Multi-Physics Simulation and Casting Defect Prediction Using FLOW$^+$

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In today's global manufacturing environment, casting buyers want foundries to deliver the parts with the desired quality at short lead times. To achieve this, foundries are turning to computer simulation for analysing and optimising the design of the cast components as well as methoding (gating and feeding) design. Most of the casting simulation packages available in the international market are however, beyond the reach of small units, which form 80% of the Indian foundry industry. Keeping this in view, the computational modelling group of CSIR-NIIST has developed a highly efficient multi-physics-based software code for modelling mould filling and casting solidification, which is suitable for a wide range of metals and gravity casting processes. The software provides the filling sequence, temperature distribution, liquid fraction and cooling curves, and predicts major casting defects including air blow holes, cold shut, misrun, shrinkage porosity and hard zones. The code has been continuously improved during the last two decades and was named FLOW$^+$, which was recently integrated with the casting design software AutoCAST. The combined programme enables foundry engineers to seamlessly carry out 3-D methods design, advanced coupled simulation, defects prediction, and casting optimisation within an extremely user-friendly environment. The mathematical model, functionality and results of the programme are briefly described in this paper, and illustrated with a few industrial case studies.

Introduction

In conventional metal casting process in foundries, the design of the methoding system for a given shape of the part depends very much on the knowledge and experience of the foundry engineers. The conventional trial and error method implies waste of material, melting energy and labour, as well as increased lead times to arrive at the optimal design that gives the desired quality with acceptable levels of yield.

Foundry trials can be replaced by computer simulation of casting process. It is found that computer simulation significantly compresses the overall lead time to develop a new casting (right first time), and also reduces the level of defects by more than half (moving towards right every time)[1]. Casting process simulation requires a complete 3-D model of the mould including part cavities, feeding and gating system. The gating system takes liquid metal from the pouring basin to the casting cavities, and the feeders supply molten metal to compensate for metal shrinkage during solidification. Proper positioning and sizing of gating ensures complete, smooth and uniform filling of mould cavities, and freedom from related defects like blow holes and cold shuts. Similarly, proper location and sizing of feeders ensures directional solidification and prevention of shrinkage porosity inside the casting. The design of gating and feeding system is modified and verified by simulation until the desired level of quality and yield are obtained.

At present, there are several casting simulation packages available in the international market. Popular ones include Magmasoft (Germany), Novaflow (Sweden), Procast (France) and Solidcast (USA)[2]. Most of these have established local offices or vendors in India to take advantage of the large number of foundry units (about 5,000). It is well-known that the average capacity of an Indian foundry is less than one fourth of that in Germany; indeed, more than 80% of Indian foundries are classified under small-scale industry. These foundries can benefit from computer simulation to improve their quality and yield, thereby move up the value chain, and start catering to the valuable export market. Overseas customers usually insist that the casting suppliers prove their capability and assure their casting quality by providing simulation reports along with quotations. In such cases, the high cost and lack of technical manpower associated with most of the casting simulation programmes become a bottleneck.

The computational modelling and simulation group of CSIR-NIIST[3], based on the expertise gained in solidification modelling during the last two decades, developed an in-house physics-based casting simulation code in collaboration with other research centres and industrial partners, with the ultimate aim of making simulation affordable to the Indian industry. This code, called FLOW$^+$, has been integrated with another indigenous software for casting methods design, called AutoCAST developed at IIT Bombay and transferred to 3D Foundry Tech Pvt. Ltd. incubated in the Institute. This paper describes the mathematical models and capability of FLOW$^+$, followed by key results, especially the prediction of different types of defects, illustrated with industrial examples.

Casting of Multi-Physics Modelling

The purpose of simulating any industrial process is to model the underlying physics so that important process variables can be identified and controlled, resulting in significant benefits in production. Metal casting involves many physical phenomena such as fluid flow, heat transfer, thermal stress, defect formation and microstructure evolution. It is well-known that most of the casting defects manifest due to improper flow and solidification of liquid metal in the mould. If these phenomena are accurately modelled, then related casting defects can be easily predicted.

