A Holistic Approach to Zero Defect Castings

Dr. B. Ravi, *Professor*
Mechanical Engineering Department
Indian Institute of Technology Bombay, Mumbai-400076
E-mail: b.ravi@iitb.ac.in, Phone: +91 22 2576 7510

Abstract

Casting rejections – as high as 8-15% in jobbing foundries – cannot be attributed to poor methoding and process variability alone. Mostcastings are designed for manufacture, not for *manufacturability*. Many defects like shrinkage porosity, hot tear, and cold shut originate from poorly designed part features (isolated junction, constrained internal feature, long thin section, respectively). Foundry engineers partially tackle the problem by tweaking the part design (for example,increasing a fillet radius or padding a thin wall), but incur additional and avoidable costs of machining and productivity loss. Ideally, design for manufacturability (DFM) should be carried out early by product engineers (foresight), instead of late DFM currently practiced by casting suppliers (hindsight). Unfortunately, d*esigners lack foundry knowledge, and foundry engineers lack design rights*. We present a collaborative system for achieving perfect castings – highquality with frugality –by integrating part, tooling, methods and process optimization, and providing feedback loops to part design. Major control parameters include: wall thickness, junctions and hole diameter (part design phase), parting line, cores and mold cavity layout (tooling design), feeding and gating system (methods design), and process settings (manufacturing). Each subsequent phase provides more information and feedback regarding part quality and cost to the designer, allowing design improvements for manufacturability without affecting functionality. A secure web-based project management system enables rapid and seamless collaboration between casting lifecycle engineers. A real-life industrial example is presented to illustrate the working of the system. Direct benefits include: first-time right castings, consistent quality, and low cost of tooling and manufacturing. Other benefits include better relations between OEM and supplier, knowledge capture and reuse for future projects, and ease of training fresh engineers.

Keywords: Casting, CAD/CAM, Design for Manufacturability, Simulation, Quality, Cost.

1. Introduction

Casting defects can be defined as the departure from conformance to customer requirements, with respect to (i) *geometry*: ex. mismatch and swell, (ii) *integrity*: ex. porosity and inclusions, and (iii) *property*: ex. segregation and hard spots. The resulting loss of foundry productivity and customer confidence is a heavy price to pay. Jobbing foundries encounter a higher level of defective castings, averaging 8-15%. Even production foundries have overall 3-6% defective castings.

Foundries try to reduce rejections by experimenting with process parameters (like alloy composition, mold coating, and pouring temperature). When these measures are ineffective, then methods design (gating and feeding) is modified. When even this is not effective, then tooling design (part orientation, parting line, cores and cavity layout) is modified. The effect of any change in tooling, methods or process parameters is ascertained by pouring and inspecting test castings. Our studies show that replacing shop-floor trials by computer simulation saves time, provides a better insight, and helps in reducing the rejections by half – froman average 8.6% before to 4.3% after, as per a survey of nearly 200 foundries carried out by IIT Bombay (Fig. 1) [1]. This is however, still very high compared to the expectations of OEM customers. They are now beginning to share the responsibility for casting quality, by working closely with their suppliers, with the aim of reducing the rejections to near-zero level.

