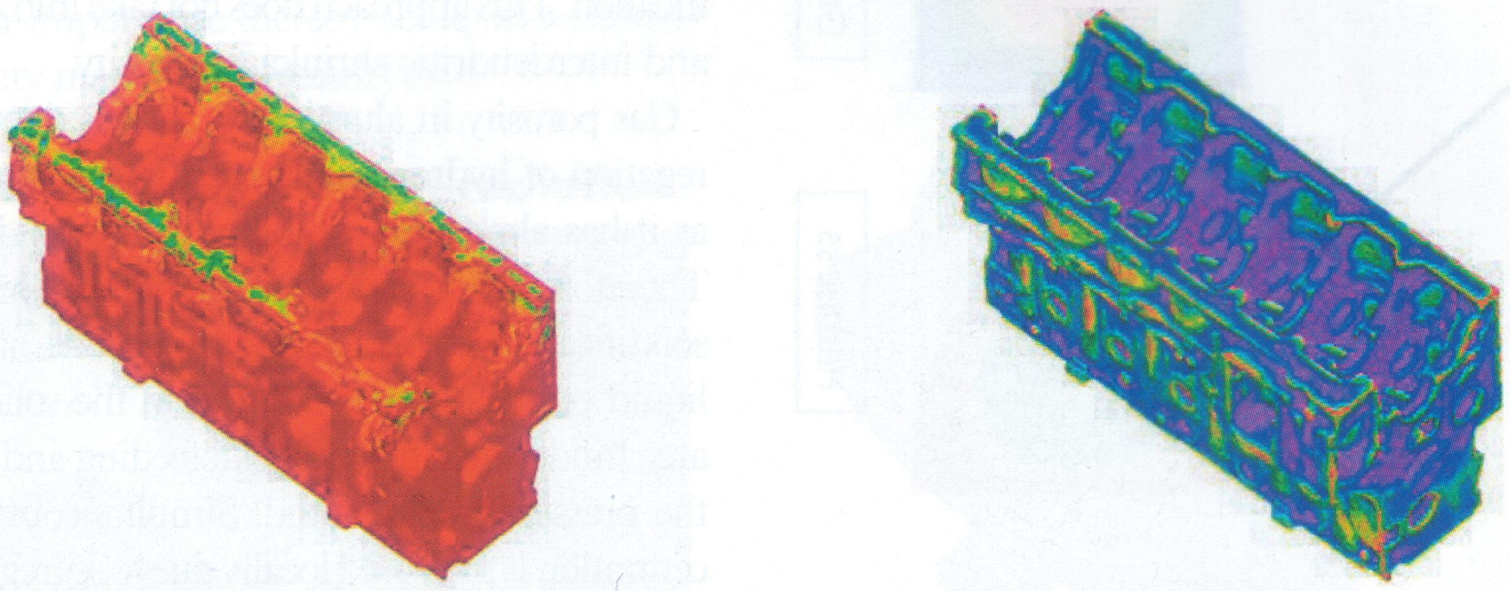


Fig 12: Fraction of ferrite (left), and nodule count (right), provide insight into the mechanical state of the as-cast part (ProCAST)

porosity, which is shown with various green levels, is quite high. Macropores are even present at some locations (eg, red zone at the centre of the zoomed region). The application of a pressure of 100 bars during the intensification phase (figure on the right) allows for the complete elimination of 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.

Industrial case study- porosity prediction with graphite expansion

Fig 10 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, but the mould rigidity is also an important factor to be considered. Indeed, the behaviour of the mould could significantly influence the pressure in the liquid metal. Using adequate physical models, it is possible today to take into account those phenomena in defects prediction.

Microstructure and mechanical properties prediction

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(r) 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 etc). Depending on the alloy type and composition, additional information will be available, for instance, grain size, dendrite arm spacing (DAS) or eutectic fractions for aluminium and nodule counts, austenite radius, pearlier and ferrite fractions for nodular cast iron (see Figs 11 and 12).

In the industrial example of a nodular cast iron engine block shown in Fig 11 (courtesy of MAN, Germany), at the carbon equivalent equal to 4.36 percent we are close to a eutectic cast iron. With the presence of Mg element in the composition, there is nodular graphite precipitation after solid phase transformation as well as ferrite and pearlite phases (see Fig 12). 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.