When molten metal is poured into a mould, the fluid flows through runners and gates and then fills the casting cavity. This is governed by the conservation equations of mass and momentum *viz.*, incompressible Navier-Stokes equations:

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \qquad (1)$$

Conservation of momentum:

$$\frac{\partial (\rho V)}{\partial t} + \nabla \cdot (\rho V V - \mu \nabla V) + \nabla P = B + S_v \qquad (2)$$

where P is the pressure, B is the body force vector which includes the force of gravity, and S_v consists of viscous terms other than those expressed by $\nabla.(\mu \nabla V)$. Appropriate initial and boundary conditions are required to obtain the solution to these equations.

Since mould filling falls under the class of free surface flows, additional equations are solved for fluid fraction and boundary conditions. These have to be satisfied at the free surface whose location is also a part of the solution procedure.

The mould filling algorithm based on Navier-Stokes approach alone is computationally expensive and takes several hours of CPU time to solve. In multi-physics simulation (coupled flow and solidification of molten metal), besides solving Navier-Stokes equations for fluid flow, one has to solve the energy conservation equation also for incorporating the heat transfer between the molten metal and the surroundings. The energy equation for heat transfer process is governed by the following equation:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{Q} \qquad (3)$$

Where ρ is the density, C_p is the specific heat, k is the thermal conductivity, t represents the time, and T represents the temperature.

$\dot{Q}$ is the heat generation term and is associated with the release of latent heat during solidification. The release of latent heat during solidification is accounted for by a heat generation term as follows:

$$\dot{Q} = \rho \Delta H_f \frac{\partial f_s}{\partial t} \qquad (4)$$

where ΔH_f represents the latent heat of solidification. For an alloy that solidifies over a range of temperatures between the liquidus and solidus, the latent heat release rate is expressed as:

$$\rho \Delta H_f \frac{\partial f_s}{\partial t} = \rho \Delta H_f \frac{\partial f_s}{\partial T}\frac{\partial T}{\partial t} \qquad (5)$$

There are several ways to describe the solid fraction variation between the liquidus and solidus temperatures for a given alloy. The simplest way is to assume that the solid fraction varies linearly in the mushy zone. Alternatively, an analytical expression such as Scheil's equation may be used. The best approach is to determine the solid fraction-temperature relationship using experimental measurements.

To solve equation (3) in a given domain requires knowledge of initial and boundary conditions. The initial conditions define the temperature distribution throughout the computational domain at some initial point in time. This includes the user-specified value of the pouring temperature of the liquid metal; and the temperature of the mould (assumed to be at room temperature, unless specified otherwise, as in the case of investment casting) for mould filling simulation. The temperature distribution at the end of mould filling simulation serves as the initial temperature distribution for solidification simulation.

The boundary conditions must be satisfied on the boundaries of the domain: both external and internal. The external boundaries are those in contact with the surroundings, such as exterior mould wall and top surface of the riser.

The most common approach is to approximate the heat flux at the external solid surfaces (mould exterior) using Newton's law of cooling as:

$$q = h(T_{me} - T_a) \tag{6}$$

This is commonly referred to as the convective boundary condition. In the above equation the terms T_{me}, T_a, q and h correspond to the mould exterior temperature, ambient temperature, flux and convective heat transfer coefficient, respectively.

The internal boundaries are interfaces of the dissimilar materials like metal-mould, mould-chill, mould-insulator and chill-metal, where each material has different temperatures and thermal properties. For metal-mould interface, the most common approach is to express the interfacial heat flux as:

$$q = h_{gap}(T_c - T_m) \tag{7}$$

where T_c, T_m and h_{gap} are the temperatures of the casting surface, mould surface and the gap heat transfer coefficient, respectively. Generally, the gap heat transfer coefficient varies with respect to time or temperature which is usually determined either by experiments or by an inverse heat transfer approach. The FLOW$^+$ software has the capability of handling specified temperature, flux or convective heat transfer coefficient, which are either constant, time-dependent or temperature-dependent. Any one of the following five types of boundary conditions can be handled:

- Specified temperature
- Specified heat transfer coefficient to the ambient
- Specified flux which can be constant or have time or temperature dependent values
- Specified gap heat transfer coefficient which can be constant or have time or temperature dependant values
- Perfect contact

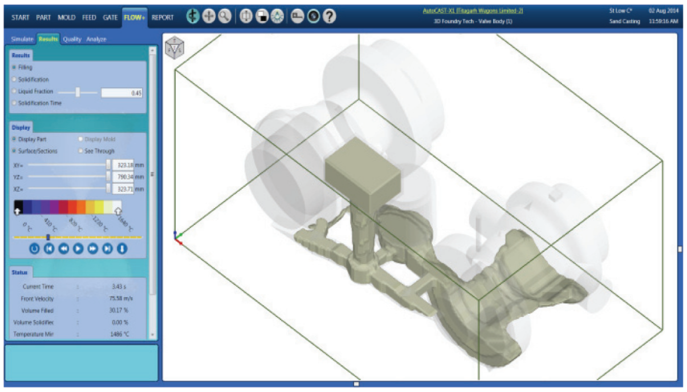
The governing energy equation along with appropriate initial and boundary conditions are solved using finite volume method on structured grid. FLOW$^+$ code uses explicit time integration scheme for transient simulation. The internal time-step for solver computations is automatically selected based on stability criteria.

Simulation Results and Analysis Tools

The main input to the FLOW$^+$ code is the structured meshed geometry of mould containing part cavity, feeders, gating channels, cores, chills, insulation, etc. along with the relevant material properties (density, specific heat, thermal conductivity). The geometric elements are created during methods design functions in AutoCAST, and the property values are taken from a comprehensive database of casting alloys and other materials. Other important parameters include the appropriate boundary and initial conditions, filling time and pouring temperature.

Once all inputs are provided, FLOW$^+$ computes the output values at every voxel (volume cell), most of them as a function of time. For mould cells, the main output is the temperature values from the instant of pouring to solidification and beyond. For casting cells, in addition to temperature, the output results include the solid fraction, air fraction, solidification time, cooling rate, etc. The amount of air entrapped in the cavity during mould filling, in terms of individual air pockets with their own state variables - pressure, temperature and density are calculated. Major results and analysis tools are briefly described here.

Flow Sequence: The initial entry of metal into the mould can be simulated to get an understanding of possible problems of turbulence, and area of mould being impacted (Fig. 1). This also helps to analyse the flow sequence which aids in gating design, especially gate balancing. Parameters such as volume filled, melt front velocity and volume solidified give a clear understanding of the flow process at any point of time during the mould filling process.



Liquid Fraction 0.45

XY= 323.18 mm

YZ= 790.34 mm

XZ= 323.71 mm

Current Time : 3.43 s

Front Velocity : 75.58 m/s

Volume Filled : 30.17 %

Volume Solidifiec : 0.00 %

Temperature Mir : 1486 °C

Fig. 1 : Flow sequence visualisation.

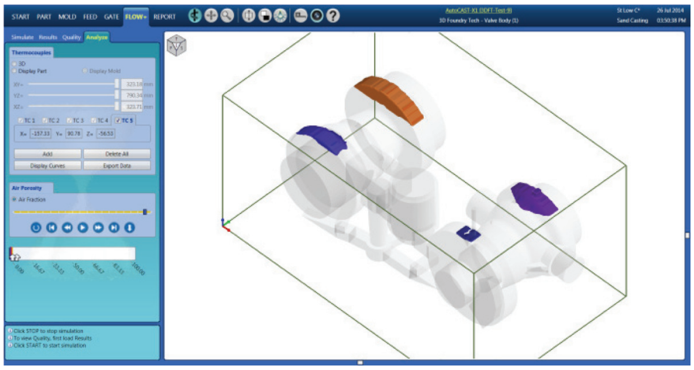


Fig. 2 : Air fraction.