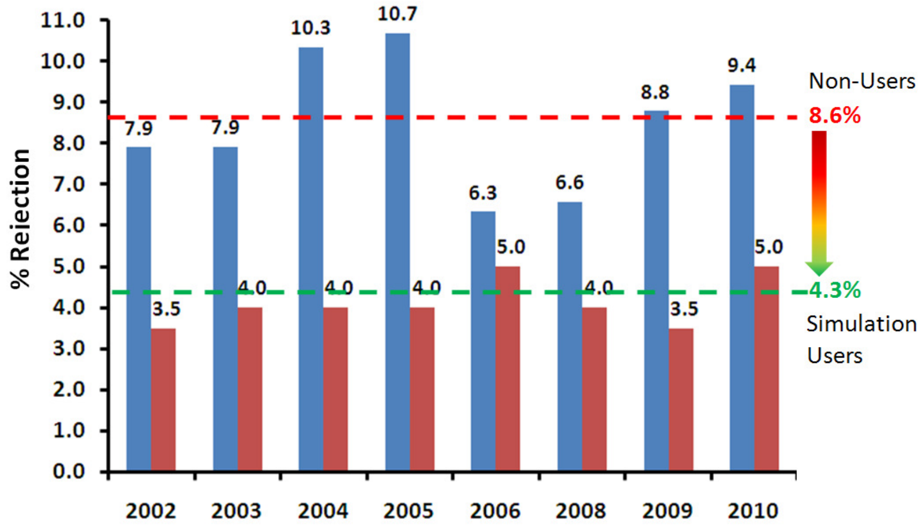

Fig.1: Simulation users have half the average rejection rate as non-users

A series of industrial studies and discussions with major original equipment manufacturers (OEMs) revealed that most parts are *designed for manufacture, not for manufacturability*. The origin of major casting defects (like shrinkage porosity, crack, and cold shut) discovered at the manufacturing stage can be traced back to part design. This is because product designers usually limit their focus to achieving the desired functionality through a suitable combination of part material, geometric features and manufacturing tolerances. They may not be aware of the extent to which part features affect quality and cost issues later (Fig. 2). For example, shrinkage porosity is caused by hot spots *in junctions* that cannot be easily fed by an external *feeder*. Hot tear is caused around an *internal feature* that is constrained by the *mold or core* during cooling. Cold shut is usually caused in a *thin section* that is far from the *gates*.

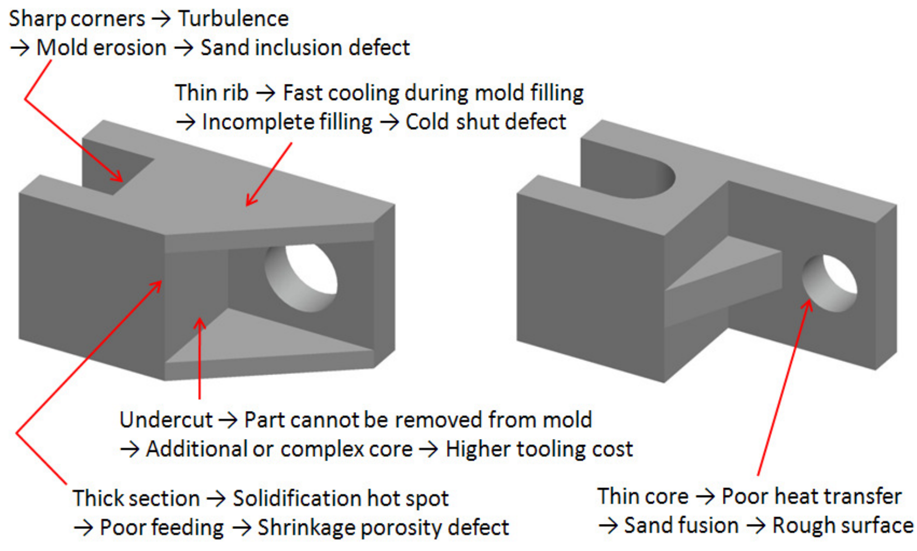

Fig.2: Effect of original and revised part design features on quality and cost

Foundry engineers *try* to achieve the desired quality through appropriate design of tooling and process parameters. Minor changes to part design are needed in most cases: draft for faces along draw direction, plugging drilled holes, increasing fillet radius, padding thin walls, and other changes [2]. These increase the weight of as-cast parts by 10-15% compared to the original design. Machining the additional volume leads to an (unnecessary) increase in cost. Still, a large number of castings are rejected, recycled or repaired, implying further (avoidable) costs.

The abovementioned wastage of resources could be avoided by early evaluation of part design in terms of product quality and cost, and modifying the design to achieve the *desired manufacturability* without compromising the *required functionality*. We refer to this as 'early DFM' that should be practiced by OEM firms, in contrast with the 'late DFM' that is currently practiced by component supply firms (described in a later section). The combined effect of part design and methods design on casting quality and cost is however, not easy to evaluate or optimize [3]. *Designers lack manufacturing knowledge, and manufacturing engineers lack design rights*. Both of them need to be equipped with the right knowledge and software tools for casting design and collaborative optimization.

