3. Pattern, Mold and Core Design

The most important decision in pattern and mold design is about the parting line. It affects and is affected by part orientation, design of pattern and cores, number of cavities in the mold, location of feeders, and channels for gating, cooling and venting. In this chapter, we will first develop a scientific definition of parting line, followed by the design of parting line, pattern, mold cavities and cores.

3.1 Parting Line Design

The parting or separation between two or more segments of a mold is necessary to create the mold cavity (as in sand casting) and also to remove the manufactured part from the mold (as in diecasting).

For any given casting geometry, a number of parting alternatives may exist; visualizing and selecting the best alternative is a non-trivial task even for simple shapes. Variations in customer requirements, quality specifications, manufacturing facilities and economical considerations may lead to different parting solutions for the same shape. For intricate parts, there is a high possibility of overlooking feasible alternatives and difficulty in assuring that the selected alternative is the indeed the best one.

To evolve a scientific approach to parting line design and analysis, unambiguous definitions of parting and related features are required, valid for all types of tooling being considered. The following definitions are proposed.

Mold segment is a distinct body, at least one face of which is in contact with the casting.

Draw direction of a mold segment is the direction along which it is withdrawn from the adjacent mold segment.

Parting surface is the surface of contact between any two segments of the mold.

Parting line is the contour of intersection of a mold parting surface with casting surface.

Parting surfaces may be classified based on the type of mold segments at the interface. Considering three types of mold segments: cope, drag and cores, we have cope-drag, cope-core, drag-core and core-core parting surface. In practice, only cope-drag interface is referred to as the parting surface. The cope-core and drag-core interfaces correspond to the portions of mold that support a core. The core-core interface is encountered in core assemblies. The interfaces between the segments of a three-part mold (cope, cheek and drag) can be treated similar to those in a two-part mold.

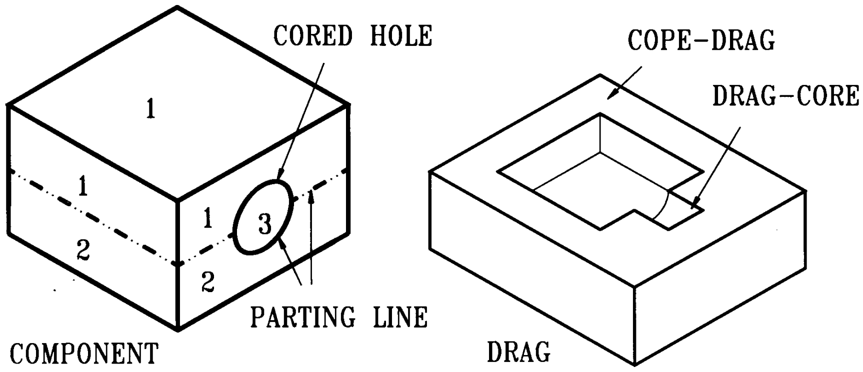

Fig.3.1: Parting line is the contour of intersection of mold parting surface (cope-drag or mold-core) with part surface.

Parting lines may be classified based on the number of planes in which the different segments of the parting line lie. A flat parting line lies entirely in a single plane. A stepped parting line lies in two planes, one of them normal to the draw direction. The segments of a complex parting line lie in multiple planes.

Characteristics of a parting line include the following:

1. Parting line divides the part surface into separate regions each produced by a different mold segment.
2. Parting line coincides with the projected boundary of the casting when viewed along the draw direction
3. The internal angle at the parting line is less than 180 degrees.
4. Parting line coincides with part of the bounding line of a parting surface.
5. Flash appears along the parting line.

Parting line identification: The first step in parting line design is to select an appropriate draw direction. One set of alternatives for the draw direction is provided by the centerlines of the minimal bounding box of the casting. Other alternatives are given by the direction of normal to large faces in the casting.

The criteria for selecting the most suitable draw direction include (in decreasing order):

1. Minimize undercuts (number and then volume of cores)
2. Minimize the total draw distance (for both halves)
3. Minimize draft allowance (volume increment).

