Steel Casting Simulation: Live!

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ABSTRACT

For wide spread use of casting simulation in industry, the software programs have to be easy-to-use, economical, reliable, and well-supported. This has been made possible by combining methoding, solid modelling (of risers and gating), simulation, and optimisation in program called AutoCAST. The solidification computation engine is based on a hybrid technique combining Vector Element Method and Finite Difference Method, enabling accurate prediction of shrinkage porosity for even complex castings in a few minutes. By incorporating algorithms for intelligent design of feeders and gating, and their automated solid modelling, the learning curve for the software has been reduced to a few hours. It has been used for live troubleshooting and optimisation of hundreds of castings in the presence of method engineers. The user-friendliness of the software also facilitates collaboration between foundry and OEM engineers to improve the casting design for ease of manufacture, leading to significant reduction in defects, costs, and lead-time. Two such cases of industrial steel castings are presented here, to illustrate the technology, methodology, and benefits involved.

1. INTRODUCTION

Although the benefits of casting simulation are well known, its penetration in Indian industry continues to be poor. The main bottlenecks are high cost of simulation software, coupled with the unavailability of qualified manpower, and technical support from the vendors. The accuracy of results (such as solidification time and location of shrinkage defects) is influenced by metallurgical models and availability of temperature-dependent material property database. The methoding or rigging (feeder and gating design) has to be decided by the user, followed by solid modelling, which requires foundry experience and CAD skills. The simulation of intricate castings may involve more time and cost than shop-floor trials, and any error in program inputs implies further delay and expenses. For wider penetration in the industry, casting simulation programs need to be easy-to-use (implying shorter training programmes), reliable (matching of predicted results with actual observations), economical (simulation cost per casting lower than shop floor trials), and well-supported by the vendors (assistance in difficult projects).

To overcome the above limitations, an integrated software program called AutoCAST has been developed, by combining scientific methoding, feeder/gating modelling, and casting simulation in a single environment. Its first version was developed in 1998, through a collaborative project between the Indian Institute of Technology, Bombay, and Advanced Reasoning Technologies Pvt. Ltd., Mumbai. The program is briefly described here, followed by industrial examples of troubleshooting and improving two steel castings produced by green sand casting.
2. CASTING METHODING AND SIMULATION

The main inputs to the casting methoding and simulation program include: (1) CAD model of the cast part in standard STL format, (2) cast metal or alloy name, and (3) type of casting process. The methoding involves three major decisions: (1) orientation and parting line, (2) core print design, (3) feeder design, and (4) gating design.

Figure 1 shows the major results of the program on a valve casting. This casting showed severe shrinkage porosity in the middle region (circled). The simulation was mainly carried out using the prevalent methoding in the foundry to troubleshoot the cause of the defect, and also benchmark the software program. An analysis of the results showed that the defect was mainly caused by thermal concentration owing to the junction of a number of cores near the affected portion. The various steps in methoding and simulation, and the underlying methodology are described here.

For casting orientation, the program considers the three coordinate axes, and suggests the direction in which the part has the least number and volume of undercuts. After selecting the orientation, the mould parting line is automatically generated to minimise the draw distance and draft volume. Cored holes are automatically recognised, and their prints are designed for weight balance and strength considerations.

Feeder design mainly involves decisions regarding the number, location, shape and dimensions of feeders and feed-aids. Automated feeder design uses geometric reasoning to suggest the best location of feeder (closest to the hot spot, on a flat surface at the top or side, preferably a thick section to facilitate settling). Its dimensions are calculated based on geometric modulus of the hot spot area, which is also automatically computed. Based on the dimensions, the feeder model is created and
attached to the casting through an appropriately sized neck. The user may modify the dimensions of
the feeder and model it again, and add more feeders, if necessary. Feed-aids such as insulating and
exothermic sleeves and covers, and chills are semi-automatically designed: the user has to only select
the location; program suggests the minimum dimensions, and creates the feed-aid model.

The feeder design is verified by simulating casting solidification using the Vector Element Method
which traces the feed metal paths in reverse to accurately pinpoint the location and extent of
shrinkage defects such as cavity, porosity and centreline shrinkage. The method is based on the
principle that the direction of the highest temperature gradient (feed metal path) at any point inside
the casting is given by the vector sum of individual thermal flux vectors in all directions around the
point. Multiple hot spots, if present, are detected by starting from several directions. Ideal feeding
implies that all feed metal paths meet and converge inside a feeder. The VEM is combined with Finite
Difference Method to achieve high reliability combined with speed of analysis.

The most important steps in gating system design include deciding the number and location of
ingates, and designing the choke (smallest cross-section among sprue, runner and ingates) so that the
mould fills in a predetermined range of time. This is required to eliminate the defects caused by slow
filling (cold shuts and misruns), or fast filling (mould erosion and inclusions). The ideal filling time
(function of casting weight, section thickness and fluidity) is suggested by the program, followed by
choke velocity (metallostatic head), and choke area, using the gating ratio. The ingate locations are
suggested by the program, which hunts for thick sections near the parting line that have low free fall
height and fewer obstructions (such as cores blocking the path of metal emerging from an ingate).

The mould filling is simulated to determine the actual filling time (to check the gating design for the
ideal filling time), and identify the location and velocity of metal impingement on mould (to
determine the possibility of mould erosion/sand inclusions). A layer-by-layer filling algorithm that
considers the instantaneous velocity of metal through the ingate (which depends on the metallostatic
head), and the area of casting cross-section being filled up, is adequate to estimate the mould filling
time. This approach is however, applicable to gravity processes only.