In the following sections, we first review the current way of casting development and related quality issues to understand why there is very little practice of early DFM in industry. Then we present our work in developing a comprehensive framework for casting DFM that integrates part design, tooling design, methods design and process planning. This approach enables evaluation of product quality and cost at each phase, and plows the information back to product engineers for design optimization. Initial results generated for an industrial casting are presented to illustrate the working and benefits of the system. The paper is written in a manner suitable to both product designers and foundry engineers; research scientists and scholars will also find several ideas worth pursuing.

2. Casting Quality – Conformance Criteria

Increasing emphasis on 'core competence' has led to a scenario where parts are designed in an OEM firm, tooling are developed in a tool room, castings are produced in a foundry, rough machined in a machine shop, inspected and heat treated by special units, then delivered to the OEM or a Tier-1 supplier for finish machining and assembly. Over time, each firm in the casting supply chain adopted new technologies and methodologies to maximize their resource utilization, continually reducing production cycle time and costs. This has yielded a significant jump in productivity.

The same is however, not true of casting quality. If we define quality as conformance of as-cast parts with respect to the original design (from OEM) within a band of tolerances as narrow as for machined or molded parts, then virtually no casting will pass. Let us briefly review the quality issues related to three types of conformance: geometry, integrity and property (Fig. 3).

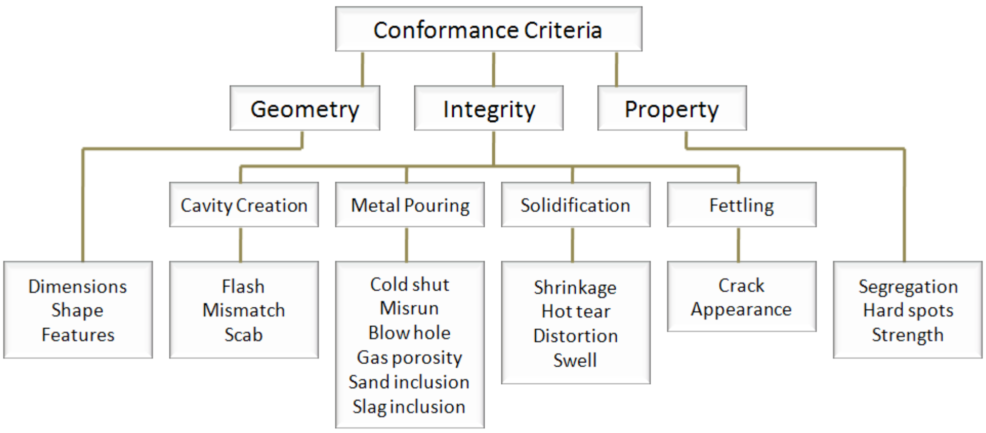

Fig.3:Various conformance criteria for as-cast part with respect to designed part

Geometry conformance is affectedby the series of transformations from part to pattern, and further on to mold cavity, as-cast part, rough-machined part, and finally finish-machined part. The OEMs usually prepare the drawings or 3D models of only the finished part; the casting supplier is forced to recreate the model of the as-cast part and tooling, introducing geometric errors. Various allowances (shrinkage, distortion, machining, etc.), draft, fillets, and plugging of drilled holes can add as much as 10-15% to the original part volume. Individual features, for example, a particular hole diameter or wall thickness may need to be drastically modified to facilitate manufacturability.
Integrity conformance can be defined as the absence of defects (both surface and internal). These can be characterized by the process phenomenon:

(i) mold cavity creation: ex. flash, mismatch, scab and rough surface
(ii) metal melting and pouring: incomplete filling (cold shut and misrun), gaseous inclusions (gas porosity and blow holes), and solid inclusions (sand and slag)

(iii) casting solidification: shrinkage (cavity, porosity, corner, centerline and sink), cooling stress (hot tear and distortion) and swell
(iv) fettling and grinding: cracks and poor appearance

The defects are often diagnosed incorrectly. While it is not surprising that shrinkage porosity (Fig.4) may be difficult to distinguish from gas porosity, identifying a shrinkage cavity as blow hole (quite common in industry) is not excusable! Wrong diagnosis can lead to wrong treatment.