The parting line can be identified using its characteristic that it coincides with the projected boundary of the casting when viewed along the draw direction. The edges of the casting are first projected on to a plane perpendicular to the draw direction. The inner segments of the projected edges are ignored and the outermost perimeter (silhouette boundary) is determined. This is projected back to the casting and the corresponding landing points are determined. These points are connected in sequence to form the parting line. If multiple landing points occur (say, along edges parallel to the draw direction) then multiple alternatives of parting lines are available for selection. Depending on the shape of the component, the above method can generate flat, stepped or complex parting lines.

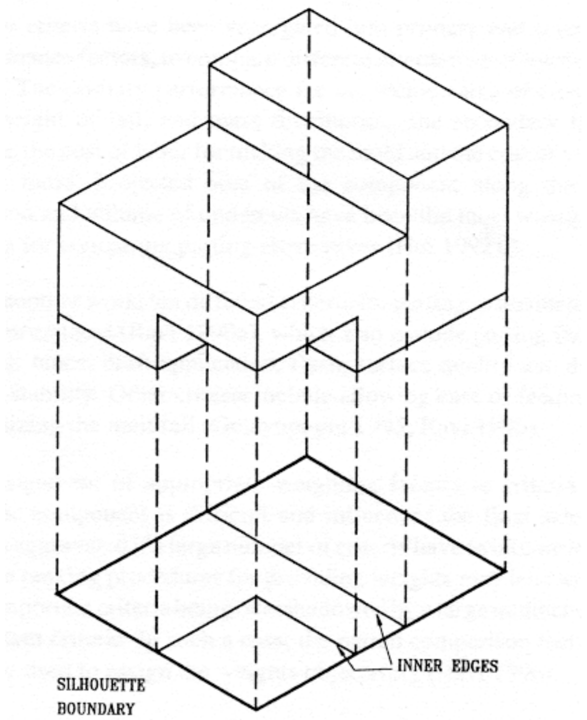

Fig.3.2: Parting line generation by back-projection of part silhouette.

3.2 Parting Line Analysis

When multiple alternatives are available, then the most suitable parting line is the one that optimizes a set of design criteria. The criteria are geometrical functions of feature parameters related to parting. They are dimensionless and return a value between 0 and 1, a higher value indicating better quality, economy or productivity. Important criteria are described below (refer to Table 3.1 for the corresponding equations).

Undercuts increase the number of elements in the mold; also the cost of a core for producing a particular feature is significantly higher than an ordinary mold of equal volume. Ideally, undercuts should be absent and the criterion evaluates to one.

Flatness criterion measures the closeness of a given parting to a flat plane by comparing the projected length of the parting line on a plane perpendicular to the draw direction with its actual length. A flat parting evaluates to one and is considered ideal. A non-planar parting increases the complexity of the tooling and should be avoided if possible.

Draw distance is the relative movement between a mold segment and the pattern (or product) along the draw direction until they are clear of each other. It affects the manufacturing cycle time and the uniformity of compaction in the case of sand molds. To evaluate the draw distance corresponding to a given parting, it is compared to the ideal minimum, which is half the smallest overall dimension of the product.

Draft applied to faces parallel to draw direction to ease the withdrawal of pattern or product from the mold results in either increased weight of the product or cost of machining the additional volume. A parting line which does not have large faces parallel to draw direction is preferred.

Flash criterion returns a higher value if the parting line is located along convex or sharp edges of the component, since this helps in trimming the flash. All edges belonging to the parting line are used in evaluating this criterion.

Mismatch between mold segments affects faces which lie on both sides of the parting line. The areas of the two portions of such faces are compared with the total area of the face to evaluate the mismatch criterion. It returns a high value if such faces lie to one side of the parting line, indicating high dimensional stability.

