Machine Design II

DESIGN FOR MANUFACTURING

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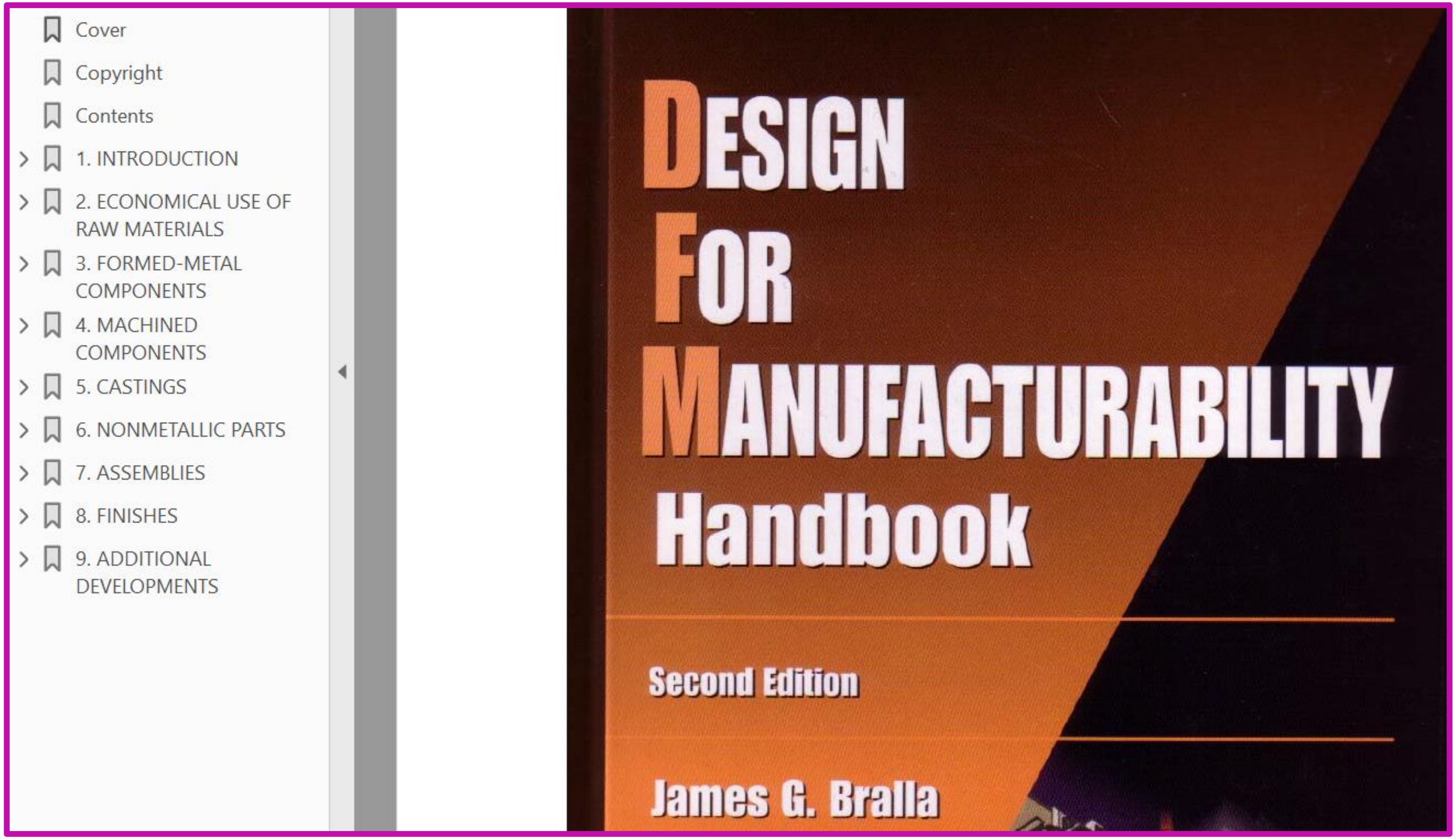

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BASIC PRINCIPLES OF DESIGNING FOR ECONOMICAL PRODUCTION

1. Simplicity.

Product **with** fewest parts, least intricate shape, fewest precision adjustments, shortest manufacturing sequence **is** least costly to produce, most reliable, easiest to service

2. Standard materials and components.

Use of widely available materials & off the-shelf parts

low-unit quantity products.
simplifies inventory management,
eases purchasing,
avoids tooling and equipment investments,
and speeds the manufacturing cycle.

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3. Standardized design of the product itself.

When several similar products are to be produced,

specify the same materials, parts, and subassemblies for each as much as possible.

→

provide economies of scale for component production,
simplify process control and operator training,
reduce the investment required for tooling & equipment.

4. Liberal tolerances.

Tight tolerances have higher costs because of

(a) extra operations such as grinding, honing, or lapping after primary machining,

(b) higher tooling costs and the more frequent careful maintenance needed as they wear,

(c) longer operating cycles, (d) higher scrap and rework costs,

(e) the need for more skilled and highly trained workers, (f) higher materials costs, and

(g) more sizable investments for precision equipment.

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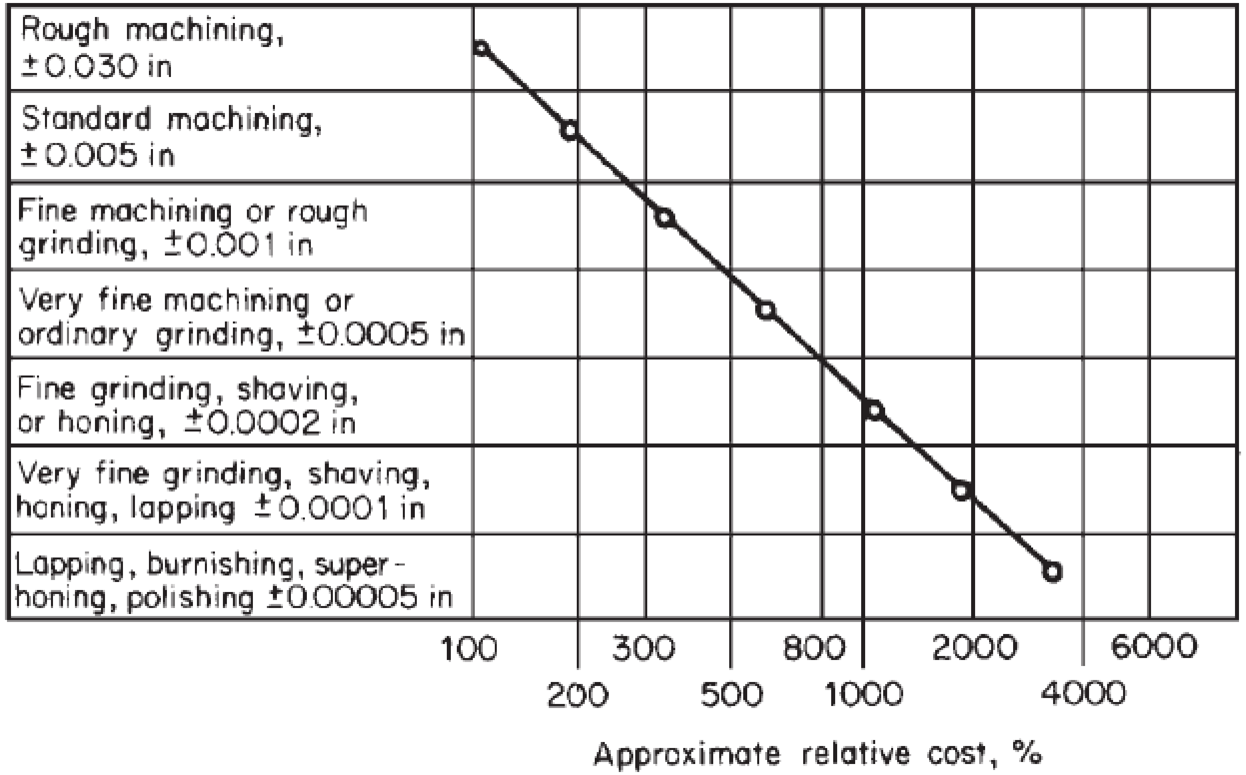

Approximate relative cost of progressively tighter dimensional tolerances.
(From N. E. Woldman, Machinability and Machining of Metals)

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5. Use of the most processible materials.

Use the most processible materials available as long as their functional characteristics and cost are suitable.

Processibility - cycle time, optimal cutting speed, flowability etc.

The most economical material is the one with the lowest combined cost of materials, processing, and warranty and service charges over the designed life of the product.

6. Teamwork with manufacturing personnel.

Designer and manufacturing personnel, particularly manufacturing engineers, should work closely together as a team.

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7. Avoidance of secondary operations.

Operations such as deburring, inspection, plating and painting, heat treating, material handling etc. can be as expensive as the primary manufacturing operation.

8. Design appropriate to the expected level of production.

The design should be suitable for a production method that is economical for the quantity forecast.

For example, die casting should be preferred over sand-molding for a mass-produced aluminium part (labor and materials savings with die castings).

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9. Utilizing special process characteristics.

Utilizing these special capabilities can eliminate many operations and the need for separate, costly components.

Some plastics can provide “living hinges” .

Powder-metal parts normally have a porous nature that allows lubrication retention and obviates the need for separate bushing inserts, etc.

10. *Avoiding process restrictiveness.*

On parts drawings, specify only the final characteristics needed; do not specify the process to be used.

Allow manufacturing engineers as much latitude as possible in choosing a process that produces the needed dimensions, surface finish, or other characteristics required.

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GENERAL DESIGN RULES

1. Simplify the design. Reduce the number of parts required. This can be done most often by combining parts, designing one part so that it performs several functions.
2. Design for low-labor-cost operations whenever possible. For example, a punch press pierced hole can be made more quickly than a hole can be drilled.
3. Avoid generalized statements on drawings that may be difficult for manufacturing personnel to interpret. Examples are "Polish this surface....Corners must be square," "Tool marks are not permitted," etc. Notes must be more specific than these.
4. Dimensions should be made not from points in space but from specific surfaces or points on the part itself if at all possible. This facilitates fixture and gauge making and helps avoid tooling, gauge, and measurement errors.

