7. Design for Castability

Castability implies ease of producing a casting, minimising cost, defects and lead-time. This is facilitated by high compatibility between product requirements and process capabilities. In this chapter, we review major design factors that influence castability and some methods for castability analysis.

7.1 Product Design and Castability

Three aspects of product design influence its castability: material selection, geometry planning and quality specification (Fig.7.1).

**Fig.7.1 Integrated product-process design for castability**

**Part material** is usually selected to satisfy the functional requirements of the product, based on mechanical, physical and chemical properties such as tensile strength, melting point and corrosion resistance. Cast metals are characterized by their casting properties such as pouring temperature, fluidity, volumetric shrinkage during solidification and slag/dross formation tendency. These influence the casting quality in terms of dimensional stability and internal integrity.

**Part geometry** directly affects the complexity and number of tooling elements (pattern and cores) and therefore their cost. The location of the parting line depends on the extent of undercuts, which in turn depends on internal features in the part. Part geometry also influences progressive directional solidification (from thin to thicker to thickest regions), which governs internal integrity. Long thin sections are difficult to fill. Critical surfaces (to be machined) can be planned in drag section of the mould to ensure a dense and smooth casting sub-surface free from any inclusions. Similarly, visualizing the cleaning of a casting helps in avoiding breakage of fragile sections of heavy castings, by adding a rib or some other means to provide additional strength. For heavy parts, lifting arrangements can be provided to facilitate handling during machining, assembly and shipping.
Quality specifications include defect-free surfaces, internal soundness (often pressure-tightness), dimensional accuracy and the desired surface roughness. Some of the major defects that lead to rejection include macro shrinkage, cracks, blowholes, gas porosity, sand/slag inclusions and cold shuts. Other defects, such as micro-porosity (in non-critical sections), dimensional inaccuracy and rough surface will lead to rejection only if quality specifications are stringent. ‘Problem’ features such as excess rib thickness, inadequate fillet radius, narrow holes and tight tolerances are quite common in cast components, which result in high percentage of defects and avoidable labour costs for repair work. Specifying a particular quality testing method (such as radiography and pressure testing) should be justified for the desired quality level, which will otherwise increase the manufacturing cost.

In general, problems discovered during manufacturing stage can be difficult to fix and expensive; it is much easier to prevent such problems by minor modifications to product or tooling design. The solution is in close collaboration between product, tooling and foundry engineers starting from concept design stage (Fig.7.2).

7.2 Process-Friendly Design

The product design affects the design of tooling and selection of process parameters, which in turn affect the product quality, lead-time and the total cost. The casting quality is indicated by percentage rejections in foundry (at casting, fettling and inspection stages), during machining and during actual use. The lead-times for sample casting development as well the productivity (cycle time) during regular manufacture are equally important. The total cost comprises the cost of materials, tooling (amortized) and manufacture (mainly energy, labour and overheads). The energy cost is significant and directly affected by casting yield. A casting design is said to be process-friendly if it is relatively easy to manufacture, implying faster development, lower tooling cost, lower energy requirement and minimal rejections. Here are a few major guidelines to improve castability.
**Part complexity**: An intricate shaped part – with contoured surfaces, thickness variations and internal features – is more economical to produce by casting than any other process. It is however, always possible to reduce the cost by simplifying the product shape. The shape complexity criterion can be expressed by a combination of three different dimensionless equations, which have to be maximized to improve castability:

(a) The ratio of part volume to the volume of its bounding box: \( V_c / (a \times b \times c) \), where \( V_c \) is the part volume and \( a, b \) and \( c \) are its dimensions along three orthographic axes.

(b) The ratio of surface area of a cube of equal volume to the surface area of the cast part, given by: \( 6(V_c)^{2/3}/A_c \), where \( A_c \) is the surface area of the cast part.

(c) In terms of the number of features: \( 1/(1+n_f)^{0.5} \) where \( n_f \) is the number of features (hole, pocket, slot, boss, rib, etc).

**Parting line**: Besides part complexity, the various factors related to parting line design also greatly affect tooling cost. A non-planar parting line must be avoided. This implies designing the product considering a particular draw direction, minimizing undercuts and tapering the sections parallel to the draw direction to provide natural draft. Critical surfaces (if any) that have to be machined must be designed at the bottom of the casting to avoid inclusions (or higher machining allowance) on them.