Mold cavity shape similar to a rectangular pocket not only conserves mold material but is also easier to manufacture. This aspect is measured by the volume ratio of the solid corresponding to the cavity in a particular mold segment and the bounding cuboid. The sides of the cuboid are either parallel or perpendicular to the draw direction.

Sub-surface quality is important for critical or machined faces of a component. It is affected by the orientation and location of such faces in the mold. The choice of draw direction and the casting orientation which results in critical surfaces being placed at the bottom of mold, yielding high sub-surface quality at these places, is preferred.

Solidification characteristics of a casting as influenced by its orientation are assessed by this criterion. It considers the ratio of the largest to the smallest section in the casting, and the height of the largest section from the mold bottom. Top heavy castings are favored, since this aids in directional solidification and facilitates placement of feeders at the top.

Side thrust may occur in permanent molds filled under pressure if the parting is non-planar and asymmetric about a vertical plane. The criterion for side thrust indicates the extent of force unbalance along one of the horizontal axes.

The score S_j of the j^{th} parting alternative is given by: $S_j = \sum_i w_i C_{ij}$

where, w_i = weight of i^{th} criterion and C_{ij} = assessment of i^{th} criterion for j^{th} parting alternative.

Table 3.1 Parting design criteria

CRITERION	FUNCTION	PARAMETERS
Undercut	$\frac{1}{1+N_C}\left(1-\frac{\sum_i V(C_i)}{V(D)}\right)$	N_C = number of cored undercuts $V(C_i)$ = volume of core *i* $V(D)$ = volume of component
Flatness	$\frac{\sum_i (\lvert \bar{e}_i \rvert \sin\theta_i)}{\sum_i \lvert \bar{e}_i \rvert}$	$\bar{e}_i$ = edge *i* of parting line θ_i = angle between $\bar{e}_i$ and draw direction
Draw distance	$\frac{0.5 d_{\min}}{\max_i (d_i)}$	d_i = distance of withdrawal of mold segment *i* d_{min} = smallest overall dimension of part
Draft	$1-\frac{\sum_i A(f_i)}{A(D)}$	$A(f_i)$ = area of face f_i ‖ draw direction $A(D)$ = surface area of component
Flash	$1-\frac{\sum_i 0.5(1-\cos\alpha_i)\lvert \bar{e}_i \rvert}{\sum_i \lvert \bar{e}_i \rvert \sin\theta_i}$	$\bar{e}_i$ = edge *i* of parting line α_i = internal angle between faces at $\bar{e}_i$ θ_i = angle between $\bar{e}_i$ and draw direction
Mismatch	$\frac{\max[\ \sum_i A(f_i^1), A(f_i^2)\ ]}{\sum_i A(f_i)}$	$A(f_i)$ = total area of face f_i $A(f_i^1)$= area of f_i in first mold segment $A(f_i^2)$= area of f_i in second mold segment
Mold shape	$\min_i \left(\frac{V(M_i)}{V(B_i)}\right)$	$V(M_i)$ = volume of cavity in mold segment *i* $V(B_i)$ = volume of bounding cuboid for M_i
Surface quality	$1-\frac{\sum_i 0.5(1+\bar{n}_i.\bar{z})A(f_i)h_i/h_m}{\sum_i A(f_i)}$	$\bar{n}_i$ = unit normal to critical face f_i $\bar{z}$ = vertical direction h_i = height of f_i from mold bottom h_m = vertical dimension of component
Solidification	$\frac{d_{\min}}{d_i}+\left(1-\frac{d_{\min}}{d_i}\right)\left(\frac{2h_i}{h_m}-1\right)$	d_i = dia of largest inscribed sphere S h_i = height of center of S from mold bottom d_{min} = dia of smallest inscribed sphere h_m = vertical dimension of component
Side thrust	$1-\frac{\sum_i (\bar{e}_i \times \bar{s}_i).\bar{x}}{\sum_i \lvert \bar{e}_i \rvert}$	$\bar{e}_i$ = edge *i* of parting line $\bar{s}_i$ = edge of parting surface connected to $\bar{e}_i$ $\bar{x}$ = x axis

