IJSRD - International Journal for Scientific Research & Development| Vol. 2, Issue 10, 2014 | ISSN (online): 2321-0613

Optimization of Gating System and Minimization of Casting Defect based on Casting Simulation: A Review

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Abstract— Investment casting process is a manufacturing process to make complex geometrical parts of metal materials in mass production. But many times different defect occurs such as shrinkage cavity or porosity. These defects can be minimized by appropriate changes in gating parameters, such as gating system location, shape and size. Improving the casting gating systems based on design principle of gating system and casting simulation with the goal of improving casting quality such as reducing casting defects and increasing yield.

Key words: Casting, Gating system, Shrinkage Defect, Solidification Simulation

I. INTRODUCTION

Casting is a process which carries risk of failure occurrence during all the process of accomplishment of the finished product. Hence necessary action should be taken while manufacturing of cast product so that defect free parts are obtained. Mostly casting defects are concerned with process parameters. Hence one has to control the process parameter to achieve zero defect parts. For controlling process parameter one must have knowledge about effect of process parameter on casting and their influence on defect. To obtain this all knowledge about casting defect, their causes, and defect remedies one has to be analyze casting defects. Casting defect analysis is the process of finding root causes of occurrence of defects in the rejection of casting and taking necessary step to reduce the defects and to improve the casting yield. During the process of casting, there is always a chance where defect will occur. Minor defect can be adjusted easily but high rejected rates could lead to significant change at high cost. Therefore it is essential for die caster to have knowledge on the type of defect and be able to identify the exact root cause, and their remedies. [1]

The volumetric contraction accompanying solidification of molten metal manifests in defects like shrinkage cavity, porosity, centerline shrinkage, corner shrinkage and sink. These defects can be minimized by designing an appropriate feeding system to ensure directional solidification from thin to thick sections in the casting, leading to feeders. Major parameters of a feeding system include: feeder location, feeder shape and size, sleeves and covers, feeder neck shape and size, chills, and fins. The effect of these parameters on directional solidification by mapping the temperature gradients between the hot spot in the casting to the hot spot in the feeder.[2]

Casting simulation can minimize the wastage of resources required for trial production. In addition, the optimization of quality and yield implies higher value-addition and lower production cost, improving the margins. Simulation programs are fast, reliable, and easy to use. This has been achieved by integrating method design; solid modeling, simulation and optimization in a single software program, and automating many tasks that otherwise require computer skills. [3]

II. COMPUTER-AIDED CASTING DESIGN

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. [4]

The methods 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. 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). [4]

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. [4]

The mould cavity layout, feeders, and gating are automatically optimized based on quality requirements and other constraints. For mould cavity layout, the primary criterion is the ratio of cast metal to mould 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 mould material and reduced productivity. The program tries out various combinations of mould sizes and number of cavities to find the combination that is closest to the desired value of metal to mould ratio. [4]

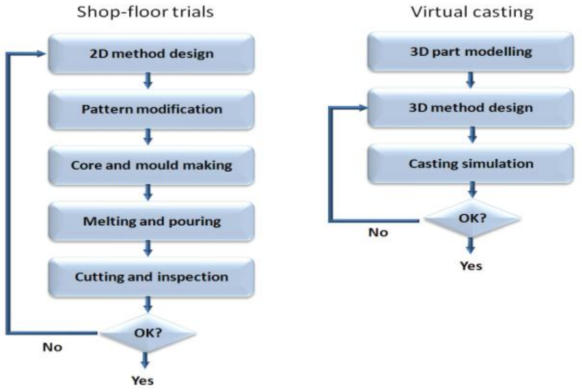

Fig. 1: Comparison of manual and computer-aided method optimization [7]

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. [4]

III. CASTING OPTIMIZATION FRAMEWORK

The proposed approach recognises three main events in casting process that affect its quality:

- The creation of a mould cavity,
- Leading molten metal into the cavity, and
- Allowing the metal to solidify.

The shape of the mould cavity is obtained by the design of mould pieces and cores, which are derived from the part geometry. The filling of mould cavity by molten metal is controlled by the design of gating channels and pouring parameters. The solidification of metal is controlled by the geometry of as cast part and feeding system (feeders and feed-aids). The parameters related to part, tooling/method and process are intricately woven with each other, and combine in different ways to affect casting quality and cost. The goal is to eliminate shop-floor trials, which consume valuable resources (material, energy, labour, and time), and yet do not provide sufficient insight to achieve consistent quality. [5]

The proposed framework for casting design and optimisation is shown in Fig. 1, comprising five stages:

- User inputs,
- Tooling/method design,
- Process simulation,
- Quality evaluation, and
- Cost estimation.