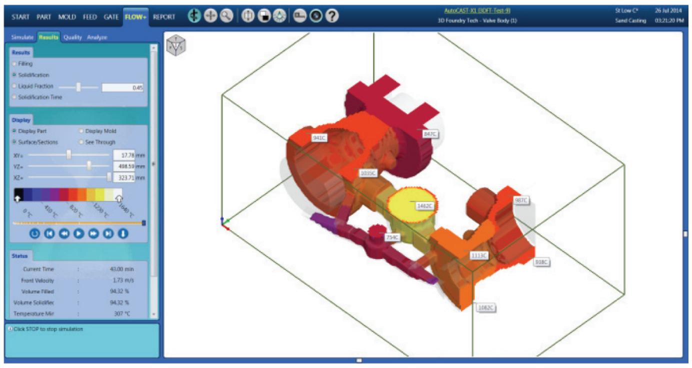


Fig. 4 : Temperatures and gradients.

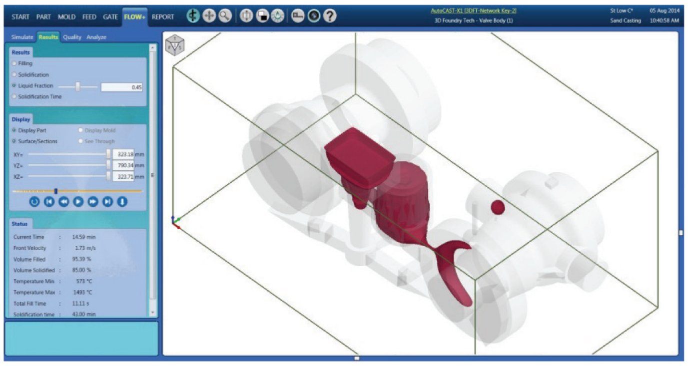


Fig. 3 : Liquid fraction.

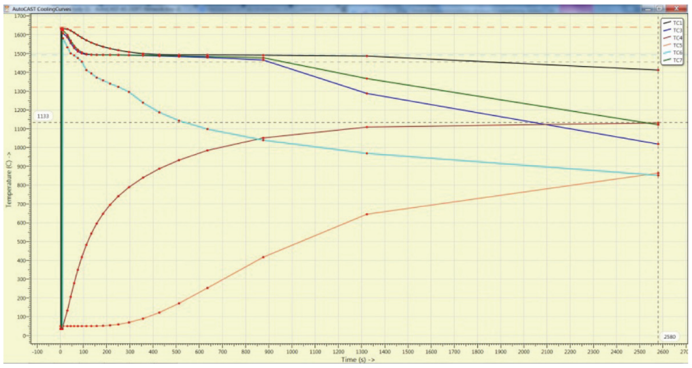


Fig. 5 : Cooling Curves.

Air Fraction: Air fraction displays the amount of air present in the cavity at any point of time during filling (Fig. 2). With the help of this tool, the user can identify regions having isolated air pockets susceptible to air entrapment. Subsequently, users can place vents within AutoCAST to eliminate air entrapment as well as blowholes.

Liquid Fraction: Liquid fraction displays the residual liquid in the casting at any point of time during solidification (Fig. 3). It shows regions that solidify last and hence may lead to shrinkage porosity. This output has proved very useful in predicting shrinkage defect – both macro and micro (different radiography levels).

Temperature and Gradients: Large difference in temperature gradients along with high temperatures causes hot tears. With temperature analysis at various sections, user can identify regions which are susceptible to meet this scenario and observe hot tear (Fig. 4).

Cooling Curves: FLOW$^+$ allows users to place virtual thermocouples inside part as well as mould and produce cooling curves (Fig. 5). Cooling curves can be used for qualitative comparison of microstructures and grain sizes.

Industrial Case Studies

The various results and analysis tools help in predicting relevant casting defects including air blowholes, misruns, cold shuts, shrinkage porosity and hard zones. Three industrial examples are presented here, one for predicting blowholes occurring during mould filling, and another for shrinkage porosity occurring during casting solidification.