3.3. Pattern Design

A sand casting pattern is similar in shape to the cast product (but not exactly the same). A sand mold cavity is a negative replica of the pattern and is produced by packing sand around the pattern. Mathematically, pattern design can be treated as a series of transformations starting from the product shape to finally obtain the shape corresponding to the mold cavity. The transformations are briefly described here.

$$[\text{Pattern}] = [T_{hole}]\ [T_{shrinkage}]\ [T_{machining}]\ [T_{distortion}]\ [T_{draft}]\ [T_{fillet}]\ [\text{Product}]$$

Eliminating holes: All holes that are produced by cores are removed from the product. Since the pattern must also produce the pockets for seating the cores, the core support geometry must be added to the product shape. This implies that the cored features must be identified, followed by the design of their support in mold (core print). Then the volume corresponding to the entire core (including its print) is to be ‘added’ to the part geometry to obtain the pattern shape.

Shrinkage allowance: To compensate the solid phase contraction of the casting. The part dimensions are increased by a certain amount, depending on the cast metal and type of mold. It ranges from 13 mm/m for aluminum alloys, 16 mm/m for copper alloys and 20 mm/m for grey iron. Note that the casting shrinks away from the mold wall, implying that while external dimensions must be increased, internal dimensions (ex. hole diameter) must be decreased.

Machining allowance: It is provided on surfaces that are machined later. It involves adding material to part surface along the direction of its normal. The amount of addition depends on the dimensional tolerance achieved by the process, sub-surface quality, part size and the type of machining (manual or automatic). The allowance ranges from 1 mm for small aluminum diecast parts to 20 mm or more for large grey iron sand cast parts.

Draft: All faces of the product that are parallel to the draw direction are provided a draft angle to facilitate withdrawal. The draft angle depends on the distance of the face from the mold parting, length of the face along the draw direction, type of face (external or internal), mold surface roughness (surface finish and application of lubricants) and the type of molding/casting process (manual or automatic). It ranges from 0.5 degree for small external faces close to parting line in automated diecasting machines, to 3 degrees or more for large internal faces in manual molding for sand casting process.

Fillets: All sharp corners must be rounded to facilitate molding and filling. While the product designers regularly provide fillets, these may not be adequate, especially in sand casting process. Too generous fillets are also not recommended, especially when only the internal corner is filleted and the opposite external corner is sharp, since this may lead to local hot spots and shrinkage porosity defect. In general, a fillet radius of 0.3-0.6 times the wall thickness is recommended.

The allowances can be combined in different ways to minimize the increase in casting volume (compared to the product volume). A fillet to a small rib along the draw direction eliminated the need for draft. A vertical face far from the parting plane, for which ample draft has been applied, may require less machining allowance.

3.4. Core Identification

Core is a separate entity placed in a mold to produce a corresponding cavity – hole or undercut – in the casting. Cores are also used for producing complex shaped pockets and special features (for example, a vertical face without draft) that cannot be produced using a pattern or mold alone.

Cores may be dispensable (in sand casting) or permanent (in die casting). In gravity diecasting, either permanent or dispensable cores may be used, usually decided by the core shape – simple or complex, respectively.

A core consists of two portions: the body of the core and one or more extensions (called prints). The body of the core is surrounded by molten metal during casting process. A core has to withstand more heat and for a longer duration than the mold. However, once the casting has cooled, a sand core must easily collapse to facilitate its cleaning out. The prints are necessary to support the core in the mold. They also conduct the heat (and gases produced by a sand core) to the mold.