3. INDUSTRIAL CASE STUDIES

The program has been successfully validated by troubleshooting and optimising several hundred
different industrial castings of ferrous, non-ferrous and precious alloys, produced in sand, shell and
metal moulds, without any major discrepancy between predicted and actual observed results
(shrinkage porosity defects). Two industrial cases studies involving troubleshooting and improvement
of steel castings are presented here.

The first case study involved a steel casting of magnet frame tube of overall size 750 mm weighing 780
Kg. It is the base part of the housing of traction motor, manufactured by BHEL Bhopal. The castings
were produced with feeders on the top face of the casting, and with bottom gating. During machining
of internal face of the three vertical walls (side and back walls with large feeders seen in the figure),
shrinkage defects of size up to 6-8 mm were observed 5-10 mm beneath the cast surface, about 150-
250 mm below the top face (Fig. 2).
Solid modelling of the casting along with the current method layout followed by casting simulation showed that a thin vertical section of casting just below the feeders is choking the supply of feed metal to the casting wall, leading to shrinkage porosity. Since there was a constraint to place the feeders on the top face only, it was decided to explore product design modification to solve the feedability problem. Accordingly, three different solutions were proposed:

1. Adding cooling fins on the wall affected by shrinkage porosity
2. Increasing thickness of the narrow section below the feeders (padding)
3. Adding one degree taper to the vertical wall as well as padding to the narrow section.

All three modifications were incorporated in the product design on the three adjacent walls. The solidification simulation was carried out to verify the three solutions (Fig. 3). All showed improved feeding characteristics, and hot spots are now seen in the feeders instead of inside the casting.
Based on the above analysis, two product design changes: padding and fins were implemented on two different castings. The trial casting with fins showed completely porosity free machined surface (Fig. 4), as predicted by simulation, and was finally implemented since it was also easier to machine the fins.

![Fig. 4. Trial castings with fins revealed defect free machined faces](image)

The second case study involved an extrusion press cylinder casting of steel of about 3.1 m height and weight 23 tons produced by Mukand Ltd., Thane. After a few years of continuous use, the casting tended to crack or leak near a square projection on the side surface (Fig. 5). Initial investigation included analysis of the cylinder for stresses developed in working condition under cyclic loads assuming the failure was caused by fatigue. It was however, observed that the projection (location of leakage) was subjected to low stresses, ruling out this hypothesis. The foundry on their part experimented with different methoding layouts, including use of local chill, feeder at the projection, and providing padding (taper on inside part of cylinder). The problem however, persisted.

![Fig. 5. The defect-prone square projection is moved up in the modified design](image)

The foundry and the OEM collaborated to analyse the problem supported by casting simulation. Their inputs from the foundry included the current method and all major process parameters. The design engineers from OEM provided a 3D model of the press cylinder and possible directions for product design modifications. The part model, methoding and process plan data was used for simulating the casting. The results of analysis showed that the section connecting the feeder with the junction solidifies much before the projection, chocking the flow of feed metal and thereby leading to potential micro porosity under the projection. It was concluded that after a few years of service, these micro
porosities get connected leading to leakage in few cases. Different solutions were modeled and simulated to alleviate the problem. This included use of padding (internal taper on the thin section to increase its thickness), but was discarded as it involved increased machining costs. After several virtual tryouts and analysis it was concluded that the micro porosity can not be completely eliminated by methoding or process parameters alone. Therefore, in consultation with the product designer, it was decided to shift the square projection to a new location closer to the feeder (Fig. 5). This did not affect the product functionality, and solved the shrinkage porosity problem since the top feeder was now able to feed the junction area (Fig.6). The casting was successfully produced, and is performing satisfactorily.

![Image](image_url)

Fig. 6. Modified press-cylinder design shows connected feed paths and hot spots inside feeder; actual casting is defect-free.

4. CONCLUSION

The bottlenecks and non-value added time in casting development can be minimised by adopting CAD, intelligent methoding and simulation technologies. These have been developed, successfully demonstrated on industrial castings, and now being used in several organisations. Several innovative algorithms, including VEM, geometric reasoning, and automatic solid modelling dramatically compressed the iteration time for methoding modification and simulation to less than one hour for even complex castings. Further, the simple and logical user interface greatly improved the learning curve for engineers, to just a few hours. As a result, even small foundries with little or no previous exposure to CAD/CAM software are able to effectively use the program to improve their casting quality, yield and productivity. It has also proven to be very useful for verifying the manufacturability of a casting and improving it by minor modifications to part geometry, before freezing the design. In future, it will be possible to offer automated methoding and simulation software and services over the Internet, enabling access to this technology to even SME foundries in remote areas.
REFERENCES


About the Author

Dr. Bhallamudi Ravi is a Professor of Mechanical Engineering at I.I.T. Bombay, where he joined in 1992 after completing his Ph.D. from Indian Institute of Science, Bangalore. His areas of research include intelligent CAD/CAM for metal casting and medical applications. Till date, he has guided five Ph.D and 32 M.Tech students, and published his work in about 135 technical papers (including 40 in refereed journals). He has also written two books: “Metal Casting: Computer-aided design and analysis” and another “Past, Present and Future of Indian Manufacturing Industry”, which won an award from former Prime Minister Shri A. B. Vajapayee. Dr. Ravi twice represented India at World Foundry Congresses in Dusseldorf (1989) and in Philadelphia (1996), assisted in a benchmarking study of American foundries (1996), and was a visiting researcher at Purdue University (2006). He is a Fellow of the Institution of Engineers, an international member of the ASME Bio-manufacturing Technical Committee, reviewer for several international journals (ASME, IEEE, IJAMS and IJPR), and has chaired several international and national conference sessions.