Case 1

A cast iron turbine casing of overall size 170 mm x 150 mm x 95 mm weighing 3.2 kg was found to have micro-shrinkage porosity in a critical junction, leading to a high level of rejection (Fig. 6). The simulation of casting solidification provided temperature values at the end of solidification, and their colour plot showed high temperature region at the defect zone. The liquid fraction plot also showed that the location is the last to solidify, thereby manifesting as shrinkage porosity. Clearly, the feeder needs to be hotter to be able to feed this region, which can be achieved by either increasing its size or surrounding it with an insulating sleeve. Additionally, a form chill can be placed under the hot spot to ensure directional solidification from the feeder to the hot spot. The modified methods layout and verification by simulation are shown in Fig. 7.

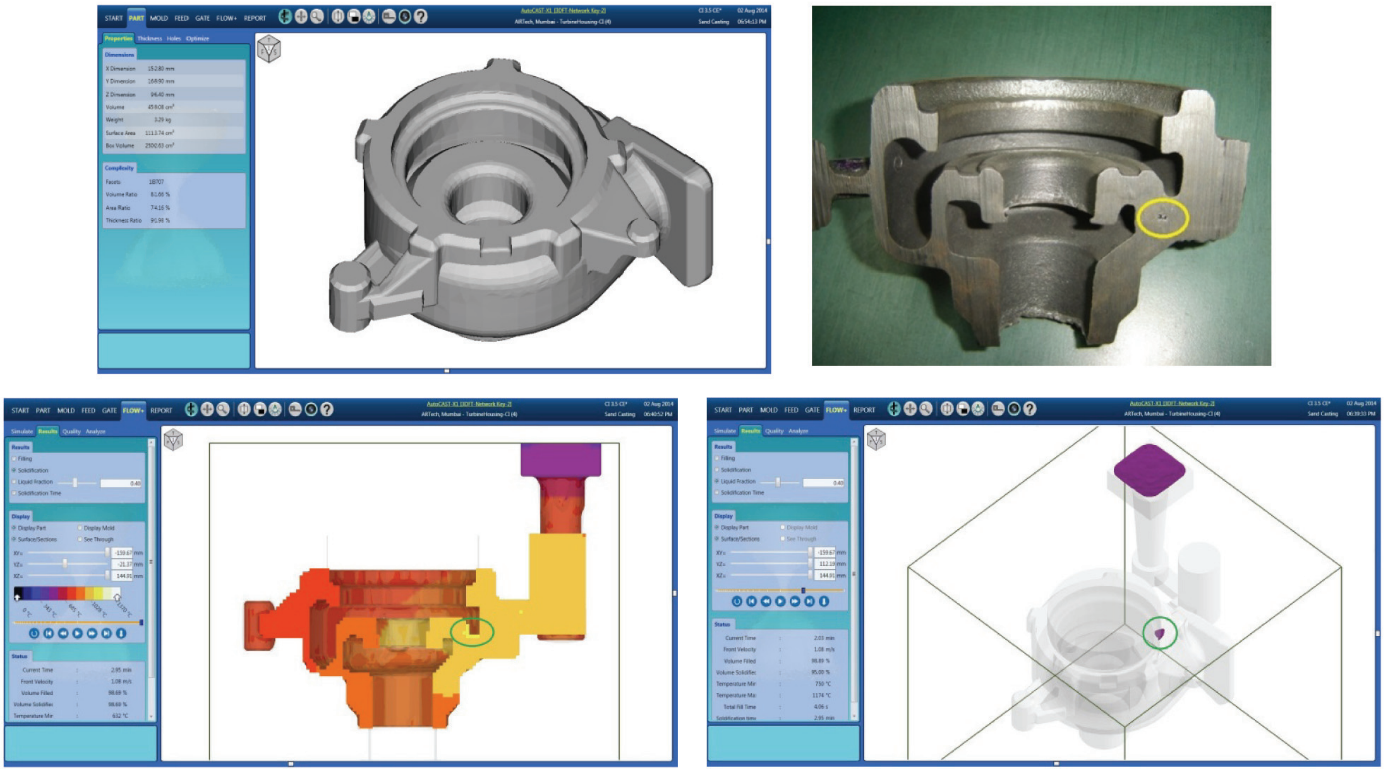


Fig. 6 : Shrinkage porosity defect simulation.

