COMPUTER SIMULATION AND ANALYSIS OF INVESTMENTCASTING PROCESS

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ABSTARCT:

Investment casting process used for precision component manufacture calls for accurate methoding design. The development times can be very high in the ***conventional trial and error based process design****. In the current competitive environment, there is a need for the foundry and casting units to develop the components and the process at quick response times. Further, the costs of development also have to be kept low to be competitive. In these circumstances,* ***FINITE ELEMENT ANALYSIS*** *based computer simulations can be of immense value to the casting units. Authors have used ProCAST a commercially available FEM package for foundry and casting simulation for analysis of investment casting of a variety of components. (ProCAST can be used as a simulation tool for analysis of other casting processes such as sand casting, high pressure/ gravity / low pressure die casting as well. However these are not part of the focus of this particular paper).*

By computer simulation of the casting process, the flow of the molten metal in the cavity, the heat transformation, the solidification, grain formation, shrinkage and stress evolution can be visualized. The details are seen on the computer in graphical form, which helps the designers to visualize the defects in the process design, to analyze the causes for the defects (such as hot tears, shrinkage porosities, cold shuts etc.). Further, the modified gating designs can be tried without resorting to the actual production of tooling. In investment casting process, the shell making, shell drying, shell heating and casting processes can be simulated in ProCAST.

The paper describes general principles of applying finite element analysis based computer simulation to investment casting processes. Prediction of defects such as shrinkage porosity is demonstrated. Using of computer simulation as a virtual investment-casting environment is demonstrated.

INTRODUCTION

1.1 History

Investment casting process makes use of an expendable pattern in the production of engineering products. Quite a few materials such as wax, frozen mercury, plastic, etc. have been used for making the expendable patterns. When wax is used as a pattern material, this process is also referred to as 'lox wax investment casting process'. Lost wax casting process is one of the oldest manufacturing techniques that dates back to 4000 – 6000 B.C. [12]. It was possibly initiated into practice when early man employed the method to produce rudimentary metallic tools. This was followed by centuries of use of this technique for jewellery and artistic products The term 'investment casting' is derived from the characteristic use of a mobile slurry, or investment, to form a mold with extremely smooth surface and high dimensional tolerance.

1.2 Process Characteristics

Investment casting process is no panacea for any problem faced by a metal caster. It, however, offers a host of merits, such as:

i) The process offers very high precision in castings.
ii) Castings of any shape or complexity can be made.Turbine blades used in aircraft jet engines are an example. Some of these have one or more casting holes as small as 0.8 mm in diameter often 100 mm or more in length cast radially.
iii) It has the capability to produce near net shaped castings. Possibility of complete elimination or substantial minimization of machining work on castings may make the process very cost effective. Moreover, there is also the scope of saving on the cost of investing in additional machine tools or hiring machinists. Most of the products do not require much finishing work except cosmetic finishing such as light buffing to remove surface discoloration. The more numerous and complicated the machining operation, the more attractive the process becomes.
iv) Any metal – from the most common to the most exotic – can be cast.
v) An investment mold being monolithic in nature, there is no flash present on the castings.
vi) Although castings of 20 kg or more are routinely produced, it is the tiny castings – weighing 10 – 20 grams – that are literally unique in this process.
vii) Thin walled castings – as thin as 0.75 mm to 1.00 mm – can be made.

viii) No elaborate and expensive tooling is involved.

ix) The dies needed for making disposable patterns are commonly made of aluminum, which can give a long life with non-abrasive pattern materials like wax. Plastic – even hardwood – dies have also been used for short run or prototypes of wax.

x) Although no undercuts are allowed, draft is unnecessary in perhaps 95% cases, the exception occurring on deep holes or between thin ribs.

1.3 Process Steps

The process involves a number of basic steps, which can be broadly divided into the following:

a) Producing a die for making disposable or expendable patterns.
b) Making of expendable patterns along with gating system.
c) Precoating the pattern assembly. This is done by dipping the gated pattern in agitated slurry and stuccoing of fine-grained sand to give the first layer of coating. The first coat is critical because it establishes the surface texture and determines how cleanly the mold will strip.
d) Investing the pattern assembly for the production of molds. Investment moulds may be made by either shell molding or solid molding. In the shell molding process successive layers of refractory are coated on the precoated pattern surface one after another and providing ample time for the layers to dry. This may be repeated 6 – 8 times to make a shell of roughly 6 mm thick. The shell molds thus obtained are quite strong. In the solid molding, suitable slurry made of refractory material and binder is poured around the precoated pattern assembly and allowed to set.
e) Removing the pattern material by heating from the solid mould or shell mould.
f) The shell molds are poured free standing on a bed of sand. Solid molds can be poured in the conventional way.
g) After solidification the mold is destroyed to retrieve the near net shaped castings.

NEED FOR COMPUER SIMULATION OF INVESTMENT CASTING

In the current environment, investment casters need to stay on the cutting edge of new technologies to remain competitive in the marketplace. The capability to produce investment-casting components of high quality while at the same time reducing product costs and development times is the challenge the foundry industry faces today. Increasingly complicated parts are being made through the investment casting process with difficult to cast alloys. Computer aided process modeling has been applied in the foundry industry for the past several years, for the following:

- Design of new components where computer simulation is used as a virtual casting unit to test the validity of the gating and process design conceived.
- Redesign of existing products and reengineering of existing processes to eliminate product defects and reducing scrap
- To enhance the yield by scrap reduction, and bringing down the rejections.
- As an R&D tool where the designers can conduct large number of experiments without resorting to producing tooling, patterns, and actual pouring.
- As a quality assurance tool where the safe operating parameters for the plant can be set. A window of safe process parameters can be set for controlling the quality.

In recent years advanced computer aided simulation technologies for casting process modeling is becoming increasingly adopted in the foundries including in India. Process Simulation provides valuable information that facilitates participation by the foundry engineer early in the product development stage. This reduces the time between the concept stage and production stage in the design life cycle of a new component. The information of temperature, molten metal flow, solidification and secondary or derived information such as cooling rates, fraction solid are available to the designer although the process in the entire domain of the casting.