As cast material properties

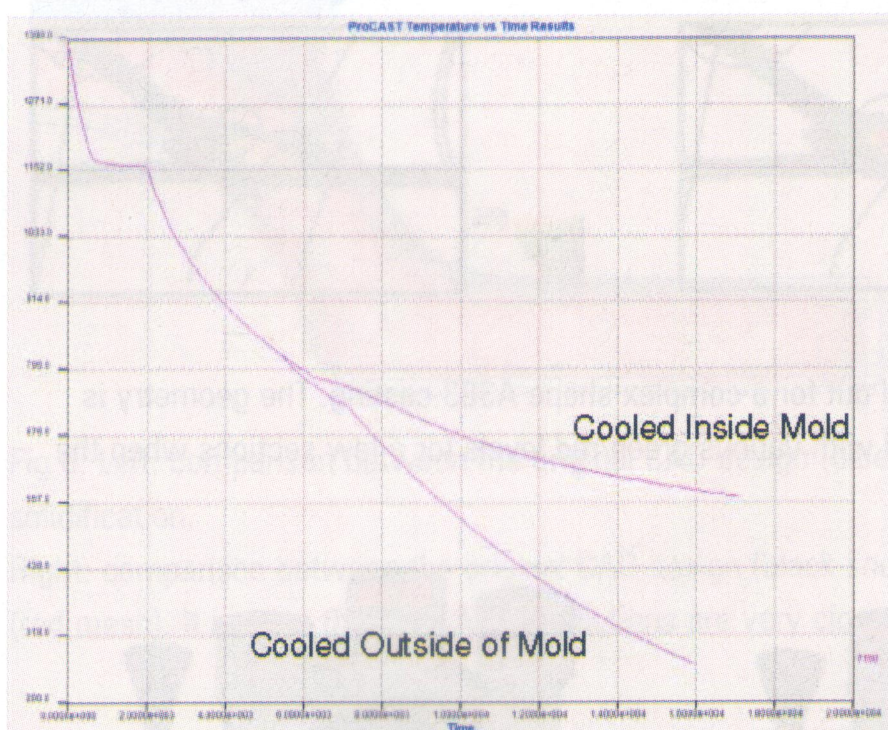


Fig 13: Cooling curves at the same location indicate the cooling rate differences when the part is cooled inside the mould versus when the part is shaken out while still above the solid state temperature

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 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 achieved) (see Fig 13). As a result, these different cooling conditions create different microstructural evolution conditions (see Fig 14). The slowly cooled plate developed a much lower tensile strength than that of the quickly cooled plate, which corresponds with experimental results [6].

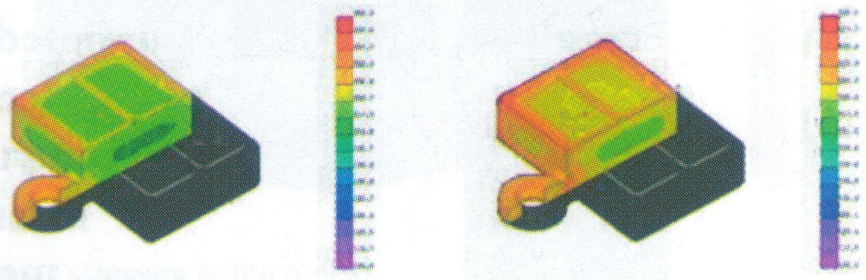


Fig 14: Tensile Strength plots display material property differences between a part that is shaken out after solid state temperature is reached (left) versus before (right) solid state temperature is reached (ProCAST) (Pictures courtesy of Caterpillar, Inc., USA)

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 to achieve this goal.

Conclusion

The effective use of computer analysis of the casting process is helping to expand knowledge of the overall foundry process, and the role of such tools continues to grow both in design of the component and optimising 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, as well as shrink and gas porosity 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. As foundries are being pressurized to shorten delivery times and become more cost effective, computer modelling tools, like ProCAST and PAM-QUIKCAST, which offer these advanced solutions, are becoming more popular in the foundry industry.

References

1) E-TIP 28, www.calcom.ch.
2) ProCAST, PAM-QUIKCAST and CALCOSOFT are commercial software distributed by ESI Group, France.
3) CAMPBELL, J., Castings, Butterworth-Heinemann Ltd, 1993.
4) 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).
5) PAMTALK 30, Material Properties prediction. ESI Group quarterly magazine.
6) ADI SHOLAPURWALLA, SAM SCOTT, "Integration of Advanced Simulation Techniques with Process Development in the Modern Foundry", AFS Metalcasting Congress 2006, Paper 06-032.

Reader Reply No.78