

Part, Tooling and Method Optimisation Driven by Castability Analysis and Cost Model

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ABSTRACT

A high percentage of casting defects in jobbing foundries can be attributed to low compatibility between part requirements, tool/method design and process capabilities. These three must be optimized in integrated manner to achieve the desired quality at the least cost without shop-floor trials. For this purpose, we present a scientific approach comprising method design, process simulation, quality evaluation and cost estimation. Simulation results are evaluated using three quality indices: *mouldability*, *fillability* and *feedability*. Costing elements include tooling, material and process. An industrial case study is presented to illustrate the entire approach. Its greatest benefits are obtained during part design, when it is easy to make changes to ensure high compatibility between various parameters.

Keywords: casting, tooling, simulation, cost estimation, optimisation.

1. INTRODUCTION

Is it possible to achieve six-sigma quality in jobbing foundries? At first glance, the question appears absurd. It is common knowledge that rejections can be as high as 20-40% at casting stage, 10-20% at rough machining stage, and 5-10% at finish machining stage. This is especially true for entirely new castings being developed for the first time.

Foundries, and indirectly, their customers, continue to pay a heavy price for poor quality ¹. The immediate fallouts include loss of productivity (saleable castings per poured metal), and the cost of cutting and re-melting rejected castings. Defective castings supplied to the customer lead to wasted machining cost, and may have to be recalled (which involves avoidable transportation cost), or repaired (high labour cost).

On the other hand, six-sigma quality is regularly being aimed at and nearly attained in many sectors of manufacturing, including semi-conductors, forging, plastic injection molding, and sheet metal stampings. Defect levels of 100 parts per million (ppm), that is, 0.1% rejections are within reach in pressure die-cast parts during regular production.

The high incidence of defects in castings is traditionally attributed to poor process planning, monitoring, and control. But a more important reason is that part design, tooling development, and casting production are carried out by

different groups with little collaboration between them, leading to *poor compatibility* between respective parameters. A good combination of part and tooling/method design coupled with an appropriate process under control is inherently capable of producing zero defects ². This philosophy is further explored in this paper.

2. CASTING OPTIMISATION FRAMEWORK

The proposed approach recognises three main events in casting process that affect its quality: (1) the creation of a mould cavity, (2) leading molten metal into the cavity, and (3) 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.

The proposed framework for casting design and optimisation is shown in Fig. 1, comprising five stages: (1) user inputs, (2) tooling/method design, (3) process simulation, (4) quality evaluation, and (5) cost estimation. 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

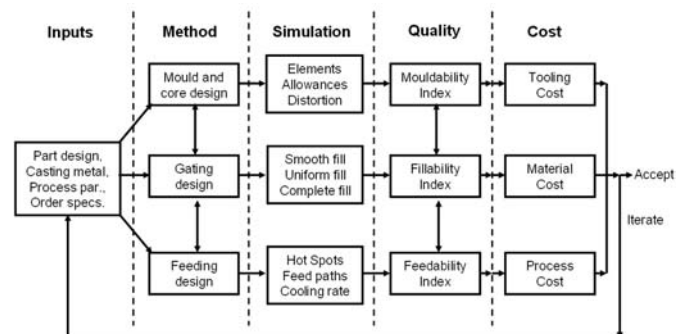


Fig. 1 : Casting design, analysis and optimization framework

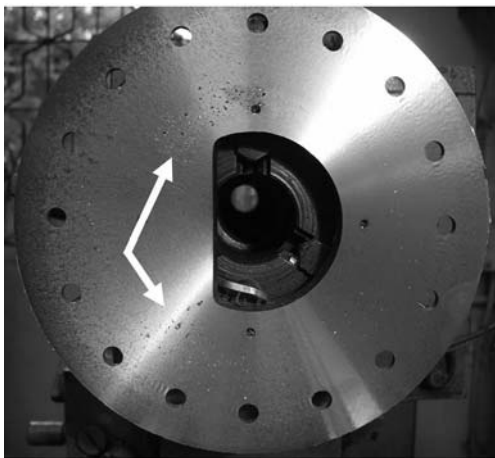


Fig. 2 : Aluminium alloy switchgear tank cover with shrinkage porosity.

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.

The various stages are described in detail in the following sections. They are illustrated using an industrial case study of an aluminium-alloy switchgear tank cover produced by gravity die casting (Fig. 2). The part size is 280 mm and weight is 6.1 kg. The existing design resulted in over 30% rejections (leakage) during pressure-test due to porosity in the flange area. We will show how the defects were minimised using the approach.