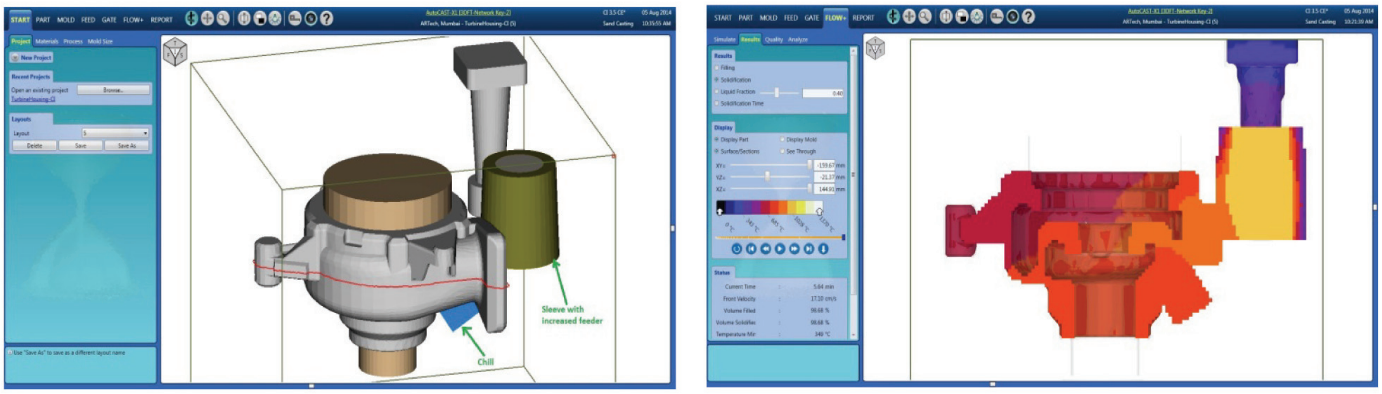
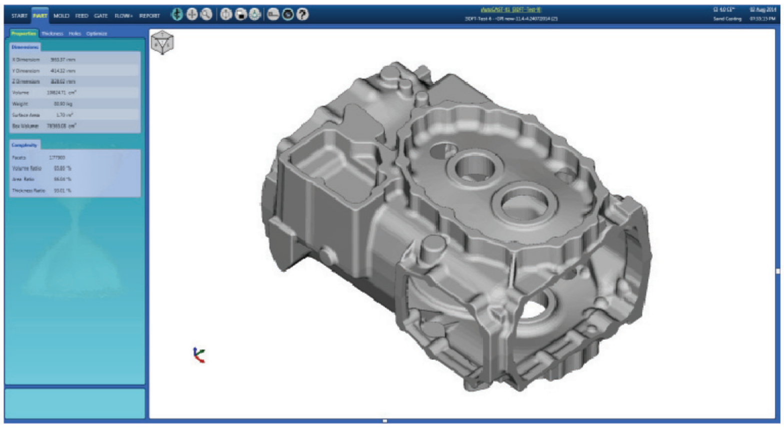


Fig. 7 : Modified methoding verified by simulation.

Case 2

This is a large cast iron part weighing over 80 kg, and with overall size 560 mm x 415 mm x 330 mm. The foundry reported blowhole defect in two locations at the top of the casting as shown in Fig. 8. A scientific analysis and suitable solution was needed without further shop-floor trials since tooling modifications were both expensive and time-consuming. Hence, simulation was carried out using FLOW$^+$ to generate the results of air fraction during mould filling and blowhole locations at the end of filing. Both results match the actual observation of defects in the foundry. The accumulation of displaced air and resulting high gas pressure are clearing leading to the blowhole formation, and the easiest solution is to provide suitable vents at those regions. Figure 9 shows the modified methods layout created using AutoCAST, giving a casting free of blowhole defect.