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5. Dimensions should all be from one datum line rather than from a variety of points to simplify tooling and gauging and avoid overlap of tolerances.

6. Designers should strive for minimum weight consistent with strength and stiffness requirements. Along with a reduction in materials costs, there usually will be a reduction in labor and tooling costs when less material is used.

7. Design to use general-purpose tooling rather than special tooling (dies, form cutters, etc.). Exception - highest levels of production, where there is labor and materials savings with special tooling

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8. Avoid sharp corners; use generous fillets and radii.
    - There is less stress concentration on the part and on the tool;
    - Both will last longer.

Exceptions –

Two intersecting machined surfaces will leave a sharp external corner, and there is no cost advantage in trying to prevent it.

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9. Design a part so that as many manufacturing operations as possible can be performed without repositioning it. This reduces handling and the number of operations and also promotes accuracy.

10. Whenever possible, cast, molded, or powder-metal parts should be designed so that stepped parting lines are avoided. These increase mold and pattern complexity and cost.

11. With all casting and molding processes, design work-pieces so that wall thicknesses are as uniform as possible. With high-shrinkage materials, the need is greater.

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CASTINGS – SAND MOULD

ECONOMIC PRODUCTION QUANTITIES

The cost of a sand mould casting includes the amortization of the pattern cost together with the manufacturing labor, metal, and overhead costs.

With short runs, the pattern may be made of wood inexpensively. High production runs require more expensive metal patterns to withstand repeated use. Such patterns, however would entail a low cost when divided among many pieces.

Handling of small orders is expensive. Making a few prototype castings can involve a unit cost 10 times as high as that of the same casting made in substantial quantities.

A light-sectioned, rangy casting will always cost more per unit of weight than the same weight in a chunk. The difference can be as much as 4:1.

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DESIGN CONSIDERATIONS AND RECOMMENDATIONS

Shrinkage

The amount of shrinkage varies with different metals, but it is predictable and can be compensated for by making patterns slightly oversize.

Shrinkage Allowance for Metals Commonly Cast in Sand Molds

Metal	Percent
Gray cast iron	0.83–1.3
White cast iron	2.1
Ductile cast iron	0.83–1.0
Malleable cast iron	0.78–1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Yellow brass	1.3–1.6
Gunmetal bronze	1.0–1.6
Phosphor bronze	1.0–1.6
Aluminum bronze	2.1
Manganese bronze	2.1
Open-hearth steel	1.6
Electric steel	2.1
High-manganese steel	2.6

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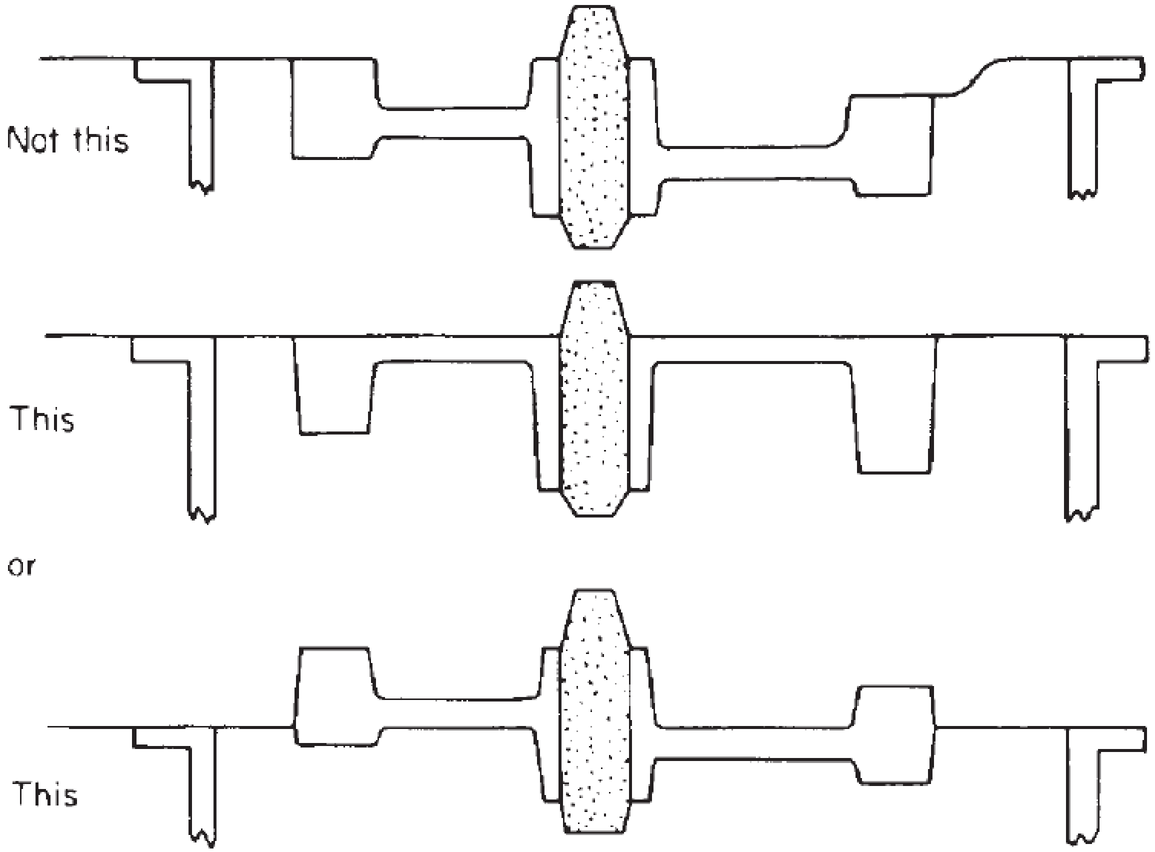
Parting Line

Straight parting lines are more economical than stepped parting lines.

Contoured parting lines result in costly patterns, less accuracy, more difficult “debugging,” higher losses, and a need for more skilled molders, all of which increase costs.



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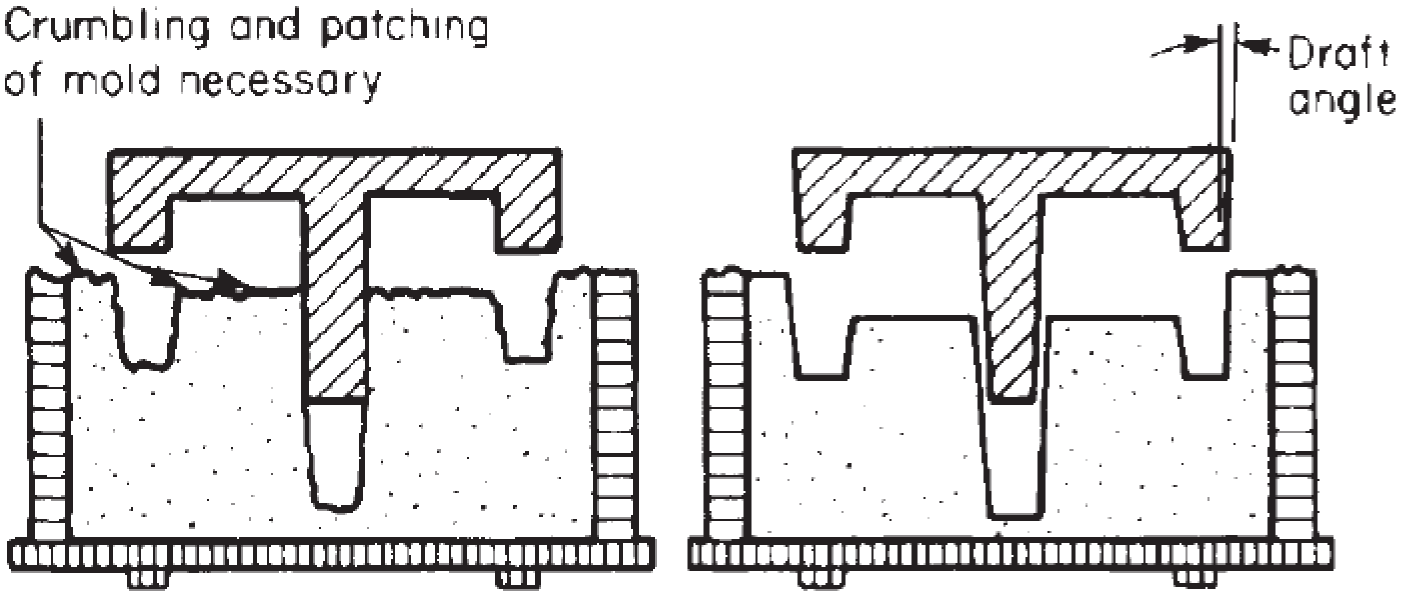
Draft

To facilitate removal, the pattern must have some degree of taper, or draft.



Poor stripping from the mold results when no allowance is made for draft.

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The amount of draft needed is related to the method of molding and drawing of the pattern, the material the pattern is made from, the degree of precision, and the surface smoothness of the pattern.

In high-production work, the draw mechanism, being quite accurate, allows the pattern to be drawn if it is of high quality even if it has little draft.

The less the draft, higher the quality of the pattern needed and greater the cost.

In high production, the higher pattern cost can be easily saved in metal weight.

Draft Angles for Outside Surfaces of Sand-Molded Castings*

	Pattern material					
	Wood		Aluminum		Ferrous	
	Pattern-quality level					
Ramming method	Normal	High	Normal	High	Normal	High
Hand	5°	3°	4°	3°		
Squeezer	3°	2°	3°	2°		
Automatic			2°	1°	1½°	½°
Shell molding					1°	¼°
Cold cure	3°	2°	2°	1°		

*The draft on inside surfaces should be twice that on the outside.

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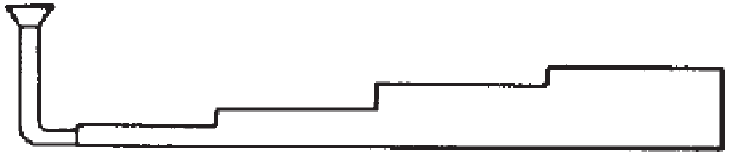
Riser location

Risers are attached to the heaviest sections. The thinnest sections are farthest from the riser and solidify first.