3. METHOD DESIGN AND SIMULATION

The method design and casting simulation is carried out using AutoCAST software program ³. The main inputs include: part model, casting alloy, and process. Method design involves three major tasks: (i) parting, mould and core design, (ii) feeder and feedaid design, and (iii) gating system design. Process simulation includes mould filling and casting solidification.

The parting line is generated to minimise undercuts and draw distance. The mould size is selected to provide sufficient gap

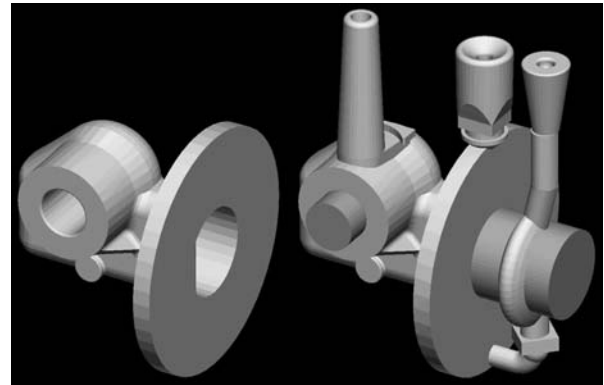


Fig. 3 : Method design and modelling (cores, feeders and gating system).

around the casting cavity. Holes are automatically recognised, and the corresponding cores (along with support) are designed to minimise failure by distortion and other modes. The above casting has a single connected hole, for which a core with two prints was created (Fig. 3).

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 fettling). Its dimensions are calculated based on geometric modulus of the region surrounding the hot spot. 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 also semi-automatically designed and modelled in a similar manner.

Gating system design includes deciding the number and location of gates, and designing the choke so that the mould fills in a predetermined range of time ⁴. The gate locations are suggested at thick sections along 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 program determines ideal filling time (function of casting weight, section thickness and fluidity), followed by choke velocity (based on metallostatic head), and choke area (using the gating ratio). Other process parameters are determined by comparing with similar previous projects ⁵.

The mould filling is simulated to determine the actual fill time and velocity of metal at different locations. It uses a layer-by-layer filling algorithm that considers the instantaneous velocity of metal through the gates (which depends on the head), and the area of casting cross-section being filled up. This approach is however, suitable for gravity processes only.

Casting solidification is simulated using the *Vector Element Method*, which traces the feed metal paths in reverse to pinpoint the location of hot spots ⁶. It is based on the principle that the direction of the highest temperature gradient

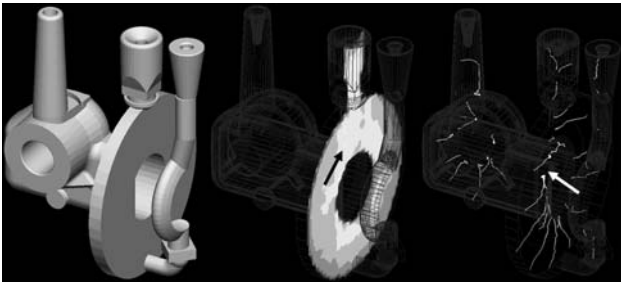


Fig. 4 : Casting simulation (temperature, feed paths) of existing design #1.

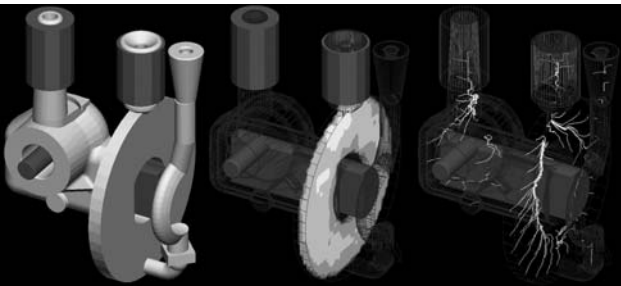


Fig. 5 : Simulation (temperature, feed paths) of improved design #2.

(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 the feed paths connect and converge inside a feeder.

For the above case study, the existing design (#1) used in the foundry was first designed and simulated (Fig. 4). This showed an inadequately fed region in the flange (isolated hot spots and arrested feed paths), matching with the observed location of shrinkage porosity. The design was improved (#2) without changing the die design, by adding insulating sleeves to feeders and chills inside cores (Fig. 5). Now the hot spot in flange disappears; feed paths converge and nearly touch the feeder. This design was implemented in practice, reducing the rejections to less than 6%.

For further improvement in quality, changes to tooling and part design also may be required. This requires proper interpretation of simulation results, and deciding the appropriate (cost-effective) design improvements. For this purpose, the engineer must have very good knowledge of simulation technology, coupled with method design and cost estimation experience: a rare combination indeed⁷. The following sections describe how this limitation can be overcome.