For the application of process model to be successful in a foundry / casting unit, the material has tool used (or the software used) should have the capability to handle the complex geometries, variety of metals and alloys cast, and flexibility to define the process to the simulation system, in a user friendly manner. There are gray areas of input such as the variation of the thermal properties of the shell (as a function of material, porosity, etc), the interface heat transfer between the melt and the shell and so on.

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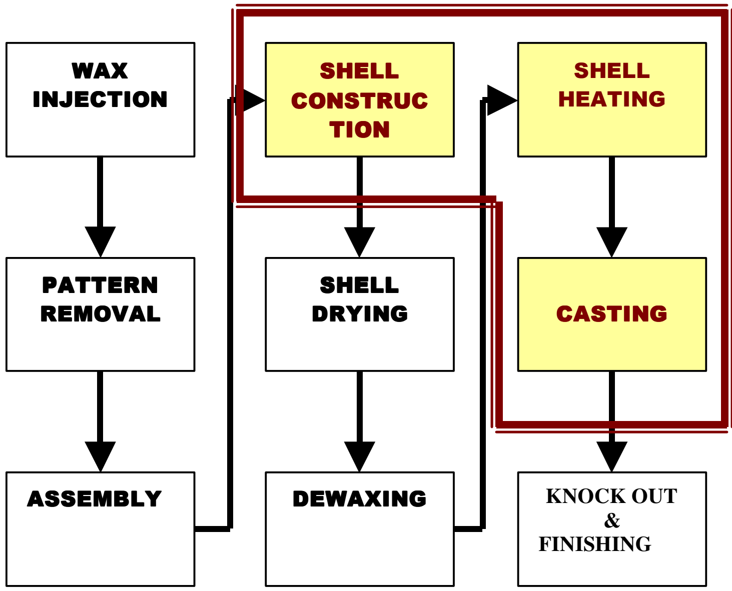

Figure 1. Flow Chart of an investment casting process in a foundry. Highlighted in RED are the processes taken into consideration for Process Modeling using *ProCAST* ™

The Figure1 shows the flow chart of an investment casting process from pattern making to knock out of the finished Casting. The highlighted in Red are the processes taken into consideration for Process Modeling using ProCAST.In ProCAST we will built the Shell around the casting depending the number of layers and thickness, after that we will assign the process parameters and carry out the Simulation.

In some advanced casting simulation tools like ***ProCAST***® these special features are included. Highlighted in this article are some case studies of simulation of the investment casting process for elimination of defects, and increasing the yield.

CASE STUDIES:

Case 1: Prediction of Gas Porosity and Shrinkage Porosity.

The case considered is a four cavity investment casting of steel jaws (ASF 23/24) for a freight trailer. The mold was made of a ceramic shell. Trapped air and shrink porosity contribute to the majority of investment casting defects and rejections. The placement and design of gates and feeders are a critical in controlling the last areas to fill. Defects are generally observed around the last region to fill, if such a region is within the geometry of the component. For a given gating design proposed, the designer needs to have an idea of where the last region to fill would be. Process modeling can give the flow of the melt in the cavities. The utility of process modeling to predict the metal flow related problems is demonstrated in this case of investment casting of a steel jaws of a freight trailer. This casting had 4 cavities and one of the cavity had a high rejection rate in the original gating set-up. Gating was redesigned with the assistance of computer simulation to obtain defect free castings.

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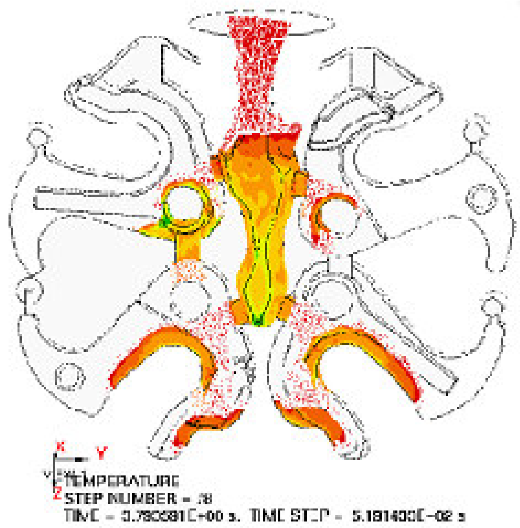
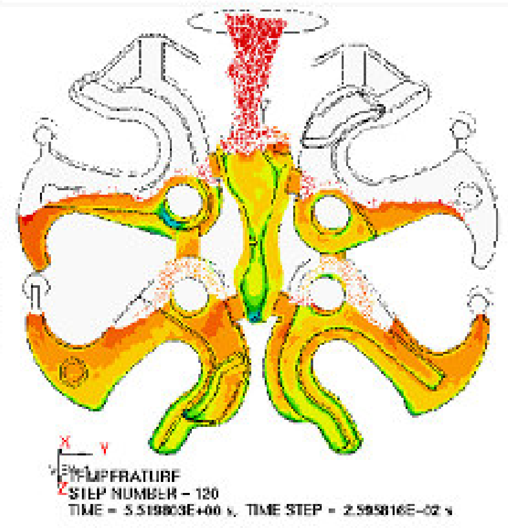
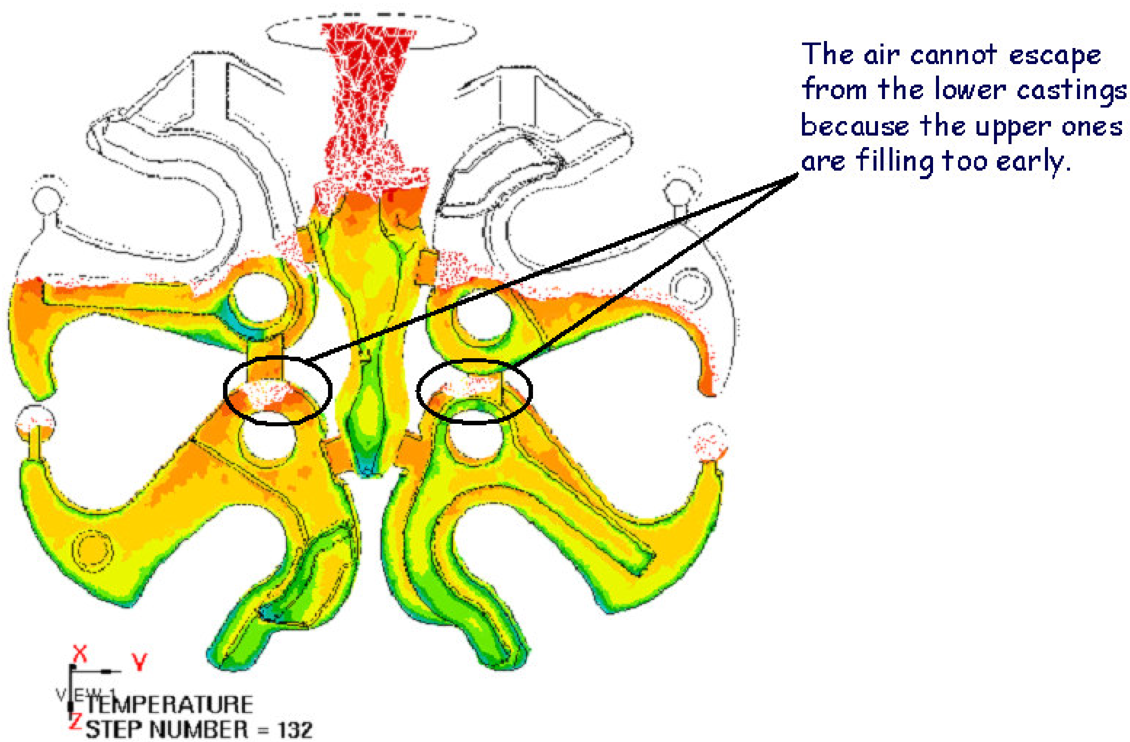