Solidification progresses toward the heaviest section and then the riser.

The designer should visualize the direction of solidification and taper sections as necessary to ensure that solidification proceeds toward the direction of risers, thus minimizing the chance for voids.



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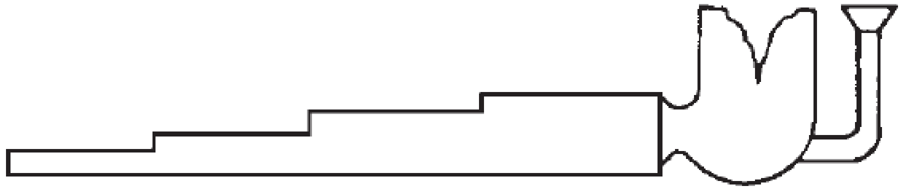

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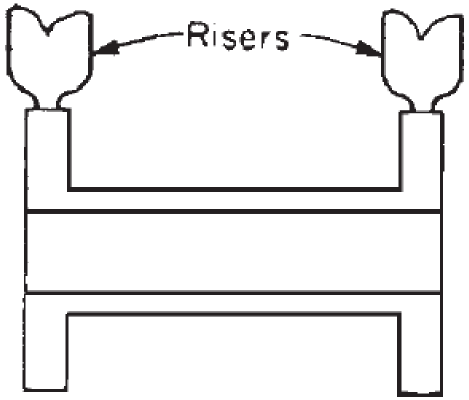

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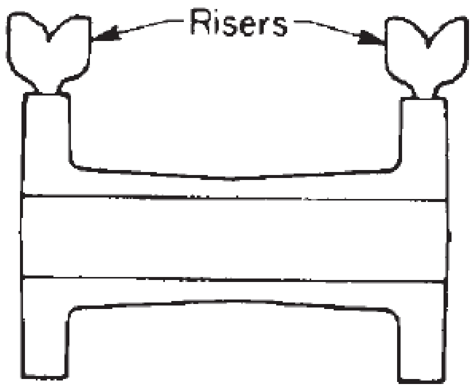

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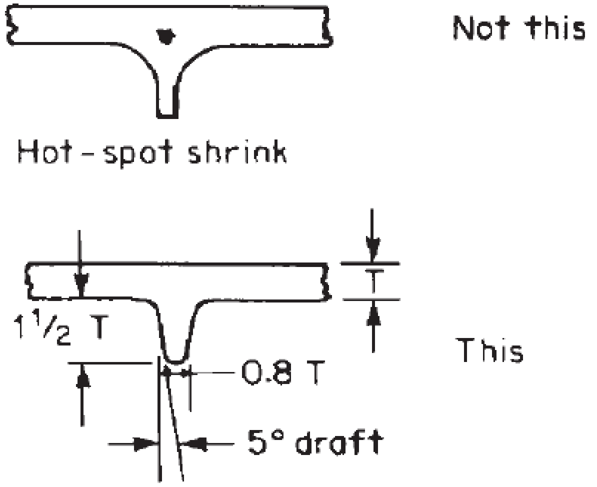
Ribs and Webs

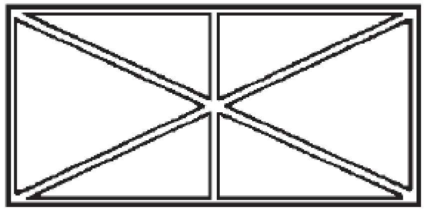
These are effective in providing increased stiffness to a component with a minimum increase in weight. Figure illustrates desirable proportions for stiffening ribs.

Heavier sections where the rib intersects the casting wall can cause hot-spot shrinks.

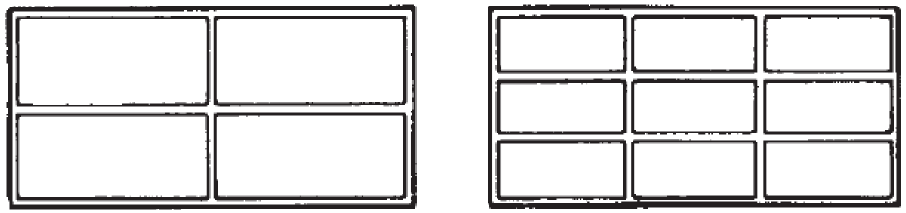
The number of ribs intersecting at one point should be minimized to avoid hot-spot effects.



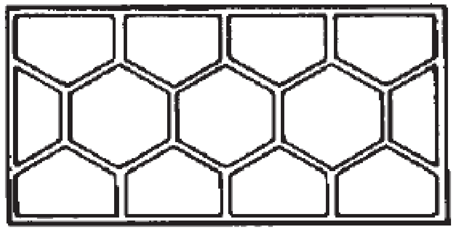
Incorrect and correct casting-rib design



Poor
(Six ribs intersect at one point.)



These are slightly improved.
(Four ribs intersect at one point.)



These are much improved.
(Only three ribs intersect at each point.)

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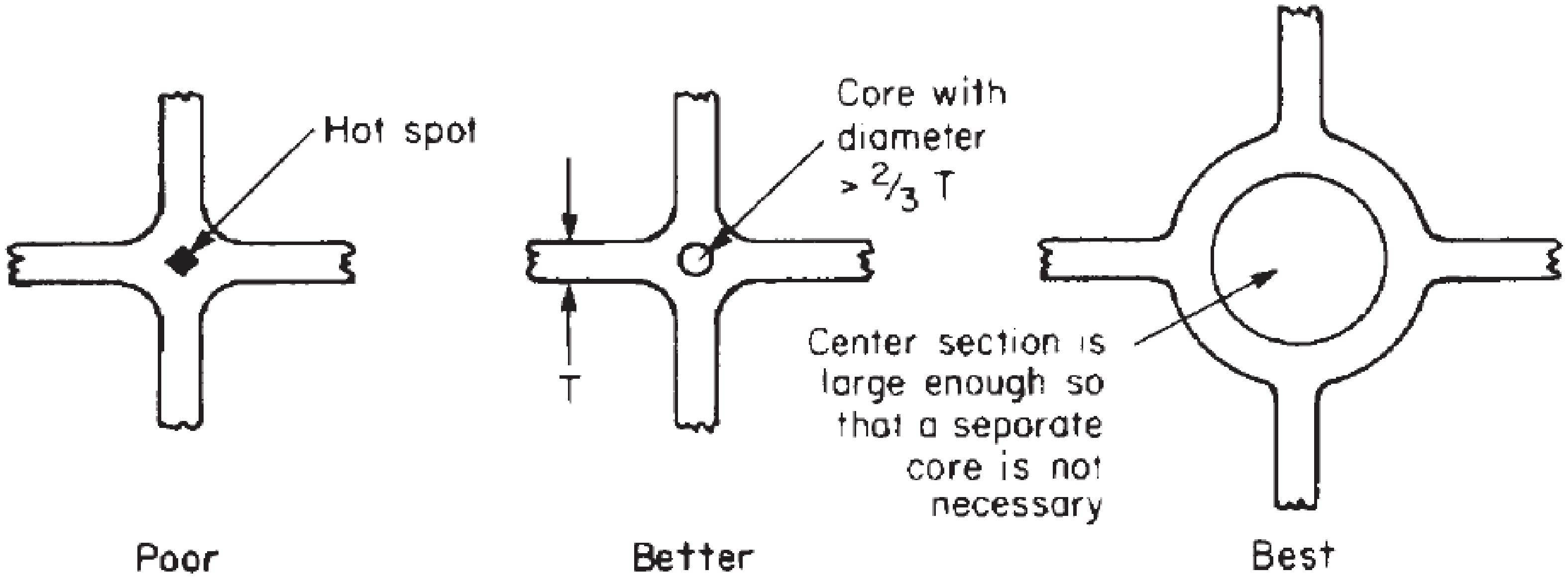

When it is necessary to bring a number of ribs or other members together at one point, a cored hole at the point of intersection will speed solidification, prevent shrink voids and structural weakness and distortion.

A preferable alternative is to use a circular web to connect the ribs, thus avoiding the need for a core piece.

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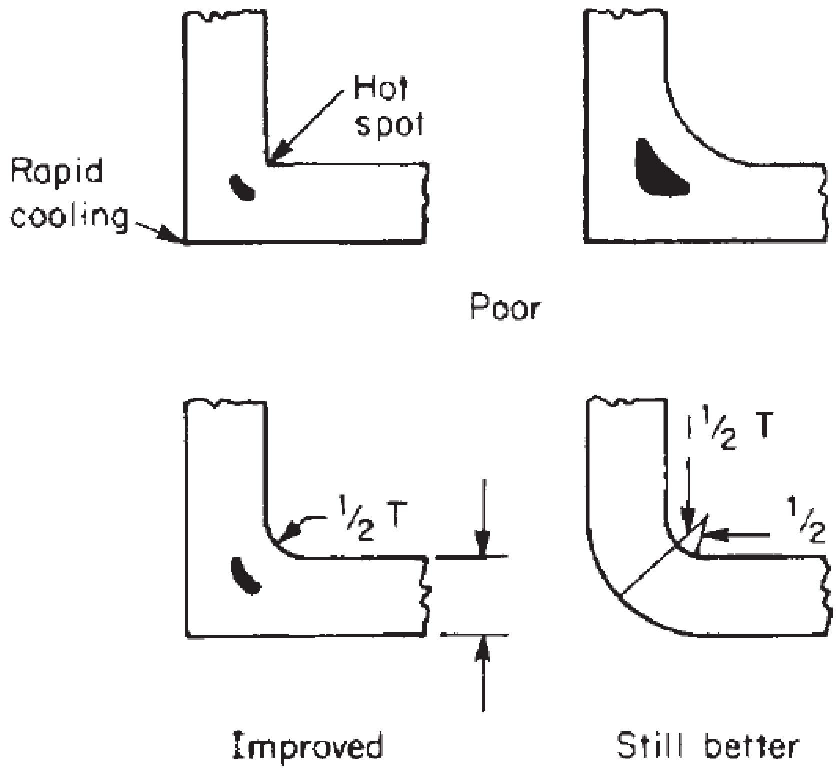
Corners and Angles

Sharp corners cause uneven cooling and molded-in stress, while rounded corners permit uniform cooling with much less stress.