**Cored Features**: Cores enable internal features (through holes, undercuts and intricate or special surfaces) to be produced in a cast product. Indeed, it would be impossible to create a complex curved hole (as in a pump or compressor casing) without dispensable cores. However, every cored feature adds to the tooling and production cost. Cores may also lead to defects related to mould filling (blow holes) and casting solidification (hot spots). The product designer must minimize the number of holes and reduce their complexity to the extent possible. The criteria related to cored holes include its minimum diameter, aspect ratio, location in a thick section, distance from edge and distance from a neighboring hole.

**Filling characteristics**: The part must be designed to minimize turbulence during filling and to promote complete filling of all sections.

Turbulence can be minimized by avoiding sudden variations in section thickness and sharp corners. This implies generous fillets to all internal as well as external corners. A tapered section may be used to connect two sections of different thickness.

Complete filling can be ensured by avoiding long thin sections in a casting, especially those far from the most suitable location of ingates. Thin annular sections, around which molten metal stream separates and again meets on the other side must also be avoided, since this may cause a cold shut or misrun.

**Solidification characteristics**: There are mainly two considerations: minimizing isolated hot spots and promoting controlled progressive directional solidification.

Isolated hot spots occur in regions of high modulus surrounded by regions of lower modulus. High modulus may be due to higher volume and/or lower heat transfer area. Examples include: boss on an annular section, near a thin core in thick section, small fillet radius at internal edge (or corner) where two (or three) sections meet, sections between two or more cores close to each other, and poorly designed junctions (Fig.7.3). The
parameters of a junction include the number of meeting sections, their thickness (absolute and relative), angle between them and fillet radius. For example, in a T-junction caused by a rib, the rib thickness must be about half of the connected wall thickness, and the fillet radius must be about 0.3 times the wall thickness. In a L-junction, the fillet at inner corner must be about 0.5 times the wall thickness (Fig.7.4).

Fig.7.3: Alphabet of junctions: from worst (*) to best (C)

Fig.7.4: Correct radius at a corner for minimising shrinkage porosity

Progressive directional solidification is achieved by gradual variation of section thickness from end sections (that solidify first) to thickest sections (that solidify last). The last solidifying sections must be designed such that feeder can be easily connected to them (at the top or side), can be easily fettled (there must be no obstruction and the section must not break), and easily finished (preferably a flat surface to connect the feeder). If the feeder is connected to a thin section that is in front of a last solidifying region, then the thin section may solidify too early and prevent feed metal from reaching the hot spot.

7.3 Castability Analysis

There are three major approaches for castability analysis: process simulation, parametric cost estimation and features-based castability checks. Based on the results of analysis, the product design can be modified (while conforming to its functional requirements) and analysed again until the targeted quality and cost are achieved.
Casting simulation: This includes mould filling, solidification, grain structure, stresses and distortion. It requires solid models of product and tooling (parting, cores, mould layout, feeders, feedaids and gates), temperature-dependent properties of part and mould materials, and process parameters (pouring temperature, rate, etc.). The simulation results can be interpreted to predict casting defects such as shrinkage porosity, hard spots, blow holes, cold shuts, cracks and distortion. The inputs however, require considerable expertise and may not be easily available to product designers. One solution is to involve tooling and foundry engineers in the product design stage, and evolve the product, tooling and process designs simultaneously, ensuring their mutual compatibility with each other. This approach is referred to as concurrent engineering.

Casting cost estimation: Several parameters related to the design of the part, tooling and process directly influence the cost of the final casting. This includes part metal, weight, shape complexity, number of holes, type of parting line (flat, stepped or complex), number of feeders, yield, metal to sand ratio, number of other elements in the mould (feedaids, filters, etc.), quality specifications (dimensional accuracy, surface roughness and internal soundness), tooling material, production quantity and lead-time desired. The cost coefficients are determined by regression analysis based on past data. The past data must be sufficient (number of cases), complete (all parameters available) and correct (adjusted with respect to the current date). The coefficients must be continuously updated to adjust for the current rates of material, labour and energy. The cost estimation equation can be used to assess the product design as well as to explore ‘what-if’ design modifications to reduce the cost. This method is however, accurate only for castings similar to the previous cases in terms of overall geometry, part metal and casting process.

Castability guidelines and checks: Several guidelines are available in technical literature and also documented in companies based on past experience in facing and solving common problems related to casting. The guidelines are illustrated by a pair of examples, one showing the problem situation and the second showing a possible solution. A few illustrated guidelines, showing a castability problem and its solution are given here (Fig.7.5-7.8).