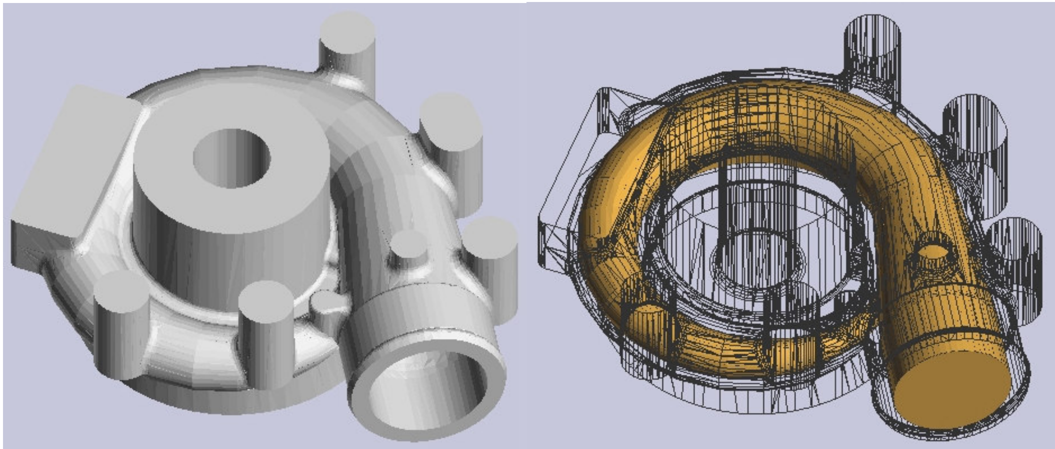

Fig.3.4: Gravity diecast compressor casing and its core

Cores for sand casting are manufactured by packing specially prepared sand in coreboxes. Core-making processes include oil sand, hot box and cold box, which are suitable for different types of applications. The cavity in a corebox is a negative replica of the corresponding part feature. The corebox is made in two segments (with a parting) to enable removal of the core. Complex cores are prepared by assembling or gluing two or more cores of simpler shapes. The core-related activities: sand preparation, core shooting, coating/treatment and placement in mold, consume significant resources. Thus the number and volume of cores must be minimized to the extent possible, to reduce tooling cost and manufacturing time.

Cored holes – through and blind, can be automatically identified by geometric reasoning. Undercuts can be identified based on the direction of face normal with respect to the draw direction of mold segments. This is explained in detail next.

A simple yet robust feature recognition methodology can be developed based on Boundary Representation of solid models. Let the part model be completely defined by a set of bounding *facets*, each facet by three *edges* and each edge by two *vertices*. Each facet is also associated with a unit normal vector that points from interior (solid) to exterior (space). The right-hand thumb rule applies to the face normal with respect to the three vertices of the facet. The model conforms to Euler's equation: $F+V = E+2$, where F, E and V are the number of facets, edges and vertices, respectively.

Edge Classification: The edges of the part model can be classified depending on the internal angle between the two adjacent faces that share the edge. If the angle is exactly 180 degrees, then it is a *smooth* edge, implying that the two adjacent facets are in the same plane. If the angle is less than 180 degree, then it is a *convex* or external edge; otherwise it is a *concave* or internal edge.

Hole Recognition: A depression feature (hole or pocket) can be defined as a set of faces each of which have at least one concave edge, and the opening of the feature comprising a closed loop of convex edges. The number of openings may be one (blind hole), two (through hole) or more. The openings are closed and the negative space corresponding to the feature is converted to a positive space to create the body of the core.

Undercut Recognition: Facets belonging to the interface between a pair of bodies being withdrawn from each other are tested for undercut condition. The bodies can be pattern and dispensable mold, part and permanent mold or permanent core and mold. If the angle between a facet normal and the draw direction of the body containing the facet is less than 90 degrees, then the face forms an undercut. The body of the core corresponding to the undercut feature can be created by extending the faces adjacent to the undercut.