Fig.4: Shrinkage defects (left to right): cavity, porosity, centerline, corner and sink

Property conformance is affected by alloy composition and manufacturing process. The related defects may be classified as: incorrect composition (ex. segregation), and inadequate properties (ex. poor tensile strength and hard spots). When the specifications are narrow (ex. smaller allowable range of composition or property values), or localized (ex. test bars to be taken from a specific section) then achieving a good conformance of properties between the cast part and designed part becomes even more difficult.

In plastic molding and metal forming, there is a much better conformance between the designed and manufactured parts. Part requirements (such as wall thickness and hole diameter) are compatible with process capabilities, resulting in less than 1% rejections. In contrast, a recent survey of about 200 foundries throughout India, representing all major metals, processes, capacities and applications showed that integrity defects alone account for average 7.4% rejections. Knowing that some defective castings go un-detected or under-reported, and by including property defects, the average rejection rate is estimated to be above 10%. Considering that most castings are hardly designed for manufacturability, this is actually good news. The credit for preventing a much higher rejection rate that would otherwise be expected, goes to casting engineers. They make minor changes to part designs, produce acceptable quality castings with the existing process (with all its limitations and constraints), and take the additional cost burden of machining the as-cast parts to bring them closer to the original design.

3. Design for Manufacturability – Current Practice

Foundry engineers spend considerabletime and effort in optimizing casting designs to reduce defects, especially those related to casting solidification. They try to manipulate the sequence of casting solidification from thin to thicker sections and finally toward feeder(s). This shifts the shrinkage defects to feeders, which are later fettled and recycled. The volume of feeders can be significant, reducing the yield by as much as 30-40% (especially in bulky castings), affecting melting costs and productivity. Further, fettling of feeders (usually, by impact and grinding) can lead to cracks and poor appearance. Hence reducing the number and volume of feeders is an important secondary objective, so that costs can also be minimized.

Directional solidification and effective feeding is sought to be achieved through the location, shape and size of feeders, as well as feeder connection to casting (neck), and feed-aids (like insulating or exothermic sleeves). Fig. 5 shows simplified representations of three common configurations of part wall thickness [4] encountered in metal castings. The first one on the left has the thickest region at one end. This feeds the intermediate thickness region, which in turn feeds the thinnest section at the other end. Connecting a feeder to the thickest section thus takes care of feeding the entire casting, making this an ideal configuration.

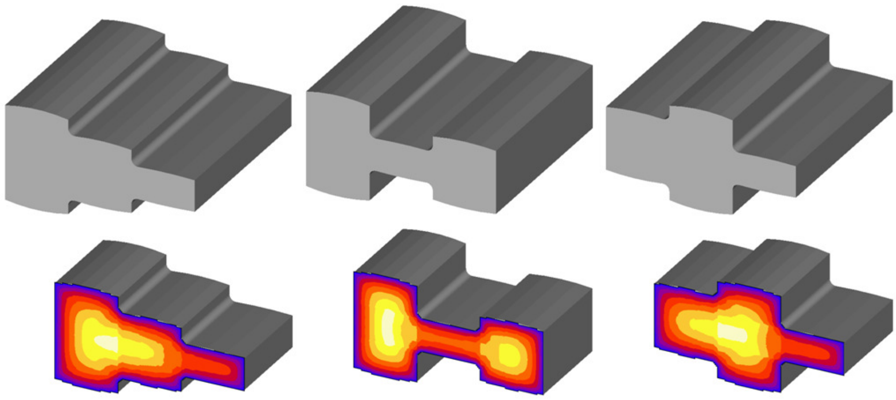

Fig.5: Section thickness configurations affect directional solidification and feeding

The second configuration has the thinnest section in the middle, leading to a major hot spot on one side and a minor hot spot on the other side. While the major hot spot can be fed by a feeder connected to the thickest section, this feed metal cannot reach the minor hot spot at the other end due to early solidification of intervening thin region. There are three foundry solutions to prevent the defect at the minor hot spot: (i) feeder for the minor hot spot, (ii) chill near the minor hot spot, or (iii) an insulation pad around the intervening thin section. All three involve additional manufacturing cost. The defect can also be prevented by three part design changes: (i) reduce the thickness of the section containing the minor hot spot, (ii) add fins to the minor hot spot, or (iii) increase the section thickness of the intervening region. Foundries often resort to the last solution, followed by machining to bring the thickness back to original design.