(a) **(b)**



(c)

Figure 2. Initial tree layout design, highlighting air pockets.

Figure 2a to 2c show the filling sequence of the metal arriving into the four cavities in particular order. As seen from the figure 2c, there is an air entrapped zone in the two bottom cavities, the metal first enters in the bottom two cavities. Even before the bottom two cavities are filled, the top two gates open up and metal begins cascading into the bottom cavities though the connection between the top and bottom cavities. This does not allow all the air and gasses to escape, leaving an entrapped pocket of gases. With no path out of the mould, these pockets will turn up as gas

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porosity defects in the final component. Figure 3 shows the cast component with gas porosity in the region as predicted by the computer simulation.

Figure 3. Air/Gas entrapment locations.

The other problem observed was shrink porosity in solidification. Figure 4 shows the X-Ray image of the component with markings for shrinkage porosity locations. When the corresponding gating and process conditions were simulated using ProCAST, the fraction solid figures and the X-Ray filter options demonstrated the same problem. The simulation was predicting the defect very accurately.

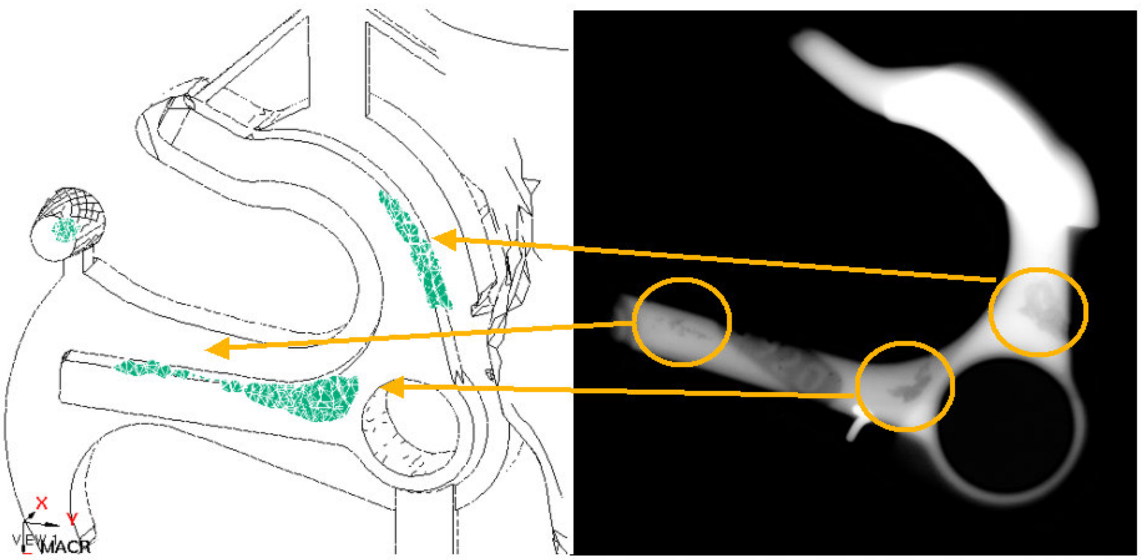

Figure 4. Macro Porosity Predicted by Simulation and X-ray analysis.

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Upon determining the causes of these defects, several possible design changes for the gating layout were studied. Using computer simulation the gating design was perfected to produce defect free castings.

Instead of the tree set-up observed in the initial design, a flatbed layout was implemented**.** **C**omputer simulation was performed on the new layout to identify any potential problems associated with air entrapment and shrink defects. The computer simulation showed a much better fill pattern without any air/gas porosity entrapment possibilities. The shrink porosity reduced Significantly. The new design as shown in figure 5 was then put into production and a remarkable improvement was observed in the quality of the casting.