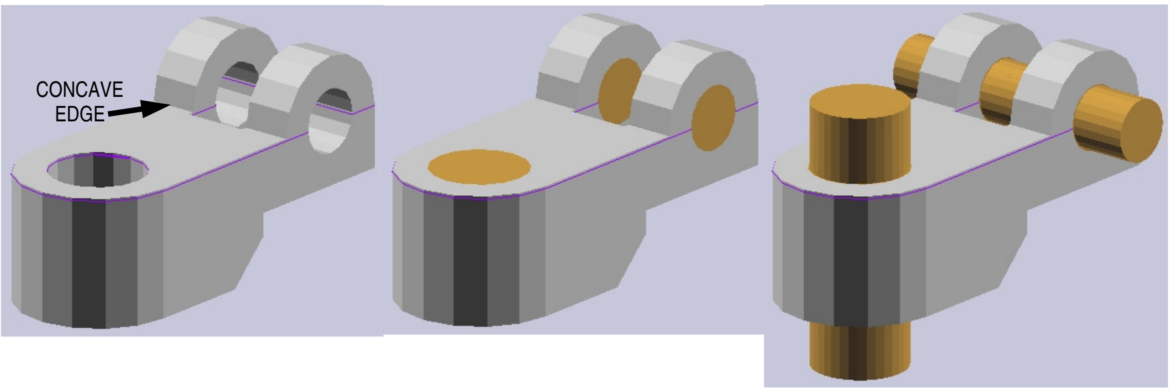

Fig.3.5: From left to right: part model with holes, core body extraction, print design

3.5 Core Design and Analysis

The print is an extension of the core body, usually along its axis. The print design depends on the direction of core axis and the number of openings. Each opening corresponds to a separate print for core support.
Major considerations in core print design are listed below.

1. The print must balance the body, so that the core stays in place during mold assembly.
2. The print must withstand the buoyancy force of the metal and not get crushed.
3. The print must not shift during mold filling.
4. The print should minimize the deflection of the core.
5. The print should maximize the heat transfer from the core to the mold.
6. The print should allow the internal gases generated in the core to escape to the mold.
7. Unsymmetrical holes should have foolproof prints to prevent incorrect assembly.
8. The prints of adjacent cores may be combined into one.

The core print design depends on the type of core:

1. Horizontal simply supported core
2. Horizontal overhanging or side core
3. Vertical doubly supported core
4. Vertical hanging core
5. Vertical bottom core

Let us analyze the forces on a horizontal simply supported core. Consider a cylindrical core of diameter d, body length l, print length a and print diameter D. Let ρ_{metal} and ρ_{core} be the densities of the molten metal and core material, respectively. Also, let σ_{comp} be the compressive strength of the mold material.

Self weight of core body $W_B = \pi d^2 l \rho_{core} / 4$
Self weight of core prints $W_P = \pi D^2 a \rho_{core} / 4$
Total weight of core $W = W_B + W_P$

Applying the first design rule to balance the core during placement in mold, we have

$$W_B \bullet W_P \qquad \dots (1)$$

The buoyancy force B on the core $B = \pi d^2 l \rho_{metal} / 4$
The net force on the core (upward) = $B - W = \pi d^2 l (\rho_{metal} - \rho_{core}) / 4$
The compressive stress on each core print $\sigma_{print} = 0.5 (B - W) / (a D)$

Applying the second rule to prevent core failure by crushing due to buoyancy forces,

$$\sigma_{print} \bullet \sigma_{comp} \qquad \dots (2)$$

The above two equations can be employed to design the dimensions of a horizontal simply supported core print. Similar treatment can be developed for other cores.

For vertical cores, there are two additional considerations. One is that the buoyancy forces transmitted by the core print may shear the top part of the mold. This is prevented by ensuring sufficient thickness of the mold wall above the core print. The second consideration is that the core print must be tapered to facilitate its placement in mold. The draft angle ranges from 2-4 degrees.

As mentioned earlier, cored holes and undercuts lead to increased tooling cost and manufacturing cycle time, and must be minimized to the extent possible. They also lead to quality problems, which may be prevented by satisfying the following design criteria.