The third configuration on the right has the thickest section in the middle. It contains a single major hot spot that feeds both adjacent sections, and ends up with a big shrinkage defect. If feeding from the top, front and back sides are disallowed due to some other constraints (say, top surface is curved and feeder will be difficult to fettle, or company name is molded), the foundry engineer is forced to provide a side feeder, leading to incomplete feeding of the central hot spot, especially when the distance between the feeder and hot spot is large.Ideally, such problems could be visualized at the design stage itself, and appropriate changes made to part design, meeting the functional requirements in some other way.

Industrial castings may have complex 3-dimensional junctions [5] combined with other features. Product engineers find it difficult to predict and optimize the effect of any design change on product quality (foresight), and leave it to foundry engineers who rely on shop-floor manufacturing trials and analysis (hindsight). It is no surprise that DFM is practiced late in product life cycle, that too when other measures fail to achieve the desired quality.

Late detection of defects that are traced back to poorly designed part features, resulting in avoidable costs and lead time for fixing such defects, are no longer acceptable. At the same time, intense pressure from competitors and customers is forcing OEM firms to share the responsibility for product quality and explore new avenues for cost reduction. Short-term price negotiations with suppliers are therefore giving way to long-term technological collaborations. Both sides are beginning to appreciate the importance of collaborative design and optimization of part, tooling and process. Unfortunately, there are no tools for early evaluation of the manufacturability of cast parts, suitable for product engineers. This gap is sought to be addressed by our R&D work.

4. Collaborative Framework for Casting DFM

Our casting DFM framework comprises four phases corresponding to part design, tooling design, methods design and process planning (Fig.6). There are three distinguishing features that overcome the limitations of the current way of casting development practiced in industry.

1. Significant and seamless flow of information from one phase to subsequent phase; the combined output of previous phases becomes the input to the subsequent phase.

2. Local optimization loops, supported by appropriate tools in each phase, to determine the best values of design parameters considering their effect on casting quality.
3. An additional feedback loop at the end of each phase, connecting back to part design, for allowing part designers to better predict part quality and cost, and modify the part design to achieve the best overall quality and cost.