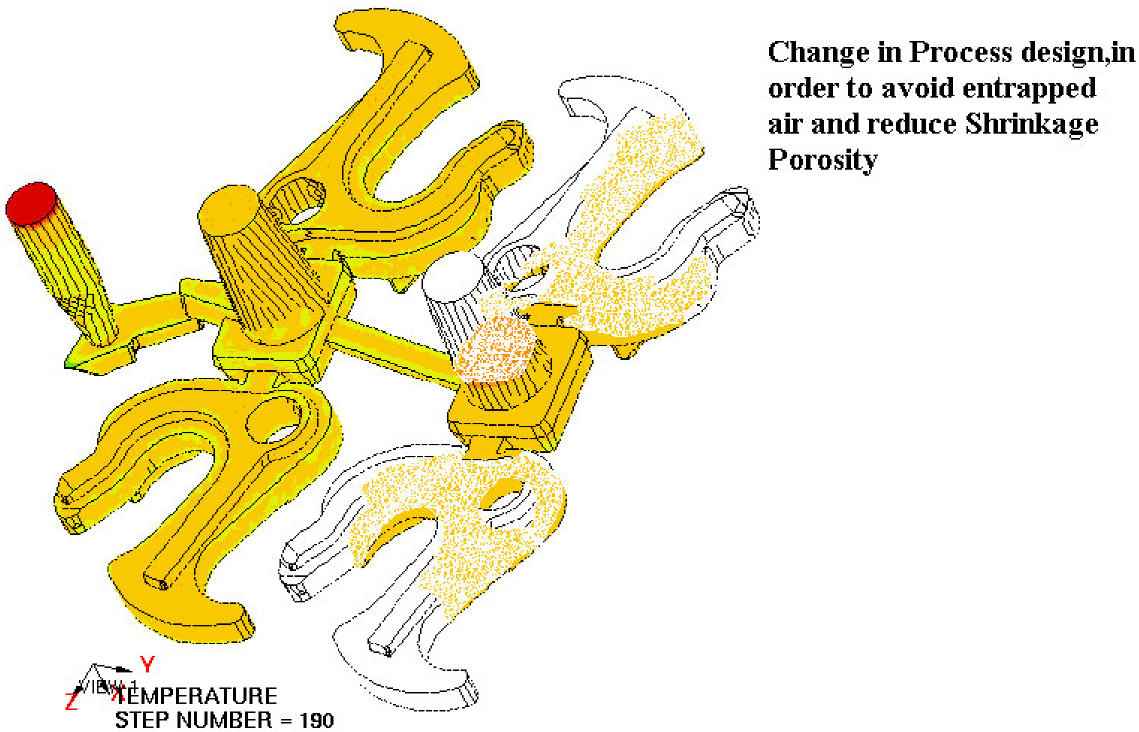

Figure 5. Modified gating design

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CASE 2: Gating Modification to Eliminate Shrinkage Porosity

This case illustrates the prediction of porosity in a two-cavity casting. During the solidification the shrinkage of the liquid phase needs to be compensated in order to avoid porosity. Gating system is designed to accomplish this possibility. Such porosities persisted in the investment casting of this component. For the initial gating design as shown in **Figure 6**, a coupled thermal - flow simulation was carried out to optimize the gating system**.** Progress of solidification front with cooling time was monitored. Figure 6b shows the fraction solid at a time close to the end of solidification. In the figures the dark red colour indicates the regions 100% solid and the other

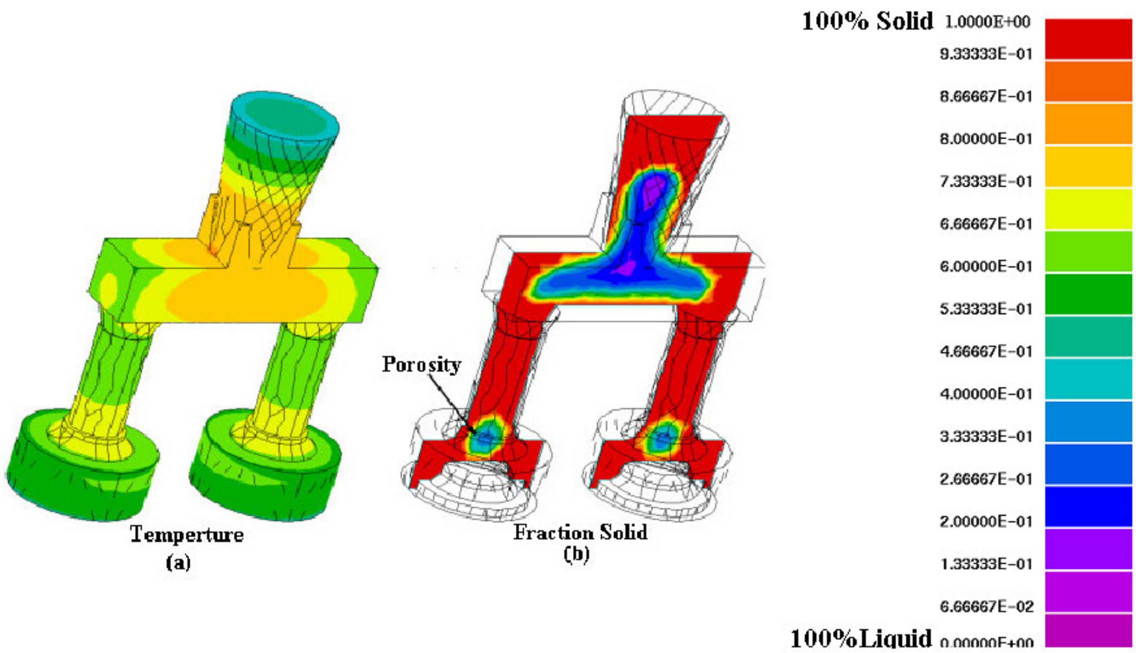


Figure 6. Initial gating design
(a) Temperature Distribution of a Multi-Cavity Casting (b) Fraction solid showing a porosity

Colors indicate various fractions of liquid fraction. In the figure 6b, it is seen that the region marked in the circle is having a liquid phase present in the region. Further, this region is surrounded by a fully solidified (100% solid) region. This is because during further solidification, the shrinkage caused in this region is unable to be compensated by feeding of the liquid metal. Depending on the extent of the liquid fraction remaining, micro-porosities of different size are formed. The thumb rule is, larger the liquid fraction, larger the size of porosity. Now, a modification to the gating is proposed. Such a design is also verified by ProCAST simulation. **Figure 6(c)** depicts the temperature distribution of the modification gating system. **Figure 6(d)** shows the fraction progress With proposed gating system modification, the porosity is eliminated.