Rounded corners that maintain uniform wall thickness provide the best results.

The crystal growth of solidifying metal progresses inward from each surface.



Outside corners radiate heat in two directions and cool quickly. Inside corners heat the sand in the corner from two directions, creating a hot spot that retards solidification.

Rounding the inside corners decreases the severity of the hot spot and lessens the stress concentration. However, too much rounding will promote a shrink defect in a corner.

Rounding both inside and outside of the corner and using same center for radii is better.

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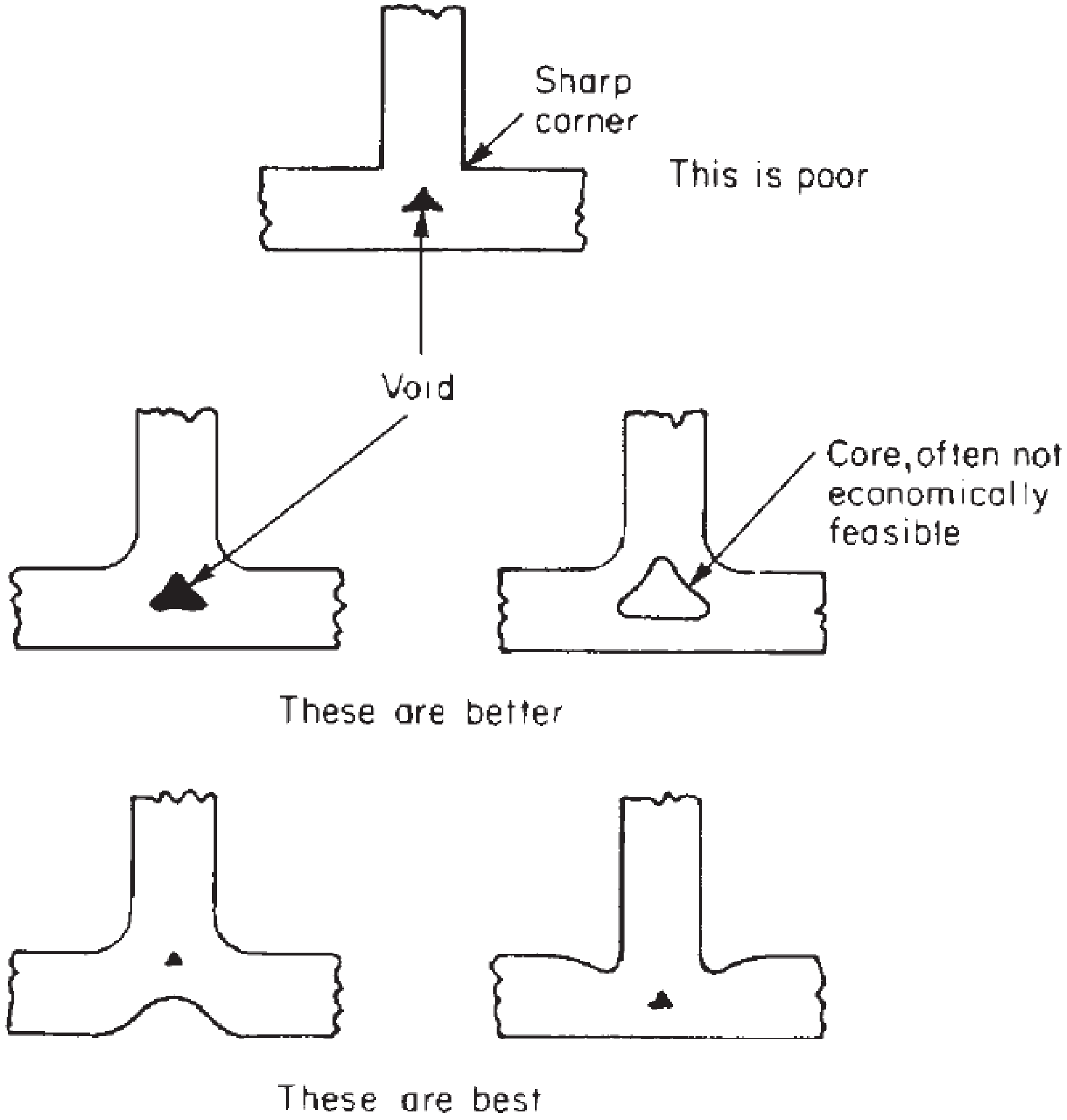
In a T section, a dished contour opposite the intersecting member minimizes the shrink so that larger inside radii can be used to minimize stress concentration and hot spots.

Two dished contours, one on each side of the center leg, are also effective.



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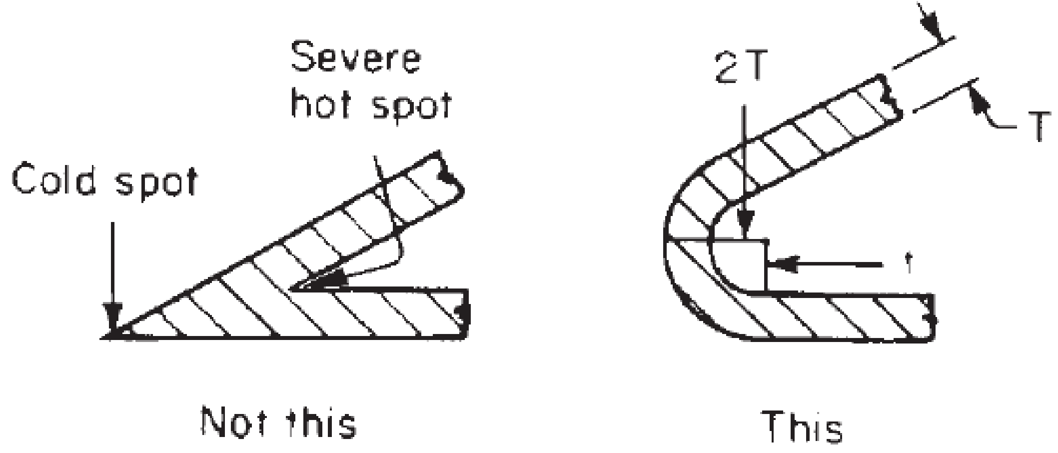
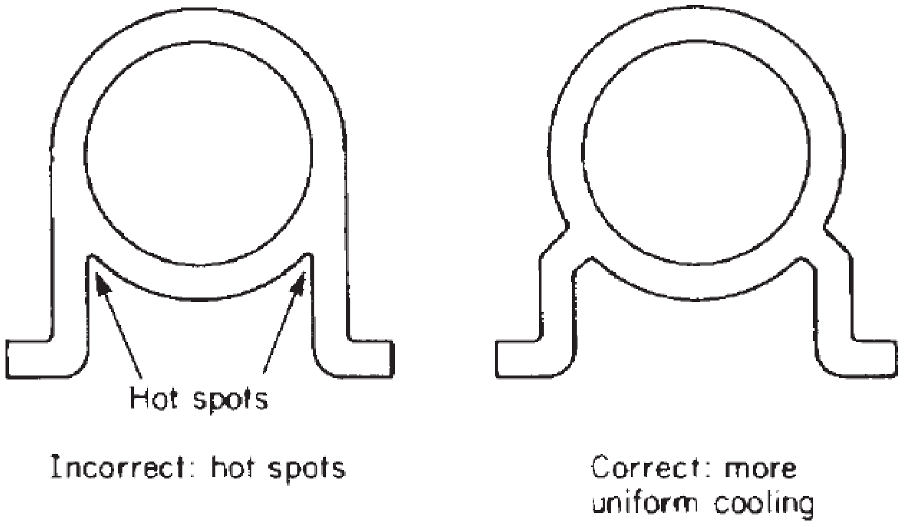
The more acute the angle, both the rapid-cooling area and the hot-spot effect are increased.



The intersection of two walls of a casting should be at a right angle, if possible, to minimize heat concentration.



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Wall Thickness

In general, problems increase rapidly if sections are too small [under 6 mm] in all metals.

The farther the metal must flow in the mold, the heavier the section must be. Therefore, there is a limit to the savings that are gained by reducing the weight of a casting.

Minimum Economical Section Thickness for Green-Sand Castings*

Section length	To 300 mm (12 in)	To 1.2 m (6 ft)	To 3.6 m (12 ft)
Aluminum	3–5 mm (1/8–3/16 in)	8 mm (5/16 in)	16 mm (5/8 in)
Brass and bronze	2.4–3 mm (3/32–1/8 in)	8 mm (5/16 in)	16 mm (5/8 in)
Ductile iron	5 mm (3/16 in)	13 mm (1/2 in)	19 mm (3/4 in)
Gray iron, low strength	3 mm (1/8 in)		
Gray iron, 138-MPa (20,000-lbf/in^2) tensile strength	4 mm (5/32 in)	10 mm (3/8 in)	
Gray iron, 207-MPa (30,000-lbf/in^2) tensile strength	5 mm (3/16 in)	10 mm (3/8 in)	19 mm (3/4 in)
Gray iron, 276-MPa (40,000-lbf/in^2) tensile strength	6 mm (1/4 in)	13 mm (1/2 in)	25 mm (1 in)
Gray iron, 345-MPa (50,000-lbf/in^2) tensile strength	10 mm (3/8 in)	16 mm (5/8 in)	25 mm (1 in)
Magnesium alloys	4 mm (5/32 in)	8 mm (5/16 in)	16 mm (5/8 in)
Malleable iron	3 mm (1/8 in)	6 mm (1/4 in)	
Steel	8 mm (5/16 in)	13 mm (1/2 in)	25 mm (1 in)
White iron	3 mm (1/8 in)	13 mm (1/2 in)	19 mm (3/4 in)

*Thinner walls are economical in shell, dry-sand, or cold-cure molded castings. Some designs of castings lend themselves to thinner walls without problems.

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Section Changes

Abrupt changes in sections should be avoided.

