Computer-aided Casting Design and Simulation

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ABSTRACT

Computer-aided casting design and simulation gives a much better and faster insight for optimizing the feeder and gating design of castings. Key inputs, steps and results are discussed here. Casting simulation however, poses several challenges: technical as well as non-technical (resources) for industrial users. We highlight the best practices based on our experience with several casting simulation projects, and directions for further research in this area to make casting simulation more easy, accessible and economical for industrial users.

Keywords: Metal casting, simulation, solid modeling, shrinkage porosity, defect prediction, casting optimization.

INTRODUCTION

The phenomenon of casting solidification, accompanies by volumetric contraction, leads to several major defects in casting including shrinkage porosity, cracks and distortion. In short freezing range alloys, especially those poured in permanent molds, the shrinkage tends to concentrate at the hot spots. In long freezing range alloys, especially those poured in sand molds, the shrinkage tends to be distributed all over the casting, though more of it still appears around hot spots. The location and extent of shrinkage porosity can be predicted by identifying regions of high temperature (hot spots) and low gradients (short feeding distance). Unfortunately, castings can be of complex shapes, and the heat transfer from all faces of the mold may not be uniform. Other factors, such as air gap formation at the metal-mold interface, convection in liquid metal, application of feedaids, presence of cores, gating system design and pouring parameters also affect the location of shrinkage porosity, making its prediction difficult, if not impossible, manually.

In recent years, computer simulation of casting solidification has gained much ground, owing to the constant and painstaking efforts of researchers to make such software tools more reliable and easy to use. A significant number of real life case studies are also available in technical journals and proceedings of conferences related to casting. Still, only a handful of aluminum foundries are using these software tools today. This is owing to several challenges posed by first-time users. We first present an overview of computer-aided methods design. This is followed by the difficulties faced by foundry users, and how to overcome them through best practices gleaned from our experience with several simulation projects and consultants.
2. COMPUTER-AIDED CASTING DESIGN

The main input is the 3D CAD model of an as-cast part (without drilled holes, and with draft, shrinkage and machining allowance). The model file can be obtained from the OEM firm, or created by a local CAD agency. Various display options such as pan, zoom, rotate, transparency, and measure are provided to view and understand the part model (Fig. 1). The cast metal and process are selected from a database. Part thickness distribution is displayed for verifying the model and evaluating part-process compatibility.
The method design involves cores, feeders and gating system. Holes in the part model are automatically identified for core design. Even intricate holes can be identified by specifying their openings. The print length is computed based on the core diameter and length (the user can change these if required), and the entire core model is automatically created. The program suggests the number of cavities depending on the mold size (selected from a foundry-specific library), considering both cavity-cavity and cavity-wall gaps. Then the part model is automatically duplicated in the correct locations as per the desired cavity layout.

To facilitate feeder location, the program carries out a quick solidification analysis and identifies feeding zones. The user selects a suitable location close the largest feeding zone, and the program automatically computes the dimensions of the feeder using modulus principle (solidification time of feeder slightly more than that of the feeding zone). The feeder model is automatically created; the user can change its dimensions or apply feedaids such as insulating sleeves and exothermic covers. More feeders can be created by specifying their positions.

The gating channels are created semi-automatically. First, the user indicates gate positions on the part or feeder model. Then the sprue position is decided, and it is connected to the gates through runners. Runner extensions are automatically created. Any type of gating system: horizontal, vertical, investment tree, and direct pouring can be created or modified within minutes. The program also suggests a suitable filling time (which can be changed by the user), accordingly computes the dimensions of the gating channels, and creates their solid model.

The mold cavity layout, feeders, and gating are automatically optimized based on quality requirements and other constraints. For mold cavity layout, the primary criterion is the ratio of cast metal to mold material. A high ratio such as 1:2 (cavities too close to each other) can reduce the heat transfer rate and lead to shrinkage porosity defects. A low ratio such as 1:8 (cavities too far from each other) implies poor utilization of mold material and reduced productivity. The program tries out various combinations of mold sizes and number of cavities to find the combination that is closest to the desired value of metal to mold ratio.