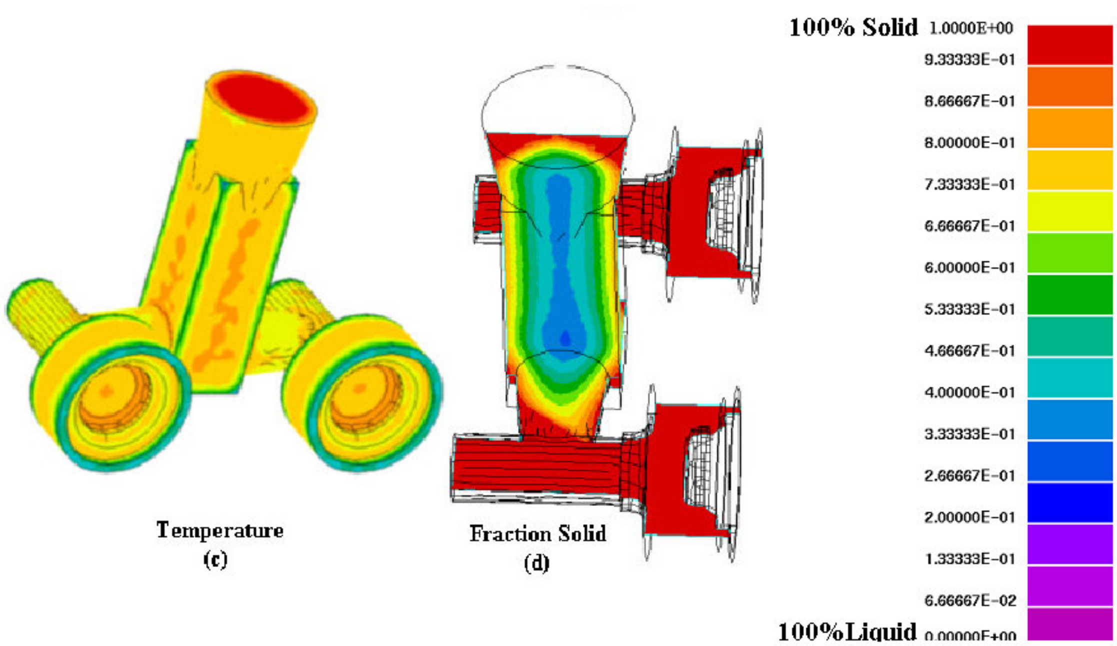
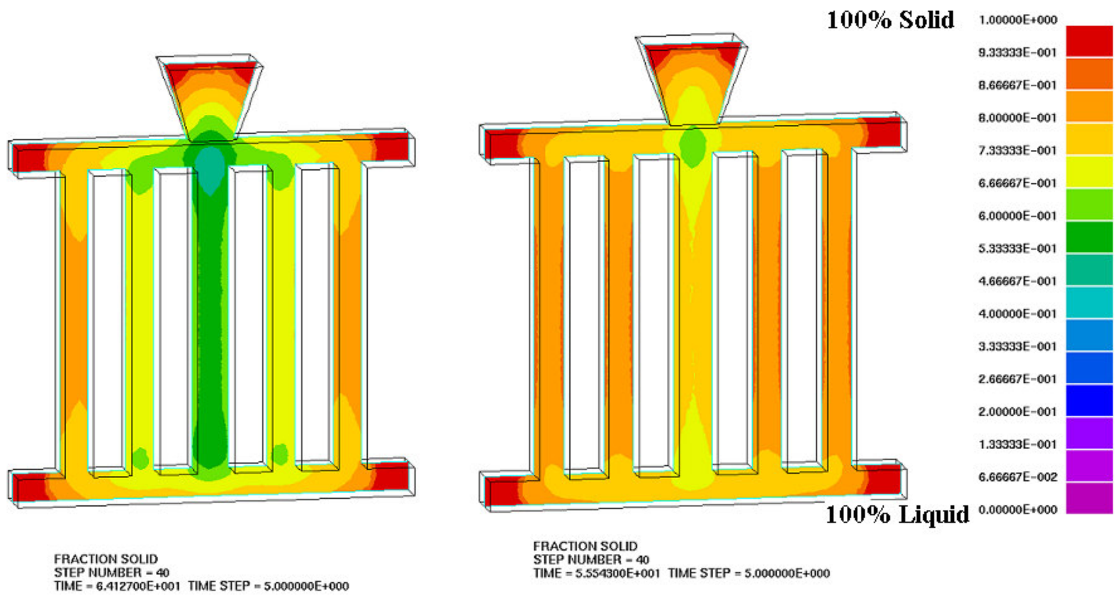


Figure 6. Modified gating design

(c) Temperature distribution of a modified gating system-using simulation and (d) Casting free of porosity.

Case-3. Effect of radiation in multimode investment casting

In multi cavity investment castings, the radiation heat transfer between cavities can have a dominant effect on the temperature transients and there by on the solidification behavior. This in turn will effect the prediction of defects. One of the unique feature of ProCAST is to take into account the effect of black body radiation in the radiation module and calculate accurate temperature distribution. Figure 7a shows the effect of considering the radiation effects on the temperature transients. Figure 7b shows the temperature distribution without considering the radiation effects. When the radiative heat loss is absent, the temperatures are seen to be higher as seen in figure 7b the designers have to be careful in using the appropriate model for the heat transfer.