<table>
<thead>
<tr>
<th>Parting Flatness</th>
<th>Undercuts</th>
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<tr>
<td><img src="image1" alt="Parting Flatness Image" /></td>
<td><img src="image2" alt="Undercuts Image" /></td>
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**Problem:** Non-planar parting line requires more complex tooling, leading to higher costs and lower dimensional accuracy of product.

**Suggestion:** Modify part design to allow a flat parting between mold segments.

**Problem:** Undercut features (with respect to the parting) need cores, resulting in higher tooling and production costs.

**Suggestion:** Modify part design to allow a flat parting between mold segments.

*Fig.7.5 Design guidelines for parting and undercuts*
Fig. 7.6 Design guidelines for cores

<table>
<thead>
<tr>
<th>Core Size</th>
<th>Core Aspect Ratio</th>
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<td>![Core Size Diagram]</td>
<td>![Core Aspect Ratio Diagram]</td>
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- **Problem:** Hole diameter is very small and is surrounded by heavy section, leading to possible hot spots and core material fusion.
- **Suggestion:** (1) Increase the hole diameter; (2) eliminate the hole (drill instead); (3) reduce section thickness around the core.
- **Problem:** Hole length to diameter ratio is very large, leading to possible dimensional quality problems or even core failure.
- **Suggestion:** (1) Increase the hole diameter; (2) provide additional supports if possible.

Fig. 7.7 Design guidelines for solidification and feeding

<table>
<thead>
<tr>
<th>Wall Thickness Ratio</th>
<th>Feeding Efficiency</th>
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<td>![Wall Thickness Ratio Diagram]</td>
<td>![Feeding Efficiency Diagram]</td>
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- **Problem:** Ratio of the thickness of largest section to smallest section is high, resulting in potential hot spots which need careful design of feeding.
- **Suggestion:** Make the thickness of various sections as uniform as possible.
- **Problem:** Feeder volume is much higher compared to the actual requirement of feed volume.
- **Suggestion:** Connect more than one casting to the same feeder or choose a smaller feeder with feeding aid.

Fig. 7.8 Design guidelines for mould filling and gating

<table>
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<tr>
<th>Thin Sections</th>
<th>Fettling of Gating</th>
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<tr>
<td>![Thin Sections Diagram]</td>
<td>![Fettling of Gating Diagram]</td>
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- **Problem:** Very thin and long sections are difficult to fill, leading to incomplete sections.
- **Suggestion:** Increase the section thickness or reduce its length.
- **Problem:** Gate size is comparable or more than connected portion of the casting, which may cause fettling problems.
- **Suggestion:** Connect the gates to thick sections of the casting.
The geometric information related to casting features can be used to carry out simple ‘health-checks’ that indicate potential problems. Casting features can be classified as base feature (rectangular, cylindrical, spherical, torus, etc.), form feature (hole, pocket, slot, boss, rib, etc.), tooling feature (undercut, parting line, core, ingate, feeder, feedaid, etc.) and feature modifier (taper, chamfer, fillet, etc.). Information about each feature (dimensions, location and orientation) and relation between features (parent, child, similar, neighbour, etc.) is required. The castability health-checks can be formulated as criteria to be maximized. For example, a rib feature may be checked for its thickness with respect to the section to which it is connected. The coefficients, if any, in the criterion equation (for example, ideal ratio of rib to wall thickness) depend on the metal-process combination. These have to be derived from past experience. Weights may be attached to the criteria to reflect their relative importance. The castability index of a given casting design is given by the weighted sum of all criteria assessments.

All of the above three methods provide a quantitative assessment of the castability of a product design. Process simulation and parametric costing indicate the expected quality and cost of the product, respectively, in absolute terms. Both require detailed inputs about the product, tooling and process, and can be used only after these designs are complete. On the other hand, features-based castability checks indicate potential problems in relative terms. They are easy to set up and can be triggered during concurrent design of product, tooling and process. In general, feature-based checks can be used first to arrive at an initial good design, then verified by process simulation to ensure defect-free a casting, and finally a parametric cost estimation can be carried out to check if the design meets the target cost.

Exercise 7.1: Suggest design modifications for the bracket casting considering (a) reduction of number of cores without using a stepped parting, (b) smoother flow with reduced turbulence, (c) reduced solidification shrinkage and improved yield.

Solution: The design modifications are given below in Fig.7.9 and 7.10.

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**Fig.7.9** Left-original bracket, right- rib relocated to reduce coring
Fig. 7.10 Left-fillets added for smooth flow, right-smaller wall to reduce porosity