The gating design is driven by the ideal mold filling time, which depends on the cast metal, casting weight and minimum wall thickness. Fast filling leads to turbulence-related defects (such as mold erosion, air aspiration and inclusions). On the other hand, slow filling may cause defects related to premature solidification (such as cold shuts and misruns). To optimize the gating design, the program simulates the mold filling and computes the total fill time. A simplified layer-by-layer algorithm is used, taking into account the instantaneous velocity through the gates (considering back pressure, if applicable), and the local cross-section of the mold cavity. This gives an accurate estimation of filling time, while being computationally efficient. If the difference between the ideal and simulated filling time is more than a specified limit, the program automatically changes the gating design, creates its solid model, and simulates the mold filling again.

The feeder optimization is driven by casting quality, defined as the percentage of casting volume free from shrinkage porosity. The user indicates a target quality. The program automatically changes the feeder dimensions, creates its solid model, carries out solidification simulation, and estimates the casting quality. The solidification simulation employs the Vector Element Method, which computes the temperature gradients (feed metal paths) inside the casting, and follows them in reverse to identify
the location and extent of shrinkage porosity. This has been found to be much faster than Finite Element Method, without compromising the accuracy of results. The feeder design iterations are carried out until the desired quality is achieved, or the number of iterations exceeding a set limit. The user can accept the results, or reject them and modify the feeder design interactively.

3. CHALLENGES AND BEST PRACTICES

There are five major challenges in computer-aided methods design: the first three are technical, and the next two are related to resources.

The first difficulty is getting the inputs required for casting simulation software, especially the geometric information. The 3D solid model of the casting is required; it must be complete (no missing faces or dangling edges) and accurate (features and dimensions). It cannot be automatically created from 2D drawings, but has to be built step-by-step by extruding 2D sketches and combining other primitive solids (such as block and cylinder), followed by modifiers (like draft and fillets). Wireframe or surface models are inadequate; mass properties must be computable. Other major inputs include material and process specifications. High end software also require accurate values of thermo-physical properties and metal-mold interface conditions, such as air gap formation and the heat transfer coefficient. This may not be available in the software database, especially for non-standard combination of metals and processes, and has to be generated by a controlled set of experiments, followed by software customization and systematic benchmarking.

The second difficulty is correct prediction of specific defects. Solidification simulation software can help in identifying the location of shrinkage defects (porosity, centerline shrinkage, sink and pipe) fairly accurately; but other defects related to solidification and subsequent cooling (such as cracks, tears and distortion) are difficult to predict reliably. Similarly, while coupled mold filling and solidification software can track the fall of temperature along a flow path, and use this information to indicate the possibility of incomplete filling, it is difficult to consider the effect of oxidation, combustion (of mold coats and sand core resins), evolution of dissolved gas and back pressure of air, which have a major influence on cold shuts, misruns and blow holes. To correctly predict different types of defects, it is important to know the underlying science, which can be imparted through suitable training programmes.

The third difficulty is changing the methods design to prevent the defects (or optimize the yield). In reality, simulation software can only produce the history of casting solidification (high end casting software can simulate mold filling, solidification and subsequent cooling) and display the results (such as color-coded images of progressive and directional solidification) for different points in the casting. The user has to interpret the results and decide the changes to tooling or product design, based on past experience, followed by simulation again to check if internal defects still occur. The software can only verify a given casting design by simulation, thereby replacing a shop-floor trial. It can substantially enhance the capability and productivity of methoding engineers; but cannot replace their experience and innovativeness.

Even if a foundry can overcome the above technical difficulties, there are two challenges in terms of resources.
The first resource bottleneck is the technical expertise required to implement and use the software, which greatly depends on the capabilities of the software as well as the profile of the foundry. The high end systems require a sound appreciation of the theory of heat transfer and fluid flow related to metal casting, essential for initial customization (which can take several days to weeks, depending on the metal-process combination of the foundry) as well as proper interpretation of results during use. A simple yet common problem in FEM-based simulation software is choosing the correct mesh size to get accurate results within the time available (say within a working day). Most of the simulation software are being converted to Windows-based systems, so that users familiar with the operating system can learn how to use the software within a few days. Still, the line of technical support has to be maintained for several weeks (and whenever a new upgrade version is released) for the engineers to learn about all the features of the software and use them effectively. In general, it is easier to train a methoding engineer how to use a simulation software, than to teach a software engineer how to develop a casting. This does not apply to solid modeling; which requires a fully trained (and preferably younger) engineer for this purpose. To overcome the problem of ‘brain-drain’ from foundries (especially small and medium) to other sectors, it is suggested that the solid models of castings be obtained from CAD service centers, and simulation be carried out by existing methoding engineers.