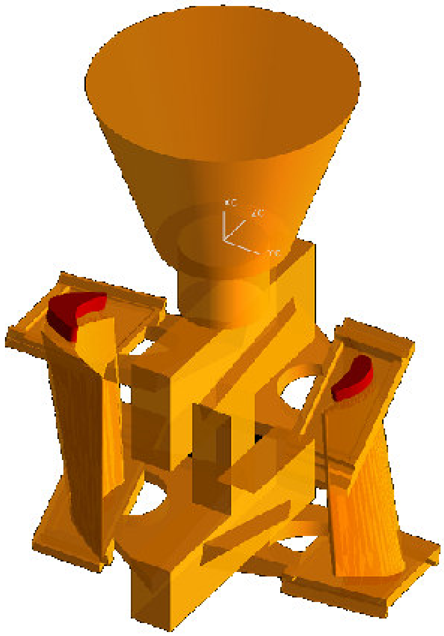


(a) With Radiation (b) Without Radiation

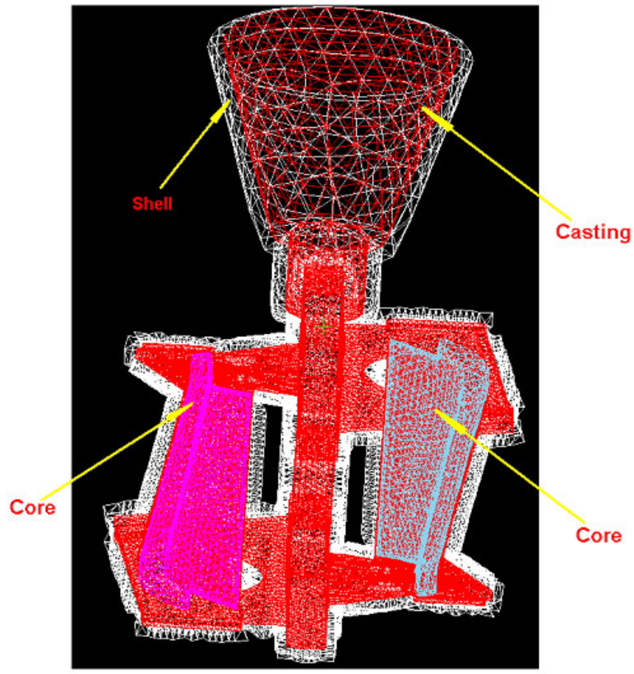
Figure 7. Shows the effect of radiation on solidification.

CASE 4: Investment Casting of Turbine Blade.

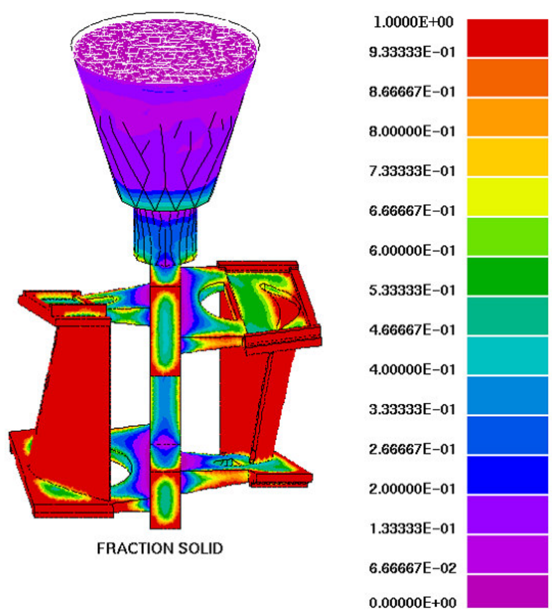
Ni alloy based turbine blades are typically, investment cast to obtain the accuracy. Figure 8 shows the solidification front in a two-cavity blade casting arrangement. Here Monel 403 is the casting material and mullite + zircon sand is used as the shell material. Figure 8a shows the CAD model of the turbine blade casting. Figure 8b shows the FEM mesh generated for the blade (component), shell and the gating. Figure 8c shows the fraction solidified at the end of the solidification curve. It is seen that the regions in the bottom plate have a large number of spots where there is about 50% volume fraction of liquid phase. This zone can be potentially dangerous to get the sound quality castings. Figure 9 shows a multi cavity casting arrangement of blade casting. The process and the gating have been optimized using ProCAST simulations.



(a) CAD Model



(b) FEM Mesh



(c) Fraction Solid

Figure 8. Shows the Two cavity Blade casting

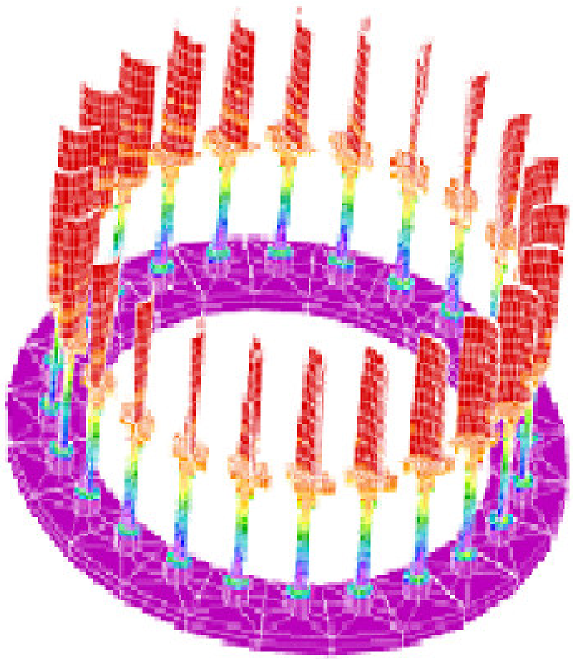
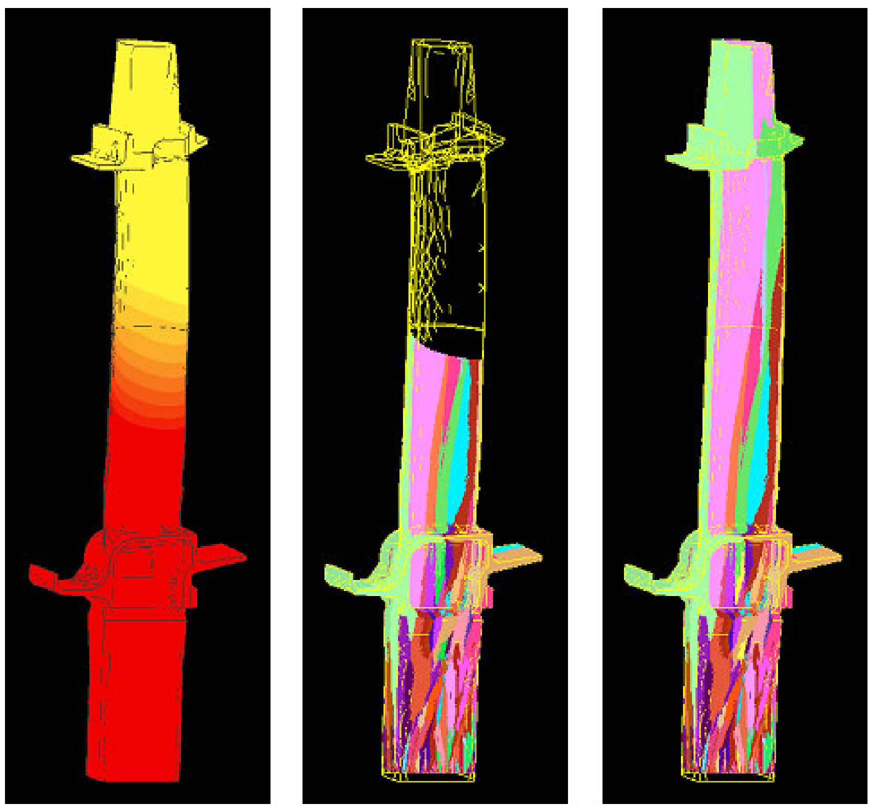