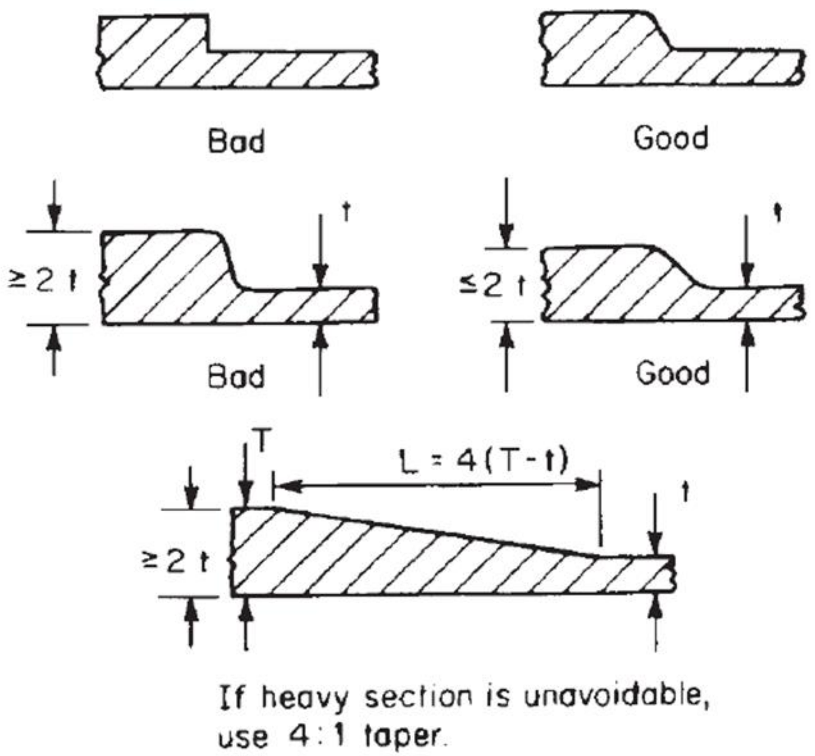
Fillets and tapers are preferable to sharp steps.

Normally, a difference of greater than 2:1 in relative thickness of adjoining sections should be avoided.

If a section change of over 2:1 is unavoidable, the designer has two alternatives:

(1) Design the section as two separate castings to be bolted together later, or

(2) Use a wedge form between the unequal sections. The taper of the wedged area should not exceed 1:4.



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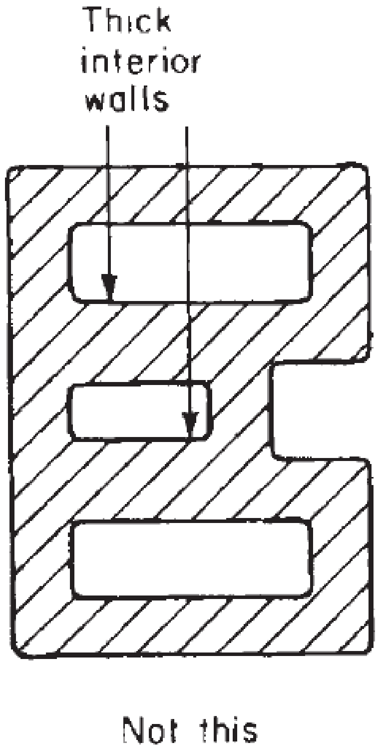
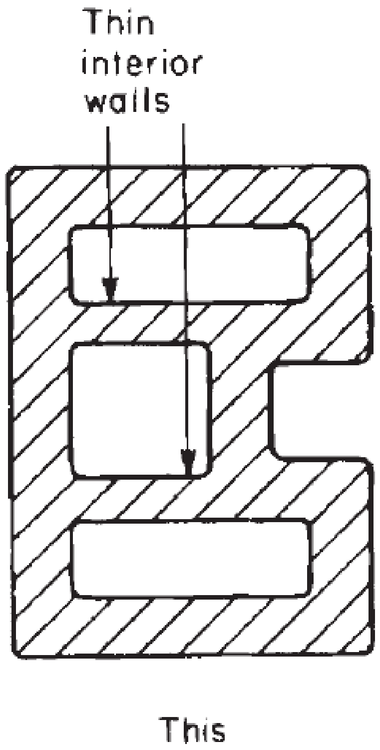
Interior Walls and Sections

Interior walls should be 20 percent thinner than exterior walls since they cool more slowly.

In this way, thermal and residual stresses are reduced and metallurgical changes are minimized





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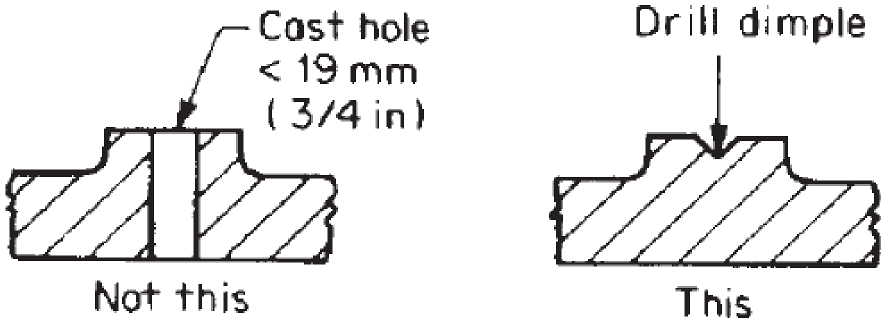
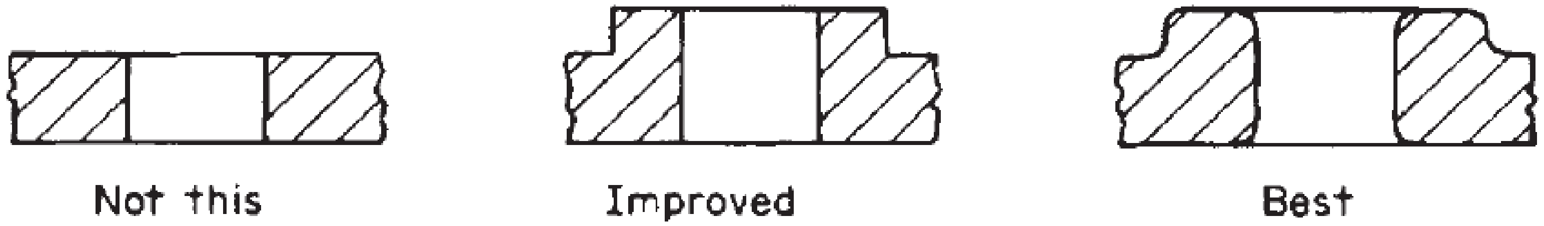
Small holes are generally not economical to mold or core. It is usually cheaper and more satisfactory to drill them. The break-even point is between 13- and 25-mm diameter. A drill dimple can be cast in the part to facilitate offhand drilling if applicable.



Holes are generally stress raisers, and they should have extra metal around them to compensate. This metal should be carefully blended to minimize hot spots and stress-raising corners.



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Cores

Cores are subject to heat and high floating pressures.

Their usual organic binders break down, releasing gases that must be vented to prevent bubbles in the metal.

The decomposed sand must be removable by cleaning processes.

Cores are expensive to make, handle, set in the mold, and clean out later.

For these reasons they should not be used if at all avoidable.

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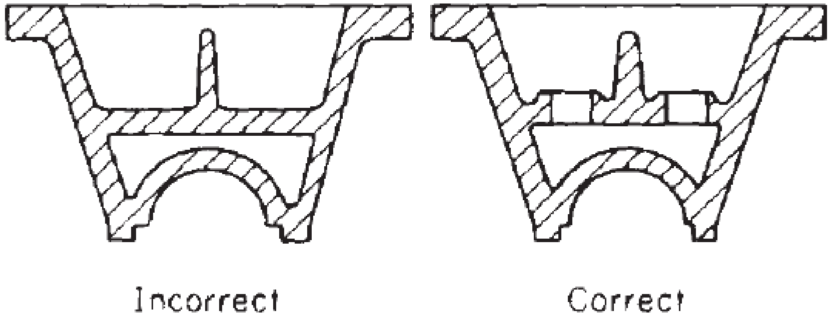
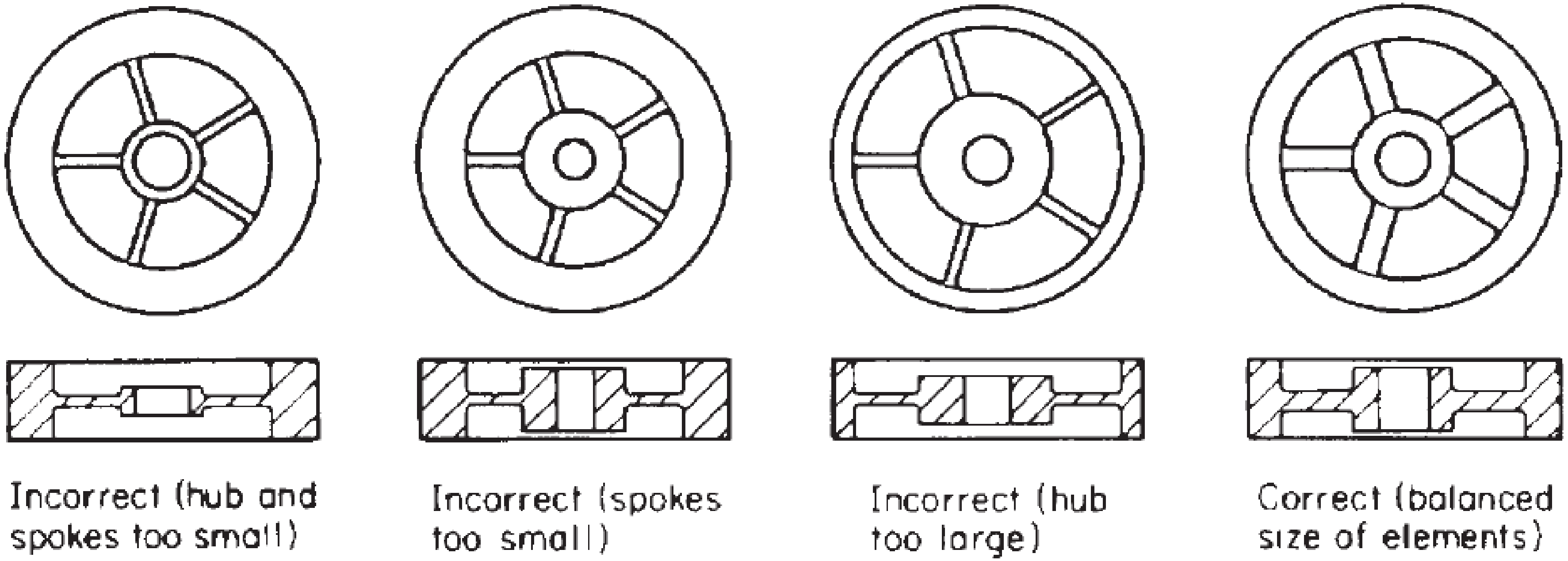
Internal pockets in castings may require cored vent holes to allow gases released during pouting to escape and to facilitate cleaning after casting.