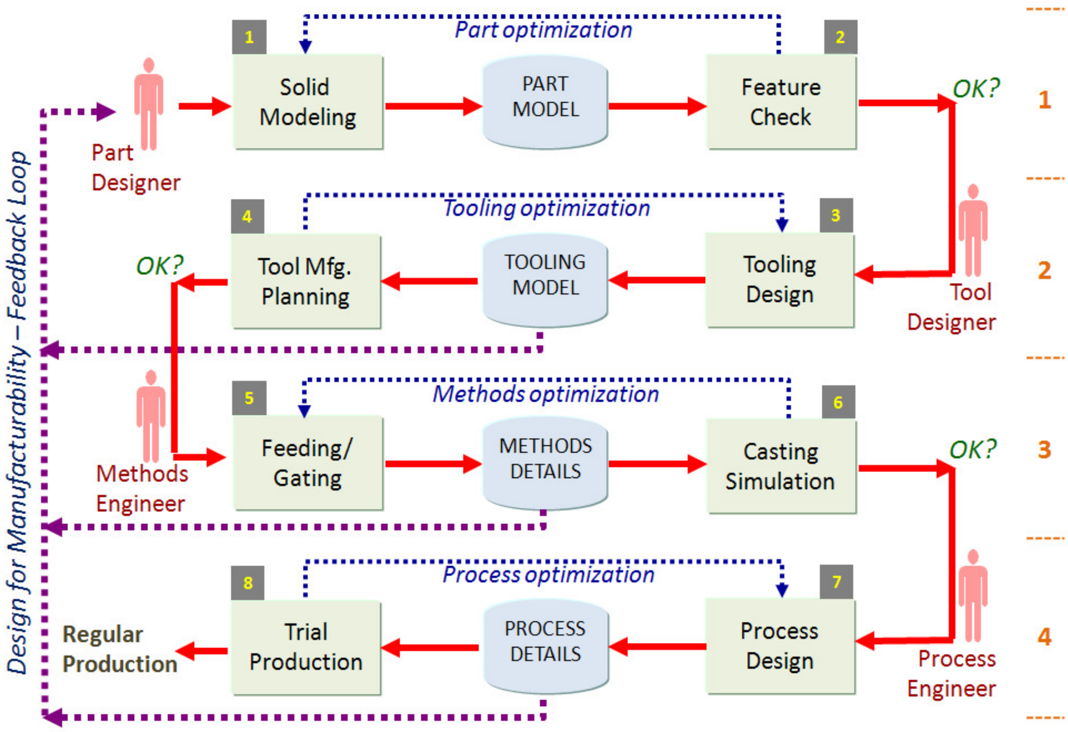

Fig.6: Multi-phase framework for casting DFM with feedback loops

Major design parameters at each phase, which significantly affect casting quality and cost, are briefly mentioned here.

Part Design Phase: Parameters related to wall thickness, junctions and through holes can be linked to part quality; part volume and overall shape complexity can be linked to manufacturing cost. Cast metal/alloy composition and manufacturing tolerance affect the selection of process parameters and finally affect all conformances: geometry, integrity and property.

Tooling Design Phase: Major design parameters at this phase are related to draw direction, parting line, undercuts, draft allowance, cored features and mold cavity layout. All these mainly affect the geometry conformance and tooling cost.

Methods Design Phase: This includes feeding and gating system design, which have a significant effect on integrity and property conformance of the cast part, as well as yield and therefore manufacturing cost.

Process Planning Phase: Major parameters in this phase that affect casting quality include furnace charge mix, melt treatments, pouring temperature, pouring timeand cooling time, along with ambient conditions (temperature and humidity).

Over the last ten years, we have developed and integrated different pieces of the above framework, utilizing the knowledge obtained from research work and experience gained from industry interactions. To ensure that the entire system is of practical use, the following guidelines have been set forth:

1. The overall goal is to ensure that the castings are right first time (fewer trials), and right every time (consistent quality) at the least possible cost.
2. Part designers with very little process knowledge and casting engineers with only basic computer skills should be able to use the system.

3. Overall computation time should be minimized by incorporating automatic good-first design suggestions, reusing the data (inputs and outputs), and efficient algorithms.

The proposed framework has been implemented using AutoCAST-X software [6]. Its working and results are illustrated with an industrial example of a ductile iron gear case casting of overall size 370 mm weighing 5.8 kg (Fig. 7). Wall thickness analysis shows a rapid transition from 35 mm to 4 mm within a short distance of about 40 mm, signifying a high thickness gradient that can possibly cause hot tears, if the mold material is hard. This is also indicated by the part-process compatibility checks [7]. The major cored feature is semi-automatically identified by specifying the three openings (top, side and bottom).

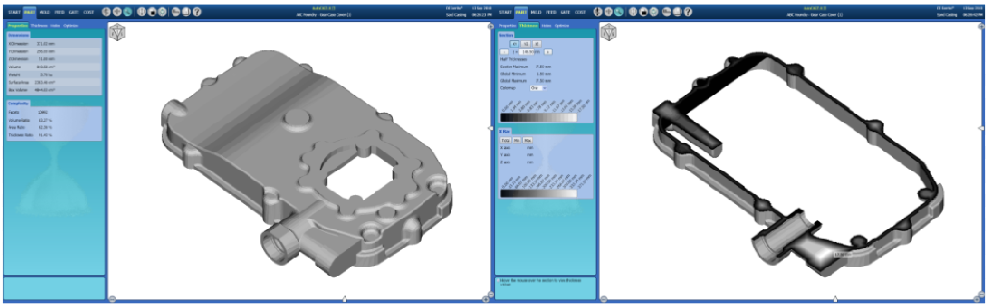

Fig.7: Part design checks: shape complexity and thickness

Tooling design involves checking the part orientation, specifying the parting line, designing the cores, and optimizing the cavity layout (Fig. 8). The cores are automatically designed by converting the cored hole to a solid body, and adding appropriate prints (core supports) at the openings. The user can modify the diameter or length of the core print if needed. The combination of mold size and number of cavities is optimized considering the weight ratio of part metal to mold material. A higher ratio (ex. 1:2, implying more cast metal) can lead to solidification problems, and a lower ratio (ex. 1:8) leads to poor utilization of mold material.