4. 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 analysis⁸. 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.

4.1 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.

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:

$$C_{\text{Mouldability_Elements}} = 1 / N^{0.5} \quad (1)$$

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_{castpart} (excluding the volume of feeders and gating).

$$C_{\text{Mouldability_Allowance}} = (V_{\text{design}} / V_{\text{castpart}})^4 \quad (2)$$

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 i with face area A through a distance d .

$$C_{\text{Mouldability_Movement}} = [V_{\text{castpart}} / \{ \sum_i (A_i \times d_i) + V_{\text{castpart}} \}]^4 \quad (3)$$

4.2 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.

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

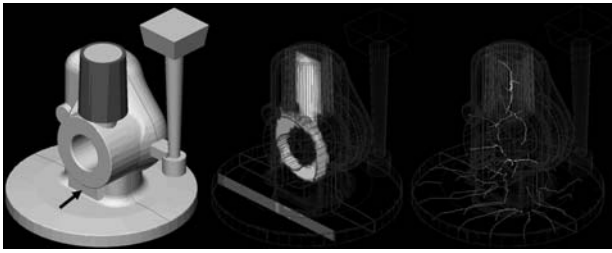


Fig. 6 : Casting simulation (temperature, feed paths) for final design #3.

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.

$$C_{Fillability_Smooth} = (2000 / Re)^{0.5} \quad (4)$$

$$Re = \rho_{metal} v_{choke} d_{choke} / \mu_{metal} \quad (5)$$

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 δ of any pair of symmetric locations i and j (or cavities in a multi-cavity mould), by comparing it with the total filling time.

$$C_{Fillability_Uniform} = 1 - (|\tau_i - \tau_j| / \Sigma\tau_{total}) \quad (6)$$

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 $\tau_{solidification}$.

$$C_{Fillability_Complete} = 1 - (\tau_{filling} / \tau_{solidification}) \quad (7)$$

5.3 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.

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 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.

$$C_{Feedability_Hotspots} = 1 / (1 + N_h)^{0.5} \quad (8)$$

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 centerline 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 d_i 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 $D_{castpart}$.

$$C_{Feedability_Feedpaths} = 1 - [\max_i (T_i \times d_i) / (T_{feeder} \times D_{castpart})]^{0.5} \quad (9)$$

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.

Table 1
Castability analysis of the three designs for cover casting.

#	Mouldability			Fillability			Feedability			Cost (in Rs, N=500)		
	Elements	Allowance	Distortion	Smooth	Uniform	Complete	Hot spots	Feed path	Cool rate	Tooling	Material	Process
1	0.71	0.58	0	0.42	0.23	0.46	0.41	0.65	0.60	413.9	880.2	83.7
2	0.71	0.58	0	0.42	0.23	0.46	0.71	0.68	0.80	413.9	887.6	65.1
3	0.71	0.58	0	0.45	0.69	0.46	0.71	0.75	0.89	303.7	895.2	57.1



$$C_{\text{Feedability_CoolingRate}} = 1 - [(|\tau_i - \tau_j| / d_{ij}) / (\tau_{\text{total}} / t_{\text{max}})] \quad (10)$$

An overall composite index of castability can be obtained by applying weights to the mouldability, fillability, and feedability criteria. In this paper, the importance of all criteria is considered equal.

5. COST ESTIMATION

The casting cost model⁹ comprises of equations to estimate the cost of tooling, material, and process, as given below. The various cost elements and factors, along with their units and values, are given in the appendix.

$$C_{\text{casting}} = C_{\text{tooling}} + C_{\text{material}} + C_{\text{process}} \quad (11)$$

$$C_{\text{tooling}} = C_{\text{simple}} \times f_{\text{complexity}} / N \quad (12)$$

$$C_{\text{simple}} = r_{\text{tooling}} \times W_{\text{casting}} \quad (13)$$

$$C_{\text{material}} = (r_{\text{metal}} \times W_{\text{castpart}} \times f_{\text{metal_loss}}) + C_{\text{consumable}} \quad (14)$$

$$C_{\text{process}} = C_{\text{moulding}} + C_{\text{melt_pour}} + C_{\text{fettling}} + C_{\text{other}} + C_{\text{energy}} \quad (15)$$

$$C_{\text{moulding}} = (W_{\text{sand}} / R_{\text{moulding}}) \times r_{\text{labour}} \times f_{\text{cast_rej}} \quad (16)$$

$$C_{\text{melt_pour}} = (W_{\text{casting}} / R_{\text{melt_pour}}) \times r_{\text{labour}} \times f_{\text{cast_rej}} \quad (17)$$