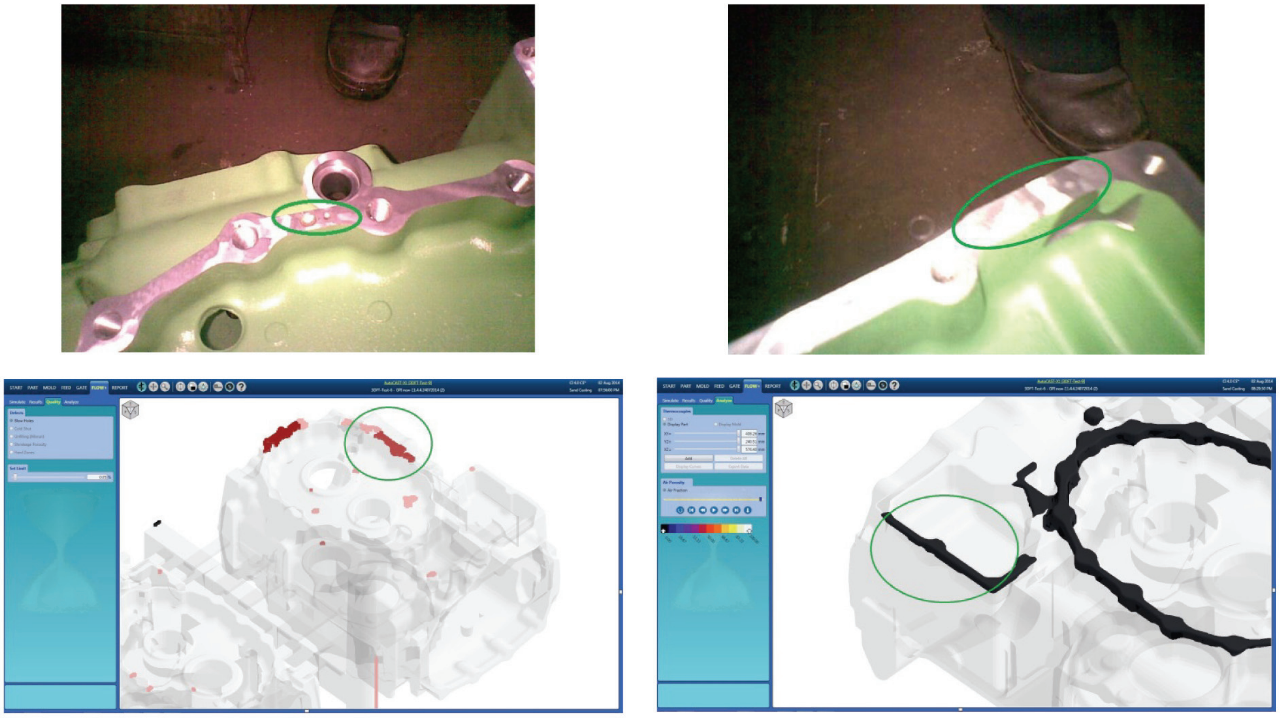


Fig. 8 : Air fraction and blow hole result match observed defects.