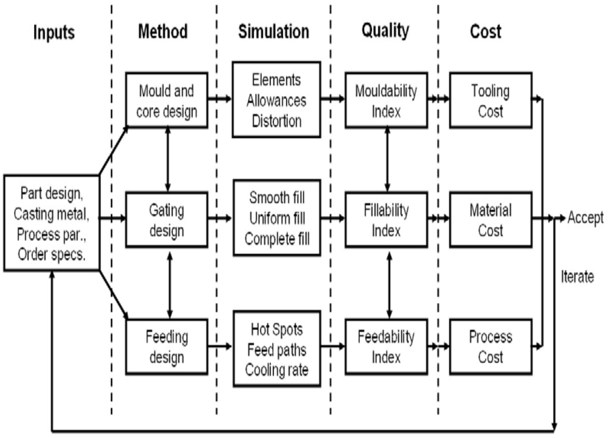

Fig. 2: Casting design, analysis and optimization framework [5]

It enables evaluating a particular design solution (set of part, tooling/method and process parameters), in terms of quality and cost, in a scientific manner. The use of an efficient simulation engine enables analysis of several different solutions to short-list those giving the desired quality. The incorporation of a cost model enables comparing alternative solutions to identify the most economical one. [5]

IV. CASTABILITY EVALUATION

The proposed framework includes automatic interpretation and evaluation of simulation results in terms of castability indices, which indicate specific problem areas and directions for improvement. This is inspired on our earlier work on castability analysis. Three new indices: mouldability, fillability, and feedability are proposed, corresponding to mould cavity creation, filling, and solidification, respectively. Each is evaluated using a set of criteria described here. The criteria are normalized to one, a higher value indicating better castability. [5]

A. *Mouldability*

The mouldability index primarily evaluates the geometric quality of the casting in terms of deviation from the designed shape. High mouldability implies minimizing the number of mould elements, applied allowances and distortion with respect to the part geometry.[5]

1) *Mould elements:*

Mould elements include mould halves, and cores, if any, to produce internal features and undercuts. The interface between each pair of mould elements is prone to displacement along one or more degrees of freedom (usually parallel and perpendicular to draw direction), creating dimensional errors in the cast part. The error is minimized when the number of mould elements N is one (ex. Investment casting shell), which are evaluated using the following equation:

$$M_{\text{ouldability elements}}=1/N^{0.5} \qquad - (1.1)$$

2) *Mould allowances:*

The application of draft on faces parallel to draw direction, machining allowance on mating or critical surfaces, and too high shrinkage allowance yields a mould cavity shape that is larger and inherently different from the designed part. The difference must be minimized to ensure casting weight is closer to the designed weight, and unnecessary machining is avoided. The criterion is evaluated in terms of the volume of the designed part V design and volume of the as-cast part V cast part (excluding the volume of feeders and gating).

$$C_{\text{Mouldability\_Allowance}} = (V_{\text{design}} / V_{\text{castpart}})^{4} \qquad - (1.2)$$

3) *Mould and core distortion:*

The casting shape may differ from the designed shape owing to another reason– distortion of mould elements during the process. The mould shape may distort owing to metallostatic pressure and graphite expansion (in grey iron). The cores may distort owing to buoyancy forces (especially in long horizontal cores with only one print support) and crushing at the interface of mould and core print (in sand casting). These are evaluated in terms of the average distance of movement of mould element with face area A through a distance d.

$$C_{\text{Mouldability\_Movement}} = [V_{\text{castpart}} / \{\Sigma_i (A_i \times d_i) + V_{\text{castpart}}\}]^{4} \qquad - (1.3)$$

B. *Fillability*

The fillability index indicates the quality of casting as affected by mould filling characteristics. High fillability implies smooth, uniform and complete filling to avoid filling-related defects such as cold-shuts and inclusions. [5]

1) *Filling smoothness:*

While it is well known that filling conditions in most castings are turbulent, any reduction in turbulence is welcome for minimizing erosion, oxidation, and inclusions. The criterion is written in terms of Reynold's number Re computed at the choke. Re is a function of metal properties: density ρ_{metal} and viscosity μ_{metal} (both at pouring temperature), and choke parameters: diameter d_{choke} and velocity v_{choke}. It is compared with the lowest value of Re for the onset of turbulence, taken as 2000.

$$C_{Fillability\_Smooth} = (2000 / Re)\ 0.5 \qquad -(1.4)$$

$$Re = \rho_{metal}\ v_{choke}\ d_{choke} / \mu_{metal} \qquad -(1.5)$$

2) *Filling uniformity:*

This is important for castings with symmetry in shape (ex. an axi-symmetric wheel, or a bracket symmetric about vertical plane), and for castings made in multi-cavity moulds. All symmetric portions of a casting (or all cavities in a mould) must start filling and end filling at the same instants of time to ensure similar conditions of filling and solidification. This minimizes variation in properties and (asymmetrically located) defects. The criterion is evaluated in terms of the maximum difference in filling start time τ of any pair of symmetric locations I and j (or cavities in a multi-cavity mould), by comparing it with the total filling time.

$$C_{Fillability\_Uniform} = 1 - (|\tau_i - \tau_j| / \tau_{total}) \qquad -(1.6)$$

3) *Filling completeness:*

Assuming adequate metal at sufficient superheat is available in the ladle for pouring into the mould, major reasons for incomplete filling are: (a) reduced fluidity of the metal as it loses heat while flowing through casting sections, and (b) back pressure due to entrapped air and gases. Both factors lead to longer filling time $\tau_{filling}$, which can be evaluated by comparing with the solidification time $\tau_{solidification}$.