Core diameter: Very small sand cores, especially in thick sections of a casting, are likely to fuse with the casting and are difficult to remove and clean later. This is caused by high heat accumulation in the core surrounded by molten metal. In diecasting, the molten metal shrinks on to the metal core, gripping it tightly, and it becomes difficult to withdraw the core later (this can be reduced so some extent by applying draft to the core body). A secondary, but important consideration is that it may be more economical to machine small holes than to produce them by cores. The minimum recommended core size depends on the part metal, casting process, thickness of the section in which the hole is located, and the length of the core (see the next criterion). In grey iron parts made by sand casting process, holes below 8 mm are usually difficult to produce by cores. In aluminum alloy diecast parts, the limiting diameter is about 3 mm.

Core aspect ratio: Narrow cores – those with large length to diameter ratio – are likely to distort during mold filling, especially under pressure. Narrow sand cores may even break. The limiting aspect ratio depends on the type of core (horizontal or vertical; simply supported or overhanging), core material, cast metal and filling pressure. For sand cast grey iron parts, the limiting aspect ratio ranges from 2 for overhanging cores to 4 for simply supported horizontal cores.

Inter-core distance: Several considerations govern the limiting distance between two cores. If two holes are too close, leading to a thin section in between, the following problems arise. First, the metal may not fill the section completely. Secondly, The in-between section may become a hot spot because cores poorly transmit heat, leading to shrinkage porosity in the section. Third, even a slight shift in the position of cores (during mold assembly or during mold filling, especially under pressure) that leads to further reduction of wall thickness in between, further aggravates the above two problems. The limiting distance is thus a function of the core diameter(s), core material, part metal and casting process. In general, the thickness of the section between the cores must be greater that the core diameter. In other words, the center distance between the cored holes must be greater than twice the hole diameter.

3.6 Mold Cavity Layout

In general, it is more economical to produce several castings in a single production mold, because of material, energy and labor savings:

1. Less amount of mold material utilized per casting.
2. Common feeders and gating system can be used, improving the yield.
3. Reduced set up time during manufacture (for mold preparation, pouring, shakeout and fettling) per casting.

The savings must offset the higher cost of tooling manufacture. Multiple cavity molds are therefore preferred only when the castings are very small compared to the smallest size of production molds and the production quantities are large. The mold cavity is usually taken up after deciding the casting orientation and parting.

The minimum distance between cavities and from any cavity to the nearest edge of the mold must be set. The minimum distance must be sufficient to: (a) prevent damage to the mold, and (b) to allow adequate heat transfer so that local hot spots are not formed in the portion of a casting close to another cavity. The minimum distance ranges from 25 mm for small castings to 50 mm for medium size castings.

The number of cavities in a mold has to be optimized in terms of metal to sand ratio:

$$\rho_{metal}\,(N_c\,V_c + V_f + V_g\,)\,/\,\rho_{sand}\,(V_{mold} - (N_c\,V_c + V_f + V_g\,))$$

where, ρ_{metal} and ρ_{sand} are the density of casting and mold materials, N_c is the number of casting cavities, V_c is the volume of a single cavity, V_f and V_g are the total volume of feeders and gating, respectively, and V_{mold} is the overall volume of mold (based on its dimensions). A low value of the ratio indicates poor utilization of mold material. A high ratio must also be avoided, since this may lead to poor heat transfer, in turn leading to defects related to casting solidification. The minimum recommended value of metal to sand ratio for ferrous castings is 1:1. In practice, it ranges from 1:2 to 1:6.

The optimal number of cavities can be determined following this procedure:

1. Choose a mold (in terms of its dimensions: length, width and height).
2. Set the minimum distance (cavity-to-cavity, cavity-to-mold edge).
3. Determine the maximum number of cavities that can be accommodated.
4. Determine the value of metal to sand ratio.

The procedure is repeated for different sizes of mold, and the mold which gives the highest value of metal-to-sand ratio (but more than the minimum limit) can be selected.

In practice, the mold cavity layout will also depend on the position of feeders and gating, especially if they are common to more than one casting. It is also possible to design the layout with different types of castings in the same mold. For example, a large casting (but not large enough for a good metal to sand ratio) can be combined with one or more small castings in the same mold.