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Allowance for Machining: Each Side

The amount of machining allowance depends on the size of the surface to be machined, the machining method and the final accuracy required.

If only flatness is desired and some unmachined areas are not objectionable, a minimum of additional metal is needed.

If a fully machined surface without imperfections is necessary, more metal must be removed.

		Allowance, mm (in)	
	Casting size, mm (in)*	Drag and sides	Cope surface
Gray iron	Up to 150 (up to 6)	2.3 (3/32)	3 (1/8)
	150–300 (6–12)	3 (1/8)	4 (5/32)
	300–600 (12–24)	5 (3/16)	6 (1/4)
	600–900 (24–36)	6 (1/4)	8 (5/16)
	900–1500 (36–60)	8 (5/16)	10 (3/8)
	1500–2100 (60–84)	10 (3/8)	13 (1/2)
	2100–3000 (84–120)	11 (7/16)	16 (5/8)
Cast steel	Up to 150 (up to 6)	3 (1/8)	6 (1/4)
	150–300 (6–12)	5 (3/16)	6 (1/4)
	300–600 (12–24)	6 (1/4)	8 (5/16)
	600–900 (24–36)	8 (5/16)	10 (3/8)
	900–1500 (36–60)	10 (3/8)	13 (1/2)
	1500–2100 (60–84)	11 (7/16)	14 (9/16)
	2100–3000 (84–120)	13 (1/2)	19 (3/4)
Malleable iron	Up to 75 (up to 3)	1.5 (1/16)	2.3 (3/32)
	75–300 (3–12)	2.3 (3/32)	3 (1/8)
	300–450 (12–18)	3 (1/8)	4 (5/32)
	450–600 (18–24)	4 (5/32)	5 (3/16)
Ductile iron	Up to 150 (up to 6)	2.3 (3/32)	6 (1/4)
	150–300 (6–12)	3 (1/8)	10 (3/8)
	300–600 (12–24)	5 (3/16)	19 (3/4)
	600–900 (24–36)	6 (1/4)	19 (3/4)
	900–1500 (36–60)	8 (5/16)	25 (1)
	1500–2100 (60–84)	10 (3/8)	28 (1 1/8)
	2100–300 (84–120)	11 (7/16)	32 (1 1/4)
Nonferrous metals	Up to 150 (up to 6)	1.6 (1/16)	2.3 (3/32)
	150–300 (6–12)	2.3 (3/32)	3 (1/8)
	300–600 (12–24)	3 (1/8)	4 (5/32)
	600–900 (24–36)	4 (5/32)	5 (3/16)

**Casting size* refers to the overall length of the casting and not to the length of a particular measurement.

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FORGINGS

Forging cost is the sum of a number of factors: metal cost including scrap, labor cost, and overhead expenses of the production facility.

Even though a forging-die set may require repair or replacement over the course of a long production run, the cost of this is treated as an operating expense according to industry practice. It is **initial die cost**, then, that controls the economics of lot size.

Forging becomes more attractive as die cost becomes a smaller fraction of piece cost. This is especially true for small parts.

A minimum economical lot size for 100-g forgings usually ranges around 5000 pieces. Very large forgings weighing from 50 kg to 500 kg may be economical in lots as small as 2 or 3 pieces. This approximation assumes ordinary conventional forgings of readily forgeable alloys.

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When only a few pieces are needed, the forging buyer can reduce die costs by ordering hand forgings made with open general-purpose dies. The time of a highly skilled person and the overhead of specialized facilities will then be major cost items.

The alloys of aluminum, magnesium, and copper along with mild steels, may be regarded as readily forgeable. There are differences among them, but some of these differences tend to balance out.

For example, aluminum can be forged at lower temperatures than steel, but it flows less readily and requires higher pressures. There are differences among alloys in each group also.

Steel forgings are usually heat-treated after finish machining to develop the static and dynamic strength properties needed in service.

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Good practice dictates that a forging drawing be prepared. Shapes and dimensions of a part as it will be forged, before any machining is done, are shown on this drawing.

Die design and processing requirements are dictated by the way in which the part is drawn.

Grain flow must be aligned with the direction of highest principal stress.

An experienced designer usually can visualize metal flow from bar stock to final forging and the resulting grain-flow pattern.

A forging manufacturing engineer may have concerns, however, about potential laps and locally excessive die wear and recommend changes to the forging drawing that may affect grain flow and the exact shape of the final part.

Flash is not customarily indicated on the forging drawing.

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It is often advisable to use metal-flow simulation software to study blocker and finisher shapes for forgings.

The simulation software shows how a metal bar changes shape under the action of the forging press or hammer, predicts total forging loads and tooling stresses, indicates where laps and other defects may form, and describes grain flow patterns.

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Parting Line

If the parting line cannot lie in one plane, it is desirable to preserve symmetry so as to prevent high side-thrust forces on the dies and the press. Such forces can be countered, at extra die cost, if they are unavoidable.

No portion of the parting line should incline more than 75° from the principal parting plane, and much shallower angles are desirable.

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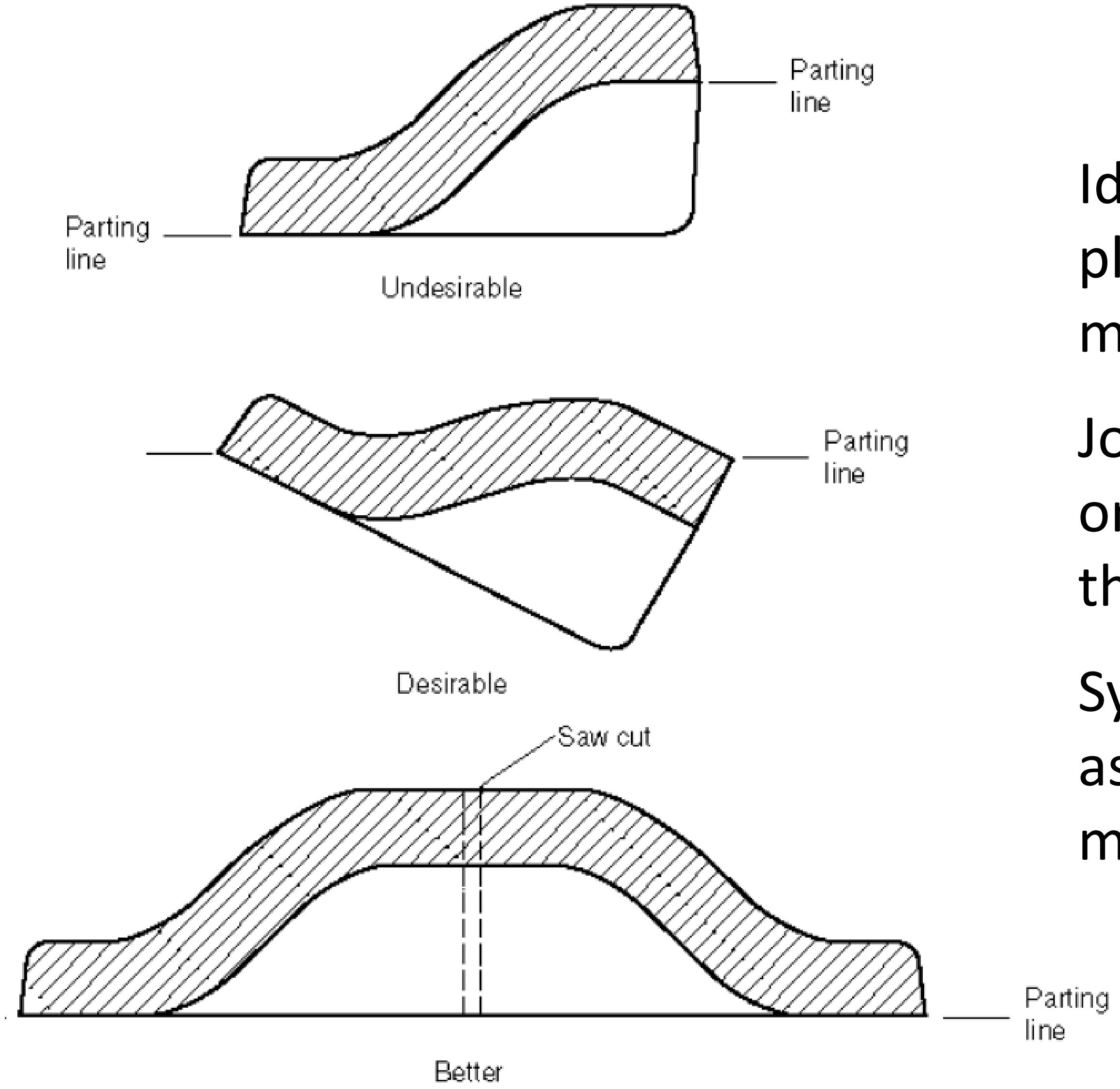


Ideally, the parting line should lie in one plane, perpendicular to the direction of die motion.

Jogs in parting lines impose side-thrust forces on the die halves. It is expensive to absorb these forces with die counterlocks.

