STEEL CASTINGS HANDBOOK

SUPPLEMENT 1

DESIGN RULES AND DATA

STEEL FOUNDERS'
SOCIETY OF AMERICA

STEEL CASTINGS HANDBOOK SUPPLEMENTS

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Steel Castings Handbook
Supplement 1

Design Rules and Data

Preface

The casting process frees the designer from the rigid lines and angles of fabricated construction. It allows him to use curves, generous fillets and section thickness changes to place metal where it is needed for strength while still reducing weight and improving appearance. Yet, there are certain basic rules for optimum design.

Rules governing the design of steel castings are based upon 1) the fluidity and solidification of steel, 2) the mechanical principles involved in the production of cores and molds, 3) cleaning, and 4) machining requirements, and 5) functionality and weight considerations. They should be understood by the designer so that steel castings can be designed as such and not merely adapted from designs for parts produced from other materials or by other methods. Quality, soundness, strength and serviceability of steel castings begin on the drafting board, not in the foundry.

That basic fact is presented in the following easy to use review of steel castings design rules. It includes data and examples to illustrate these rules which are applicable to numerous casting configurations. A more detailed discussion on designing steel castings is found in part two, chapters four through eight of the 5th Edition of the Steel Castings Handbook, published by the Steel Founders' Society of America.

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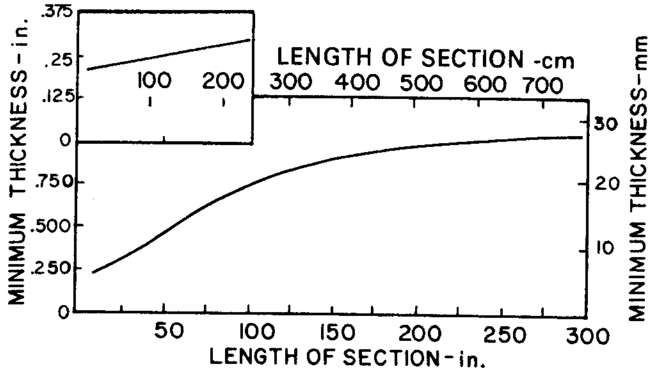


Fig. 1 Minimum thickness of sections as a function of their largest dimension. Note: The curve represents the best design condition wherein molten steel enters at one position of the casting and must run the lengths prescribed on the chart. Special techniques may permit the running of thinner sections than shown.

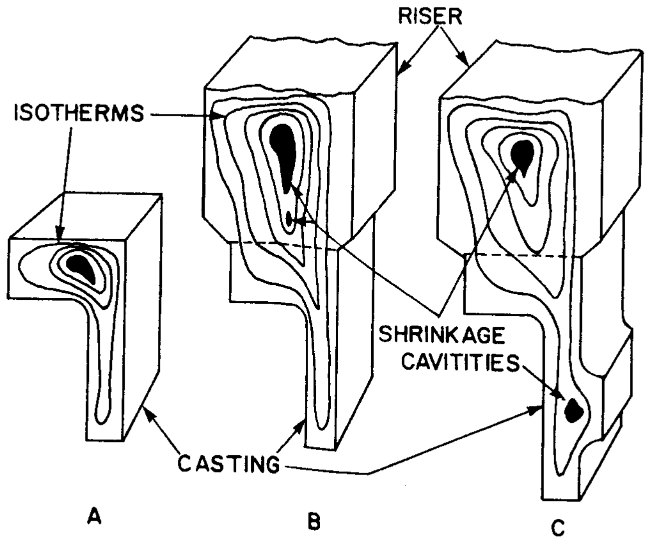


Fig. 2 Formation of shrinkage cavities.

Close and effective cooperation between design engineers and foundry engineers is necessary because a quality product at the lowest cost can be manufactured only after the fundamental principles of acceptable engineering practice are understood and applied in the casting drawing.

Manufacturing costs and, hence, selling prices are measurably affected by casting design and adherence to the fundamentals. It is almost axiomatic that a cast design that results from a thorough analysis of service stresses and expected use combined with the application of design fundamentals from the foundry standpoint will yield the most economical part.

Specific design characteristics with respect to achieving optimized manufacturing economics are discussed below.

CASTABILITY

Minimum Section Thickness

The rigidity of a section often governs the minimum thickness to which a section can be designed. There are cases, however, when a very thin section will suffice, depending upon strength and rigidity calculations, and when castability becomes the governing factor. In these cases it is necessary that a limit of minimum section thickness per length be adopted in order that cast steel sections will fill out completely.

Molten steel cools rapidly as it enters a mold. In a thin section, close to the gate which delivers the hot metal, the mold will fill readily. At a distance from the gate, the metal may be too cold to fill the same thin section. A minimum thickness of 0.25 in. (6 mm) is suggested for design use when conventional steel casting techniques are employed. Wall thicknesses of 0.060 in. (1.5 mm) are common for investment castings and sections tapering down to 0.030 in. (0.76 mm) can readily be achieved.

It should be pointed out that for a given thickness, steel flows best in a narrow, rather than in a wide, web. If the 0.25-in. (6 mm) thick section is longer than 12 in. (30 cm), then additional thickness should be provided in accordance with the values of Figure 1. The curve of this chart represents the best design conditions wherein molten steel enters at one position of the casting and must run the lengths prescribed on the chart. The designer should recognize that provisions may be made by the foundryman through the application of special techniques to pour even longer members through thinner sections than indicated by the graph. However, such applications are usually responsible for increased cost of production.