Figure 9. Shows the Multi Cavity arrangement of Blade Casting

Case-4: Microstructure modeling in directional solidification:

For microstructure prediction modeling an additional tool in proCAST software, CAFÉ model is used. CAFÉ stands for cellular automata finite element. This module is the product of research at CALCOM and Swiss Federal Institute of Technology. Figure 10a shows the temperature distribution during the directional solidification of Ni turbine blade. Figures 10 b and c show the microstructure evolution during the solidification. Figure 11 shows the comparison of the ProCAST CAFÉ predicted microstructure with the actual microstructures. Figures have two different cases of rate of solidification one leading to a coarse grain structure and other leading to a fine grain structure.



(a) **(b)** **(c)**

Figure 10. Directional Solidified Blade

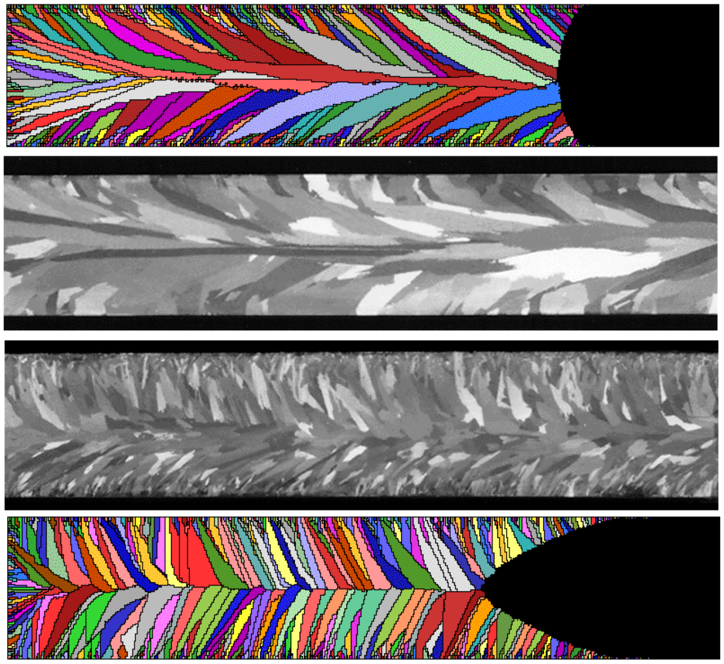
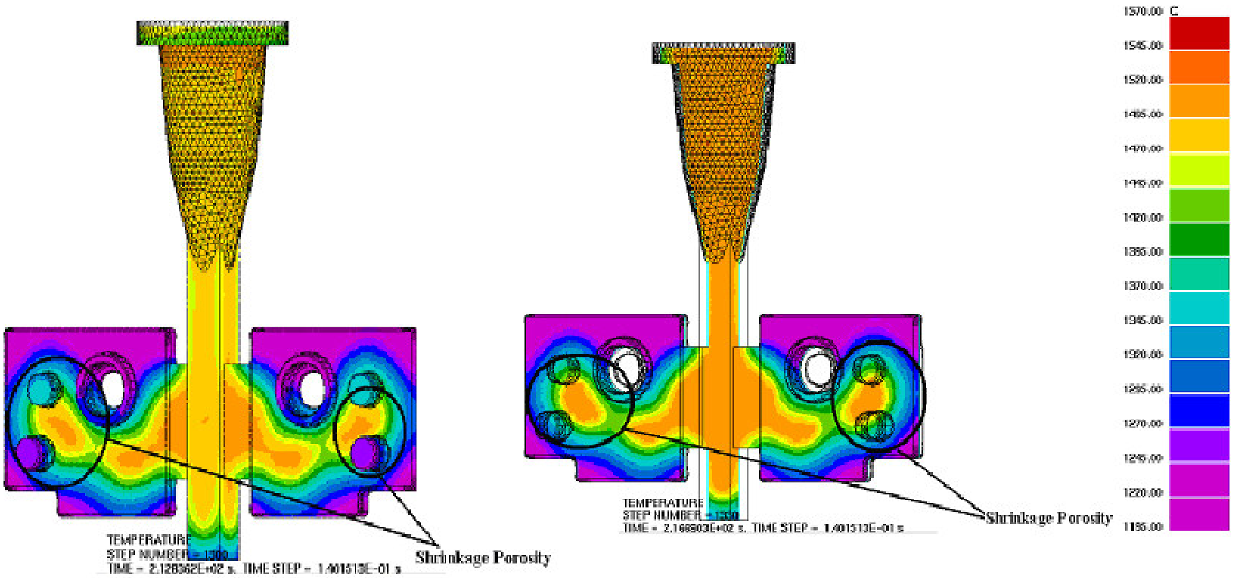


Figure 11. Shows the comparison of the ProCAST CAFÉ predicted microstructure with the actual microstructures

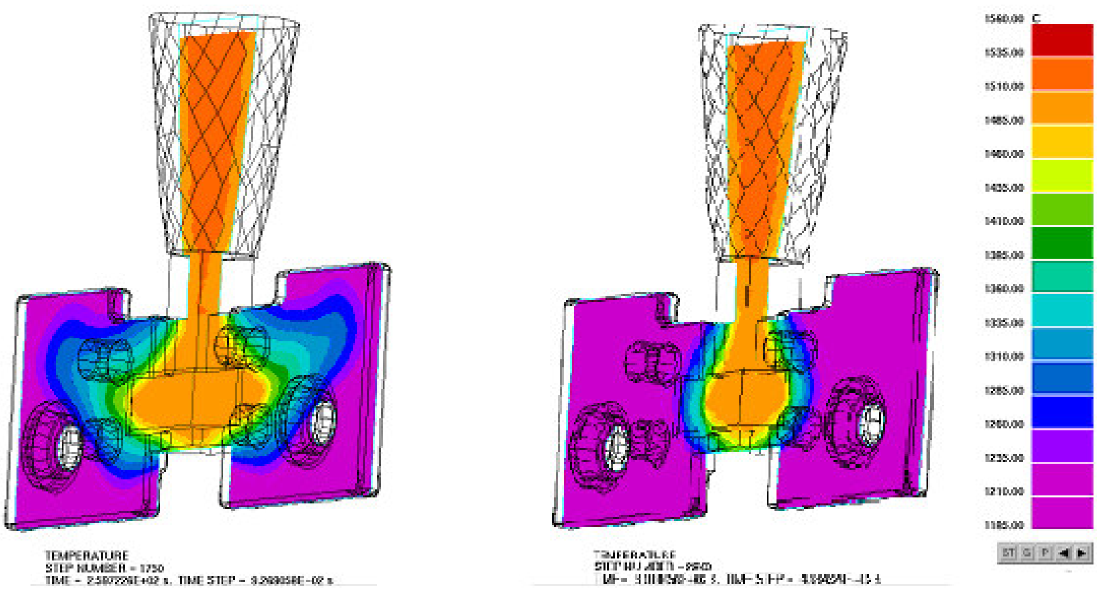
CASE 5: Gating Modification to Eliminate Shrinkage Porosity