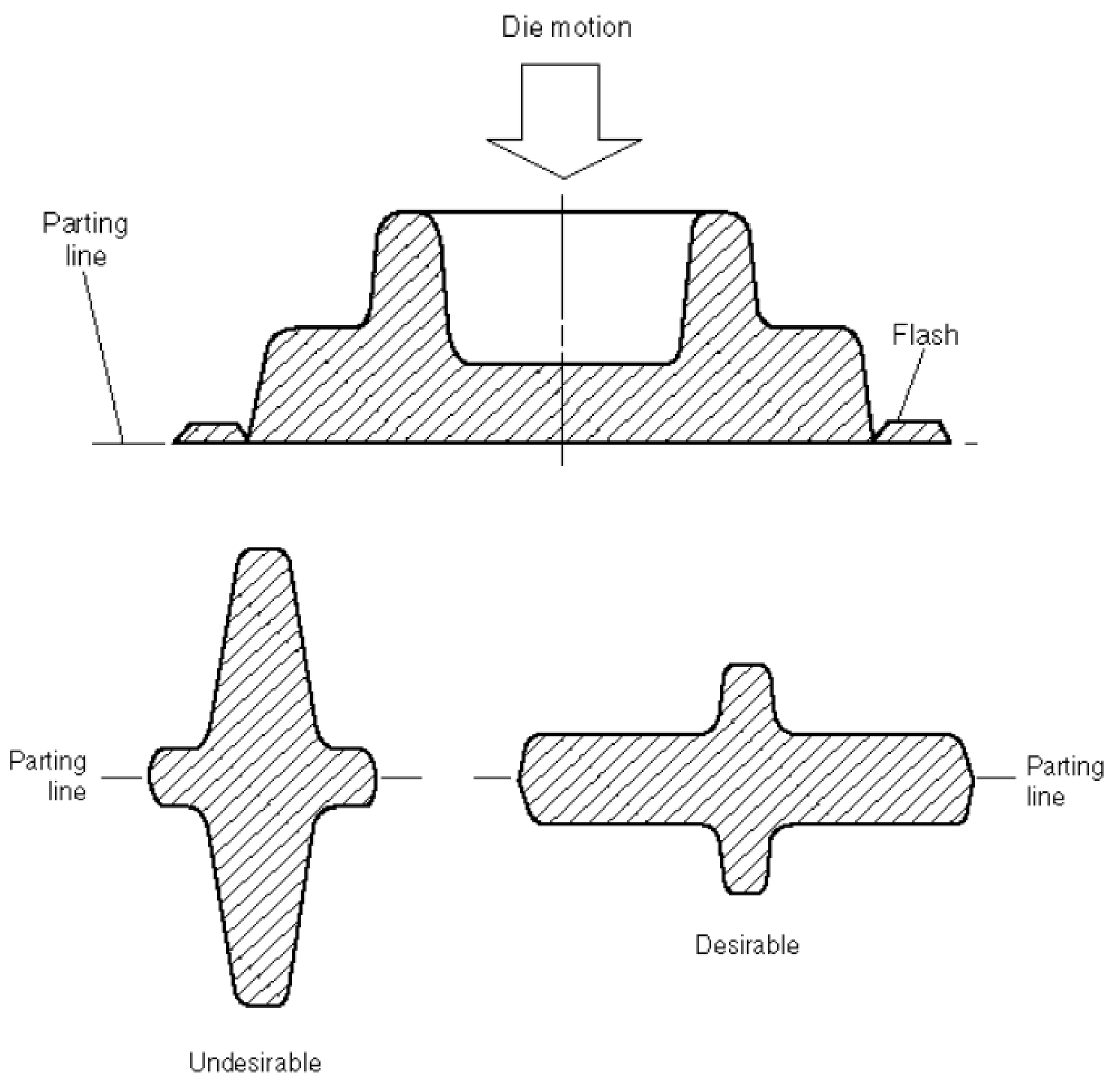
Symmetry can be achieved by forging pieces as pairs. If they are right- and left-handed mates, this approach has extra merit.

DESIGN FOR MANUFACTURING

An obvious essential is to select a parting line that will not entail any undercuts in either die impression, since the forging must come out of the die after it is made.

Because metal flow at the parting line is outward into the flash gutter, grain flow in the forging has a corresponding pattern. Depending on the way in which the part will be loaded, it may be desirable to change parting-line location to control grain flow.

DESIGN FOR MANUFACTURING



The parting line here is in one plane perpendicular to die motion, and the impression is entirely in one die half.

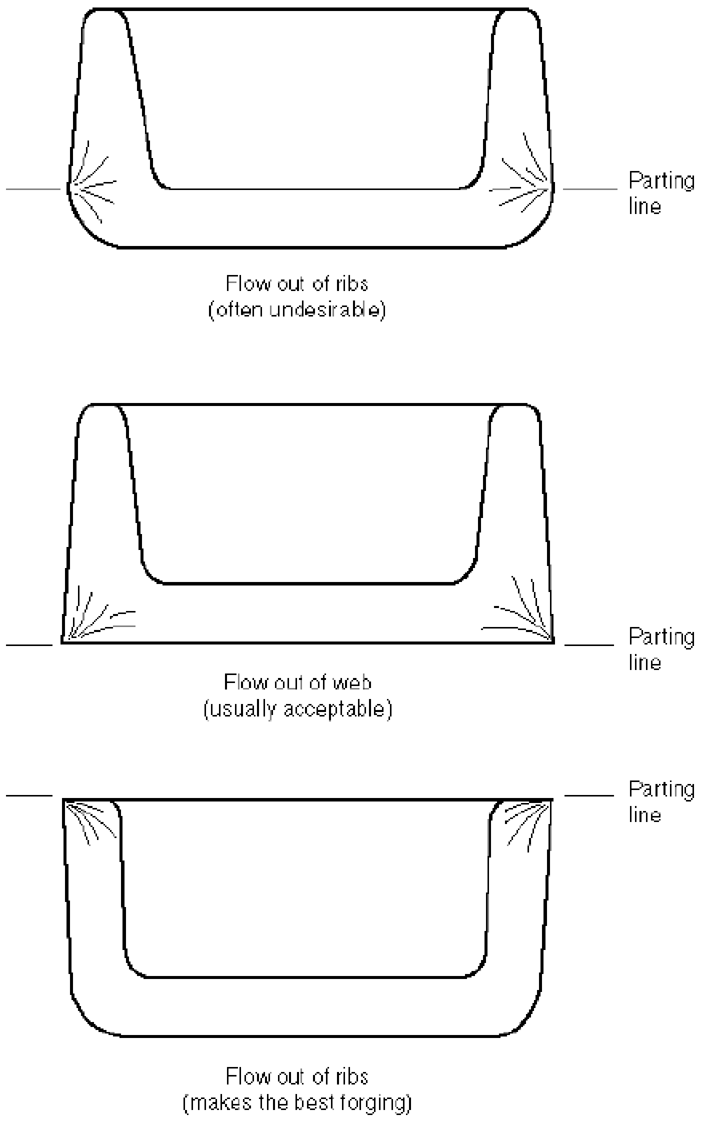
This is usually the most economical tooling arrangement for two-part impression dies.

When there is a choice, locate the parting line so that metal will flow horizontally, parallel to the parting line.

DESIGN FOR MANUFACTURING

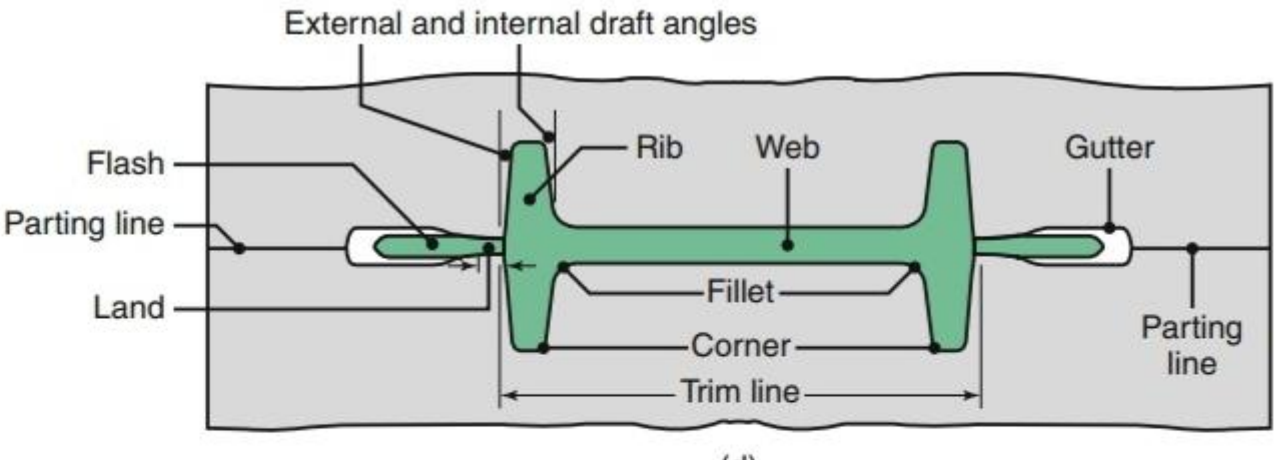
The parting line location governs when the constricted grain flow associated with flash will occur on the part.

The designer can locate the parting line to achieve the objectives of each part's function.

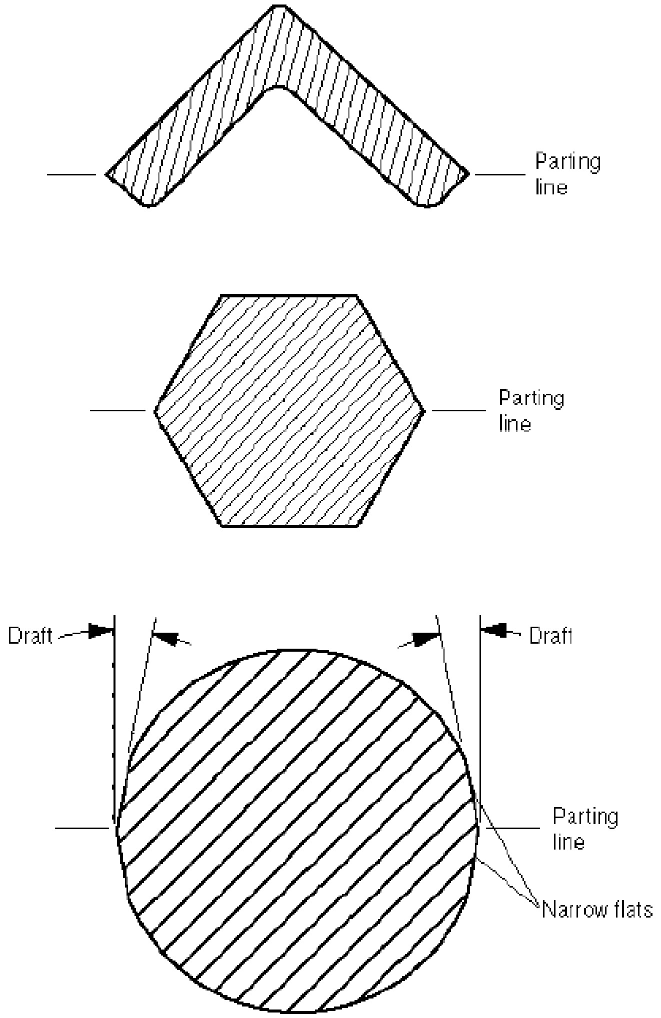


DESIGN FOR MANUFACTURING

Draft



(d)



These shapes have natural draft. Usually, the cylindrical section will be modified slightly to provide draft in the narrow region next to the parting line.