The second difficulty is about the economic viability of the simulation software. Most of the simulation software available today have uniform pricing internationally, making them relatively expensive for small and medium foundries in developing countries. A careful economic analysis must be carried out, considering: (1) current levels of rejections due to defects that can be reliably predicted by simulation, (2) current yield and the increase possible by the use of simulation, (3) average number of trials and the lead time to develop a new casting by current practice, and their reduction by the use of simulation, (4) effect of loss of customer base and their satisfaction owing to the current levels of rejections, including surprises at the machining stage, and (5) average value addition in current castings, and increase in value addition for new (more complex) castings to be taken up with the aid of simulation. In general, it is possible to reliably predict and eliminate the shrinkage porosity problem in short freezing range castings of even complex shape, while ensuring the maximum possible yield for a given layout of feeders and gating, and reduce the number of trials to just one. Jobbing foundries developing several casting projects every year, with large order weight per project (number of castings x weight of each casting) will be able to recover their investment within a few months. Indeed, with customers expecting castings of assured quality delivered within the shortest possible time, the use of simulation software has become a necessity rather than a luxury.

The AutoCAST software described earlier overcomes the above difficulties by combining scientific methoding, feeder/gating modelling, and casting simulation in a single user-friendly environment, and automating many tasks that are difficult for most users. 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 latest version (AutoCAST-X) has over 200 major improvements, including automatic multi-cavity layout, high accuracy coupled with speed, and the easiest-to-learn user interface among all casting simulation programs. It is illustrated by an industrial example of troubleshooting and improving an aluminium-alloy switchgear tank by gravity die casting.
4. INDUSTRIAL CASE STUDIES

Figure 2 shows the major results of the program on an aluminium-alloy valve casting produced by gravity die 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. This problem is so severe that the best solution would be to redesign the part to reduce the thermal concentration at the defect area, and to allow feed metal to reach the area.

Figure 3 shows an industrial case study of an aluminium-alloy switchgear tank produced by gravity die casting. The casting is about 280 mm in size, and weighed 6.1 kg. It was found to leak during pressure-test, and rejections were as high as 35%. The methoding was modelled as produced in the foundry, and simulated to locate two regions of shrinkage locations leading to leakage.

After a few iterations, an improved methoding was finally obtained by placing a chill in the cores and insulation on feeders, and verified by simulation. This enabled rejections to be reduced to less than 5% without additional shop floor trials. Adopting this methodology during product development phase itself would have ensured even lower rejections and saving of resources (material, energy, labour, and time) otherwise spent for casting trials.
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 functionality over the Internet, enabling access to this technology to even SME foundries in remote areas.

REFERENCES

SPEAKER PROFILE

Dr. B. Ravi is a Professor of Mechanical Engineering at IIT Bombay. He completed his engineering degree from National Institute of Technology, Rourkela in 1986, followed by Masters and Ph.D. from Indian Institute of Science, Bangalore in 1992. His areas of research include casting design and simulation, product lifecycle engineering, and Bio-CAD/CAM. Till date, he has guided seven Ph.D. and over 40 Master students. His work is published in 160 technical papers, and a book on Metal Casting: Computer-aided design and analysis. He is a sought-after speaker and consultant, and has assisted over 50 organizations ranging from small foundries to global MNCs. The casting software AutoCAST developed by his team is in use in nearly 100 organisations, including many engineering and research institutes. He is a Member of ASME Bio Manufacturing Committee, Fellow of the Institution of Engineers, and member of review boards of several international journals like ASME, Biofabrication, IEEE, IJPR, and Rapid Prototyping. He twice represented India at World Foundry Congresses: Dusseldorf in 1989, and Philadelphia in 1996. He has won several awards, including the WTI Foundation award for his draft manufacturing policy ‘The Past, Present and Future of Indian Manufacturing Industry’, given by former Prime Minister Mr. A.B. Vajpayee. He recently established the OrthoCAD Network Centre at IIT Bombay in collaboration with Tata Memorial Hospital and NFTDC Hyderabad, to develop tumour knee prostheses for children affected by bone cancer.