$$C_{\text{fettling}} = (W_{\text{casting}} / R_{\text{fettling}}) \times r_{\text{labour}} \times f_{\text{complexity}} \times f_{\text{cast_rej}} \quad (18)$$

$$C_{\text{other}} = (C_{\text{moulding}} + C_{\text{melt_pour}} + C_{\text{fettling}}) \times f_{\text{other_labour}} \quad (19)$$

$$C_{\text{energy}} = C_{\text{melt_energy}} + C_{\text{other_energy}} \quad (20)$$

$$C_{\text{melt_energy}} = r_{\text{energy}} \times E \times f_{\text{efficiency}} \times f_{\text{cast_rej}} \times f_{\text{metal_loss}} \quad (21)$$

$$E = W_{\text{casting}} \times (L + (s_{\text{avg}} \times T_{\text{tap}})) \quad (22)$$

$$C_{\text{other_energy}} = C_{\text{melt_energy}} \times f_{\text{other_energy}} \quad (23)$$

The tooling complexity factor $f_{\text{complexity}}$ indicates the increase in the cost of tool manufacturing compared to a simple shape (cube), in terms of surface area (longer machining time), and surface curvature (higher machine hour rate). This was 6.16 for design 1 and 2, and 4.93 for design 3.

6. RESULTS AND CONCLUSION

The castability evaluation and cost estimation for different designs of the tank cover casting are shown in Table 1. The order size is 500. The earlier design # 2 (in Fig. 5) exhibits higher feedability (fewer hot spots, better cooling rate), and reduced process cost. However, the poor filling uniformity in flange area prompted exploration of a different orientation of the casting, and padding of the area below the side hole, prone to high differential cooling rate (Fig. 6). This design (#3) required only one feeder, exhibited improved feed paths (lower temperature, better connection) and cooling rate.

Tooling and process costs decreased. The cost of a new die required to implement the new design will be offset by improvements in casting quality, productivity, and economy.

The method design, modelling, simulation, castability analysis, and cost estimation for each iteration took less than one hour on a standard computer (Pentium IV CPU, 1 GB RAM, Windows operating system). This was possible by integrating all tasks in a single system. During training sessions, it was found that even senior method engineers with only basic knowledge of computers were able to use the system within a single day of familiarisation. Thus this approach promises to break the entry barriers of using computer-aided casting technologies in even small and medium foundries. The system is applicable to all alloys cast by gravity processes. It can also be used by OEM engineers, at the product design stage itself, when it is easier to make changes to ensure the highest compatibility between product, tooling and method design. This will ensure 'foundry-friendly' casting designs, better appreciation of process limitations in achieving quality, and cost reduction through collaborative engineering.

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APPENDIX

		<i>Unit, Value</i>
C_{simple}	cost of tooling for a simple part of same volume	Rs.
$C_{consumable}$	cost of consumable materials (cores, feedaids, etc.)	Rs.
$C_{moulding}$	labour cost for mould and core-making	Rs.
C_{melt_pour}	labour cost for melting and pouring	Rs.
$C_{fettling}$	labour cost for cleaning and fettling	Rs.
C_{other}	labour cost for other tasks in casting	Rs.
C_{energy}	energy cost in casting process	Rs.
C_{melt_energy}	cost of melting and superheating the metal	Rs.
C_{other_energy}	total cost of energy other than melting	Rs.
$W_{castpart}$	weight of as-cast part (without feeders, gating)	Rs.
$W_{casting}$	weight of casting (including feeders, gating)	Rs.
r_{metal}	cost rate of metal (weight basis)	Rs.130/kg
$r_{tooling}$	cost rate of tooling (weight basis)	Rs.4000/kg
r_{energy}	cost rate of energy (per kwh)	Rs.3/kWh
r_{labour}	cost rate of labour (per unit time)	Rs.40/hr
$f_{complexity}$	tooling complexity factor	6.16,6,16,4.93
f_{metal_loss}	factor for metal loss in casting process	1.03
f_{cast_rej}	factor for casting rejection	1.35,1.05,1.01
f_{other_labour}	factor for labour required for other tasks	1.0
$f_{efficiency}$	factor for furnace efficiency	3.0
f_{other_energy}	factor for energy other than melting	1.0
$R_{moulding}$	production rate of moulding (weight basis)	-
R_{melt_pour}	production rate of melting & pouring (weight basis)	50 kg/hr
$R_{fettling}$	production rate of fettling (casting weight basis)	3000 kg/hr
E	energy required for melting	J
L	latent heat of fusion of metal	390 kJ/kg
s_{avg}	average specific heat of metal	1 kJ/kg.K
T_{tap}	tapping temperature of metal	700 C