This case illustrates the prediction of porosity in a two-cavity casting. During the solidification the shrinkage of the liquid phase needs to be compensated in order to avoid porosity. Gating system is designed to accomplish this possibility. Such porosities persisted in the investment casting of this component. For the initial gating design as shown in **Figure 12**, a coupled thermal -flow simulation was carried out to optimize the gating system**.** Progress of solidification front with cooling time was monitored. The Shrinkage Porosity is observed near the Bosses. Figure 12a shows the Temperature distribution during solidification. Similarly Figure 12b shows the Temperature distribution with section.



(a) **(b)**

Figure 12. Shows the Initial gating System.



(a) **(b)**

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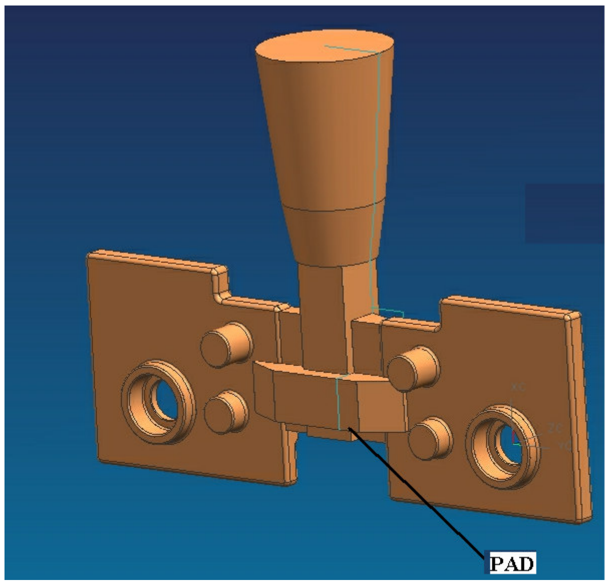
Upon determining the causes of these defects, several possible design changes for the gating layout were studied After the observing the Shrinkage porosity near the bosses they shifted the Gating Location and provided the Pad near the Bosses so that it would overcome the Shrinkage. Figure 13a, 13b shows temperature distribution during solidification Figure 13c shows the CAD model with Pad.



(c)

Figure 13.Shows the Modified gating System

CASE 6: Gating Modification to Eliminate Shrinkage Porosity

This case illustrates the capability of the ProCAST to simulate the two-cavity casting with different ingate location. Figure 14 shows the arrangement for the same with temperature distribution.. The shrinkage porosity is observed in one of the casting. Upon determining the causes of these defects, Gate location was changed for one of the casting.

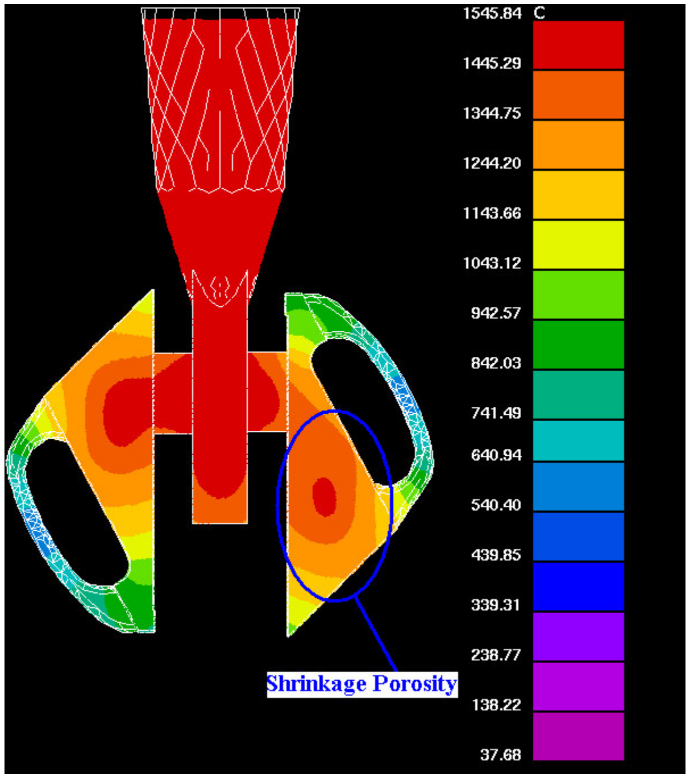


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Figure 14. Shows the Two-cavity arrangement with different in gate position.

CONCLUSION

Advanced casting simulation tools like *Procast* ™ allow the foundry engineer to quickly bridge the gap between design and manufacturing. Optimization or improved efficiency during the manufacturing cycle leads to substantial time and cost savings. Productivity, quality improvements are possible by meticulous usage of simulation procedure.

Finite element analysis based computer simulations are useful for:

- Prediction of defects
- Verification of the validity of gating
- Experimenting with different gating arrangements
- Checking different process conditions (shell thickness, shell material, number of cavities, pouring temperature etc.)
- Optimisation of process to improve the yield (by reducing the rejections, by minimizing the scrap volume.
- Prediction of microstructure.
- Optimisation of the process to get desirable microstructure.

- Development of safe operating parameters and process window for quality assurance.
- Rapid design and development of the casting from concept to customer, by significant compression of development time.

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