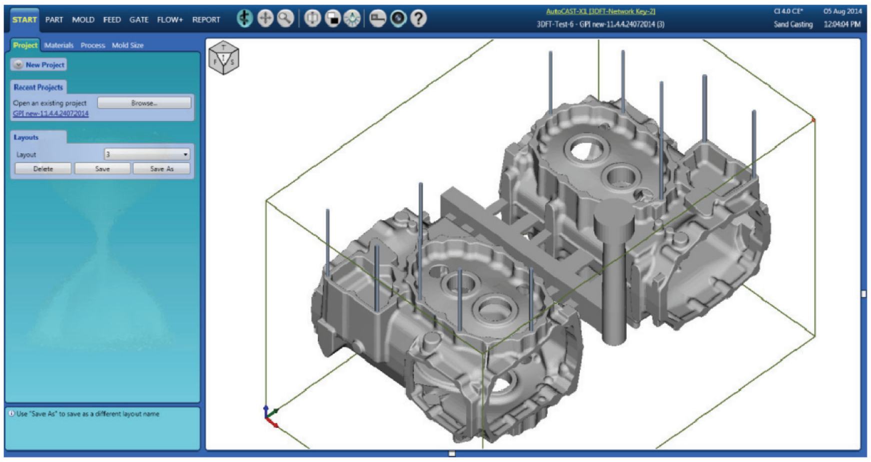


Fig. 9 : Modified methoding with vents.

Case 3

This is a honeycomb structure with section thickness of walls equal to 6 mm, and overall length 600 mm. Aluminium alloys were poured at a temperature of 700° C and head of 350 mm, leading to partial filling of the structure, as shown in both simulation and actual casting (Fig. 10). The simulation programme allowed virtual trials with many different combinations of alloy composition, pouring head and temperature, finally leading to a complete structure.

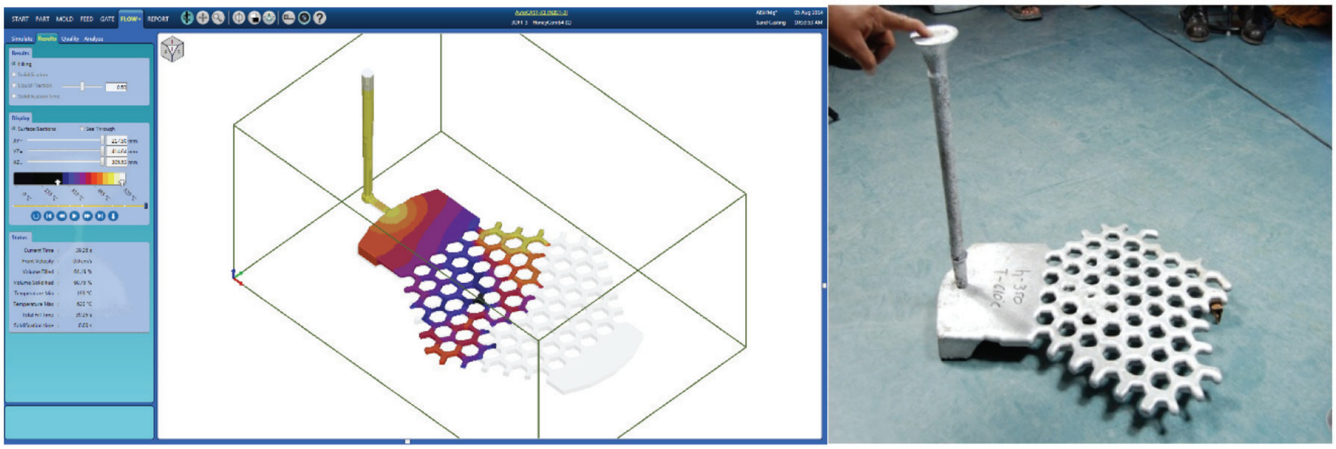


Fig.10 : Simulation and actual casting with misrun.

Conclusion

Casting simulation reduces the development time of new castings, and improves the quality and yield of castings. For widespread application, especially by small foundries, the software must be affordable, reliable, and truly easy to use. This has been achieved by integrating two indigenous software codes, one for 3D methods design and another for coupled multi-physics simulation of mould filling and casting solidification, in an extremely user-friendly environment. This has overcome the limitations of conventional simulation programmes that require scientific knowledge and computational skills, and are affordable to only large foundries. AutoCAST with FLOW$^+$ are enabling even SME foundries to benefit from casting simulation technology, with the added satisfaction of contributing to the continuous improvement of an indigenous software product.

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