The methods design is verified by simulation of mold filling and casting solidification. In mold filling, the impact of melt jet on mold wall (or cores) is evaluated to ascertain the possibility of mold erosion and thereby sand inclusions. The total filling time is evaluated against the ideal filling time and rate for the given cast metal, weight, wall thickness and pouring temperature (fluidity). If the simulated filling is too short, it indicates the possibility of turbulence-related defects; too long filling indicates the possibility of unfilling defects. Other parameters, such as vertical rise of metal in mold coupled with gas generation and escape can be modeled to predict the occurrence of blow holes. In such cases, the gating design is semi-automatically optimized to ensure filling in the correct amount of time. Casting solidification simulation gives the temperature profile, gradient map and solidification time (Fig. 9). These are useful to predict shrinkage related defects, including shrinkage porosity and hot tears, based on which the feeding system design is optimized to achieve the desired quality at the highest possible yield.

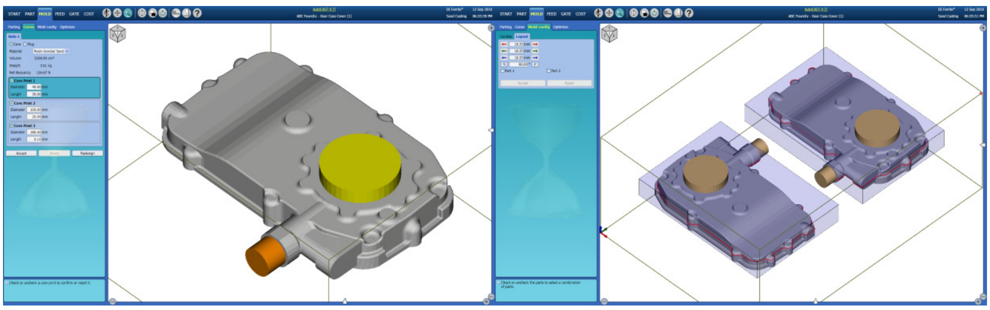

Fig.8: Tooling design: cores and cavity layout

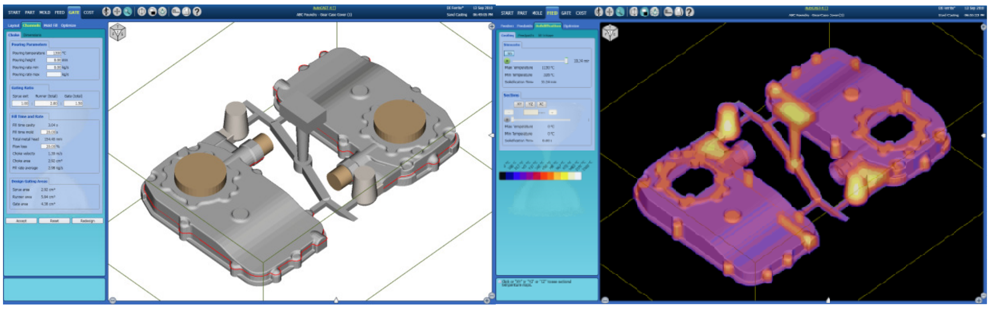

Fig.9: Methods design (feeders and gating) and casting simulation

Casting costs estimation includes tooling, direct metal, indirect materials (mold, core, feedaids, etc.), energy, labour and overheads [8]. This is very useful for comparing different layouts (combination of part, tooling and methods design) so as to select the most frugal one. The final tooling and casting for this example are shown in Fig. 10.