Low-draft and no-draft forgings can be produced in some metals, such as aluminum and brass. This usually applies to selected surfaces for which reduction or elimination of draft yields significant benefits.

DESIGN FOR MANUFACTURING

Typical Draft Angles

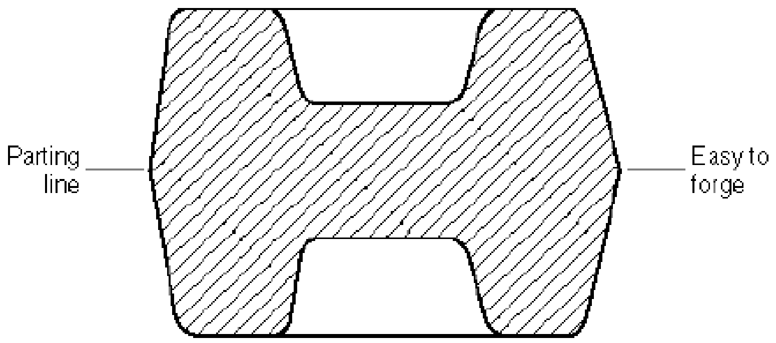
Alloy family	Draft angle, °
Aluminum	0–2
Magnesium	0–2
Brass and copper	0–3
Steel	5–7
Stainless steel	5–8
Titanium	5–6

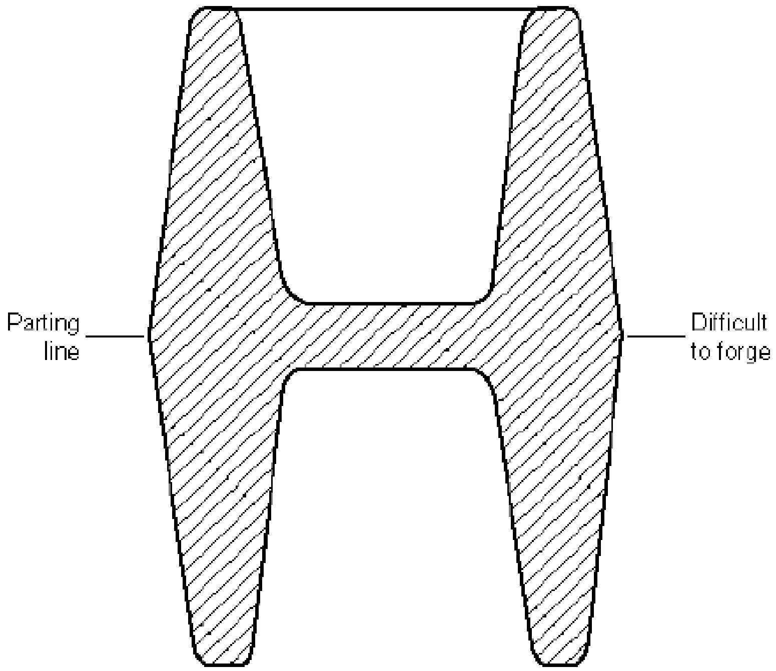
DESIGN FOR MANUFACTURING

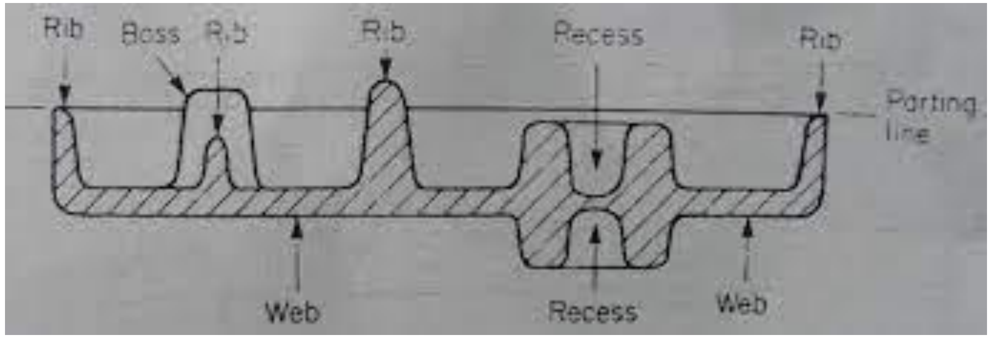
Ribs, Bosses, Webs, and Recesses

As the web becomes thinner and the ribs become deeper, forging difficulty increases.

Metal flow is relatively easy to manage when ribs and bosses are not too high and narrow, and it is easiest when the web is relatively thick and uniform in thickness.







DESIGN FOR MANUFACTURING

Forging becomes more difficult when large amounts of metal must be moved out of relatively thin webs into such projections as deep ribs and high bosses. It is helpful to taper such webs toward the ribs and bosses.

Deep recesses also are easier to forge if they have spherical bottoms.

Surface textures, designs, and lettering on forged surfaces are simply very small ribs and recesses. Locate these features on surfaces that are as nearly perpendicular to die motion as possible, and locate them away from zones of wiping metal flow.

Raised lettering and numbers can be produced by milling recesses in the die. It is more difficult to achieve die projections that will form recessed symbols on the forging.

DESIGN FOR MANUFACTURING

Radii

Forgings are designed with radii on all their external corners except at the parting line.

It would require a sharp internal angle in the die to form a sharp corner on the forging.

This is a vulnerable stress raiser; also, excessive pressure would be required to fill sharp corners. Both considerations suggest generous corner radii.

A common practice is to call for full radii at the edges of all ribs and the same radius on each corner of a boss, web, or other shape.

Fillet radii on a forging correspond to corners in die impressions that metal must round to fill ribs and bosses.

If metal flows past a sharp corner and then doubles back, the forging may be flawed with a lap or cold shut, and the die may not fill completely. This is more likely if the sharp die corner or sharp fillet in the forging is near the edge of the piece.

DESIGN FOR MANUFACTURING

While all radii should be ample for easy forging, they can be made smaller in readily forgeable metals whenever there is a good reason for doing so. Adding forging costs should be justified by the benefits gained.

The deeper the impression, the larger the radius should be, both at the fillet around which metal must flow and at the corner that must fill with metal.

Typical Minimum Radii for Forgings

	Minimum radius, mm (in)	
Depth of rib or boss, mm (in)	Corner	Fillet
13 (½)	1.6 (1/16)	5 (3/16)
25 (1)	3 (⅛)	6.3 (¼)
50 (2)	5 (3/16)	10 (⅜)
100 (4)	6.3 (¼)	10 (⅜)
200 (8)	16 (⅝)	25 (1)
400 (16)	22 (⅞)	50 (2)

DESIGN FOR MANUFACTURING

Machining Allowance

Design features that promote easy forging add to the metal that must be machined away. Ample draft angles, large radii, and generous tolerances can all have this effect.

The machining allowance should allow for the worst-case buildup of draft, radii, and all tolerances.

Extra metal is sometimes provided to keep critical machined surfaces away from the grain-flow pattern that occurs in the flash region near the parting line.

Machining allowances or finishing allowances are added to external dimensions and subtracted from internal dimensions.

DESIGN FOR MANUFACTURING

TOLERANCES

Dimensions generally parallel to the parting plane and perpendicular to die motion are subject to length and width tolerances.

When a forged projection extends more than 150 mm from the parting plane, dimensions to its extremities, measured parallel to die motion, are also subject to these tolerances.

Length and width tolerances are commonly specified at 0.3 percent of each dimension, rounded off to the next higher 1⁄2 mm.

DESIGN FOR MANUFACTURING

Die-Wear Tolerances

These tolerances apply only to dimensions generally parallel to the parting plane and perpendicular to die motion.

While this tolerance is applied routinely to all horizontal dimensions, as a practical matter, dies are subject to severe wear only in the zones of harsh metal flow.

Multiply each horizontal dimension by the appropriate factor, and round off the tolerance to the next higher 1⁄2 mm

Typical Die-Wear Tolerances*

Alloy family	%
Aluminum, 2014 (UNS-A92014)	0.4
Aluminum, 7075 (UNS-A97075)	0.7
Magnesium	0.6
Brass and copper	0.2
Mild steel	0.4
Alloy steel	0.5
Martensitic stainless steel	0.6
Austenitic stainless steel	0.7
Titanium	0.9
Superalloys	0.8
Refractory alloys	1.2

*Plus variations of external dimensions and minus variations of internal dimensions.

DESIGN FOR MANUFACTURING

Die-Closure Tolerances

Dimensions parallel to die motion between opposite sides of a forging are affected by failure of the two die halves to close precisely.

Effects of die wear on these vertical dimensions are included in the die-closure tolerances. An added tolerance of 0.3 percent applies to any projection that extends more than 150 mm from the parting plane.

DESIGN FOR MANUFACTURING

Straightness Tolerances

For relatively long, thin parts, a typical straightness tolerance is 0.3 percent of length.

When this aspect of forging accuracy is critical, forged parts are often straightened in secondary cold operations.

Flash-Extension Tolerances

The most common flash-removal method is by a punching operation in contoured dies. This may produce clean, trimmed edges, but a small bead of flash is allowed.