$$C_{Fillability\_Complete} = 1 - (\tau_{filling} / \tau_{solidification}) \qquad -(1.7)$$

C. *Feedability*

The feedability index indicates casting quality as affected by solidification characteristics. High feedability implies absence of isolated hot spots in the casting, well-connected feed paths, and proper cooling rates, to avoid solidification-related defects such as shrinkage porosity and cracks. [5]

1) *Hot spots:*

A hot spot or temperature peak inside a casting is a potential location for shrinkage porosity, since it solidifies last, and there are no adjacent locations with liquid metal to compensate volumetric contraction 8 at the hot spot during its solidification. Each hot spot has to be eliminated by either attaching a feeder, or a chill. The criterion evaluates the number of hot spots N_h using the following equation.

$$C_{Feedability\_Hotspots} = 1 / (1 + N_h)^{0.5} \qquad -(1.8)$$

2) *Feed paths:*

Feed metal flows to a freezing region from an adjacent hotter region along the direction of maximum thermal gradient (perpendicular to local isotherm). The feed path stops when the gradient becomes zero. If the stopping location is inside the casting, then it leads to shrinkage or centreline porosity. Ideally, all feed paths must connect and end inside the feeders, indicating controlled directional solidification. The criterion is evaluated in terms of the (highest) temperature T_i at the end of a feed path, and its distance di from the nearest feeder or another feed path. These are compared with the highest temperature T_{feeder} in the last solidifying feeder, and the maximum size of the cast part $D_{castpart}$.

$$C_{Feedability\_Feedpaths} = 1 - [\max i\ (T_i \times d_i) / (T_{feeder} \times D_{castpart})]^{0.5} - (1.9)$$

3) *Cooling rate:*

High differential cooling rates between adjacent sections prevent feed metal flow (contributing to shrinkage porosity), and can lead to tears and cracks. This can occur in castings with differential wall thickness poured in metal moulds, or when chills are placed at a section between the casting and a feeder. The criterion is evaluated in terms of difference in solidification time τ of two adjacent sections i and j, and the distance d between them, normalized using the ratio of solidification time τ_{total} and maximum thickness t_{max} of the casting.

$$C_{Feedability\_CoolingRate} = 1 - [(|\tau_i - \tau_j| / d_{ij}) / (\tau_{total} / t_{max})] \qquad -(1.10)$$

An overall composite index of castability can be obtained by applying weights to the mouldability, fillability, and feedability criteria. [5]

V. FEEDABILITY ANALYSIS

Feedability implies every point inside the casting receives feed metal to compensate for solidification contraction. The most probable locations for shrinkage porosity inside a casting are characterized by high temperature, coupled with low gradient and low cooling rate. High temperature (could be a peak, a ridge or even a plateau) signifies fewer directions from where liquid metal can flow in to compensate for solidification shrinkage. Low gradient implies that even if liquid metal is available at a neighbouring region, there is insufficient thermal pressure for the flow to actually take place. Low cooling rate implies that all the neighbouring regions have solidified earlier consuming the feed metal from feeder and no feed metal is available for the region that has lowest cooling rate. Feedability analysis and improvement framework based on computation of temperature, gradient and cooling rate is therefore suggested for integrated product and method design (figure 3).[6]

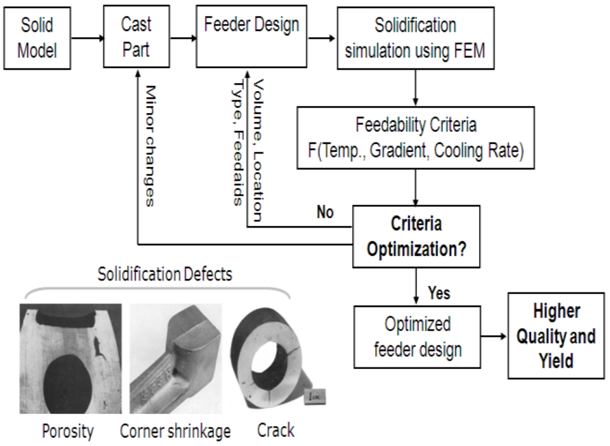

Fig. 3: Framework for feedability analysis [6]

Feedability score criterion is proposed for quantitative comparison of alternative part and method designs. Lower the temperature, higher the gradient, and higher the cooling rate better is the feedability score. Locations in casting that have higher feedability score will be less prone to shrinkage porosity defect. Critical locations in the casting that are prone to such defects can be thus evaluated by the feedability score criterion. [6]

VI. CONCLUSION

The application of computer aided methoding, solid modeling, and casting simulation technologies in foundries can able to minimize the bottlenecks and non value added time in casting development, as it reduces the number of trial casting required on the shop floor. The framework presented can be applied with any simulation software to assess the feedability of any product, process and method design. Such analysis done early during product design stage can help in evolving the most effective part, method and process resulting in higher yield with better quality.

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