Casting process planning is carried out by modifying the plan for a similar casting retrieved from a database [9]. The actual process parameters are however, difficult to control, even in an automated foundry. Each casting manufactured during trials or initial batch production is indeed a research experiment, since none of the process parameters (like material composition and pouring parameters) can be held at exactly the same value for each casting. By recording the value of each process parameter, as well as the quality parameters of the resulting casting, a rich source of data is generated that can be mined to pinpoint the optimal and avoidable range of values of each process parameter.

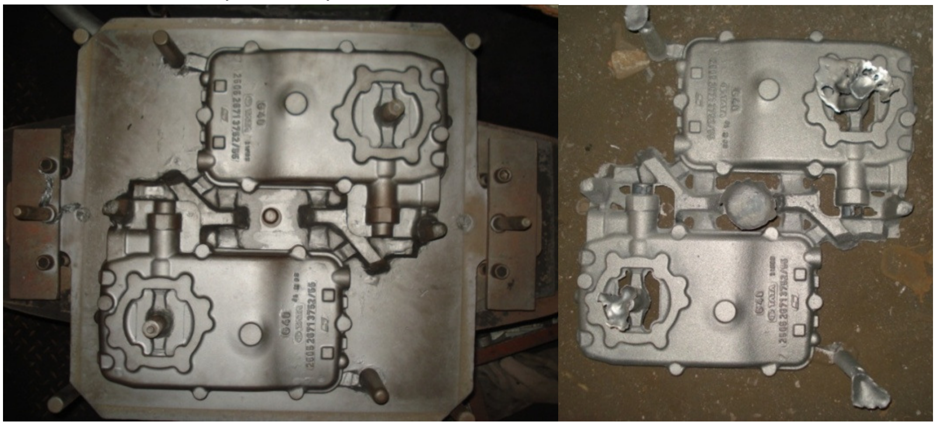

Fig.10: Actual tooling fabrication and casting with feeding and gating system

A web-based environment has also been built for product and foundry engineers to collaborate on a casting development project. Product engineers can upload the 3D CAD file of the casting design, which can be downloaded by foundry engineers for tooling and methods design. They can upload the project file back to the web site, and product engineers can view the simulation results to understand the location and cause of potential defects. They can make minor modifications to eliminate such defects. External consultants can also be involved to facilitate the DFM process.

5. Summary and Conclusion

Zero defect castings can be produced by collaborative design of part, tooling, methods and process parameters using a user-friendly system. At the part design phase, thickness checks enable preliminary evaluation of part manufacturability with respect to process capability. At the tooling design phase, parting line, cores and mold cavity layout can be semi-automatically designed and analyzed. The methods design includes semi-automatic design and 3D modeling of feeding and gating system, followed by mold filling and casting solidification, to predict quality issues more accurately (compared to part design phase). A cost model enables comparing alternative designs. Finally, process optimization is carried out based on the results of shop-floor trials.

The total lead time is minimized by suggesting good-first design parameters at each phase, thereby reducing the number of design iterations. The parameter values are obtained using analytical models available in literature, supported by empirical and phenomological models developed through our long association with Indian casting industry. These models are being continuously refined and improved based on industry feedback. The probability of occurrence of defects can be progressively reduced as the feedback from each phase is linked to product design. The need for very few inputs, coupled with the ease and speed of use, makes this technology eminently suitable for DFM applications by product engineers in OEM firms.

Thereis seamless flow of design data from preceding phases to subsequent phases, and feedback from each phase regarding quality and cost, back to part design. The entire approach has been implemented in such a manner that it can be used by part designers with very little process knowledge and casting engineers with only basic computer skills. The project data is securely stored and managed in a web-based system for access by casting lifecycle engineers. As a result, better collaboration between foundries and their OEM customers is made possible to achieve the desired quality and frugality.

In summary, the current approach to late DFM (that involves looking back, or hindsight) practiced in industry has to be transformed into early DFM (looking ahead, or foresight). Thus potential quality issues can be predicted early in product lifecycle, and prevented by suitable changes to design parameters. Casting DFM coupled with process control has the potential to achieve zero defects at the least cost. We welcome OEMs and foundries to test our system and collaborate toward further improvement. This work is throwing up many challenges that need a new generation of researchers to come and help the 'mother of all industries.'

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