INTERNAL SOUNDNESS—DIRECTIONAL SOLIDIFICATION

Steel castings begin to solidify at the mold wall, forming a continuously thickening envelope as heat is dissipated through the mold-metal interface. The volumetric contraction which occurs within a cross section of a solidifying cast member must be compensated by liquid feed metal from an adjoining heavier section, or from a riser which serves as a feed metal reservoir and which is placed adjacent to, or on top of, the heavier section.

The lack of sufficient feed metal to compensate for volumetric contraction at the time of solidification is the cause of shrinkage cavities. They are found in sections which, owing to design, must be fed through thinner sections. The thinner sections solidify too quickly to permit liquid feed metal to pass from the riser to the thicker sections.

Risers are only effective within certain limits. The casting design may be such that it is impossible to feed isolated sections of increased mass. For example, section A in Figure 2 would have a shrinkage cavity at the position shown if the section were not fed by a superimposed riser as shown in B. The manner in which the casting solidifies is shown by the isotherms in the casting and riser. The boss located on the lower part of casting C will contain a shrinkage cavity, unless

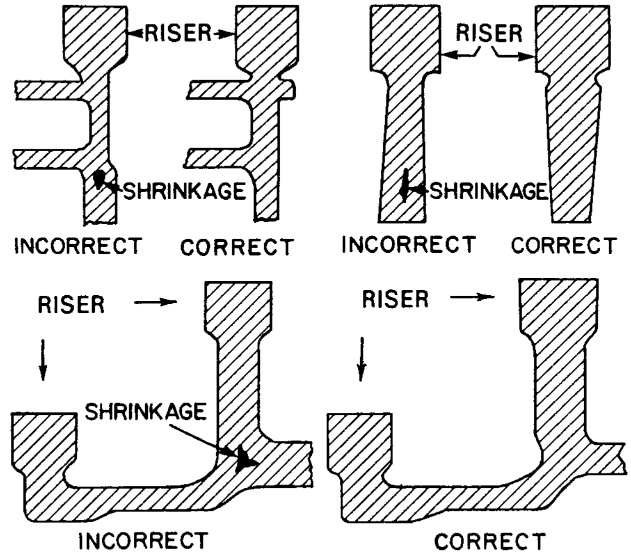


Fig. 3 Schematic examples of design sections showing correct arrangements to improve casting soundness (1).

chills are used as discussed later, as the riser will not feed a heavy section through a lighter section in the normally constructed sand molds.

Joint efforts by design engineers and foundry staff are beneficial if optimum soundness, i.e. freedom from shrinkage cavities, is desired for a cast part. These joint efforts are needed because the shape of a part can often be finalized for functionality as well as directional solidification. Directional solidification, beginning at the thinnest section, progressing through the heavier sections to the riser(s), ensures feeding and hence the absence of shrinkage cavities. Special aids, such as tapers, ribs, and chills may be used to enhance directional solidification conditions. These aids are discussed in the following paragraphs.

Tapers

Tapered designs are preferred in which all members of a casting increase in dimension progressively towards one or more suitable locations where risers can be placed to offset shrinkage as illustrated in Figure 3.

Recommended tapers, in./in. or cm/cm, of casting sections are computed according to the equation below:

$$\text{Taper} = -0.0164\,W + 0.0648\,T$$

W represents the width of the section (in. or cm) and T its thickness (in. or cm). In the case of plates, the value for W should be taken as 2T.

It is suggested that the metal taper values should be uppermost in the mind of designers who require radiographically sound sections. The required taper can then be built into the design initially.

Padding

If design parameters do not permit the use of a continuous taper on a casting section, then the foundry engineer must resort to the use of metal padding to bridge the gap between one heavy section and another isolated heavy section, so that directional solidification may proceed through the thinner joining member.

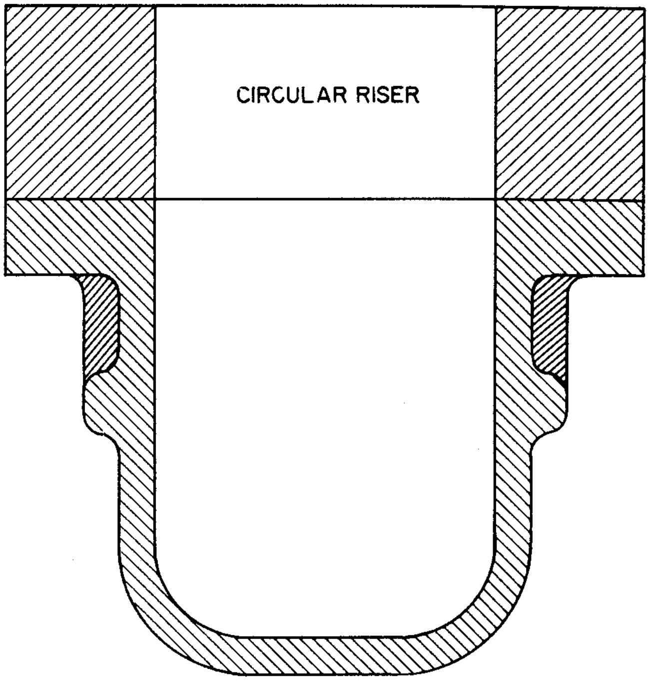


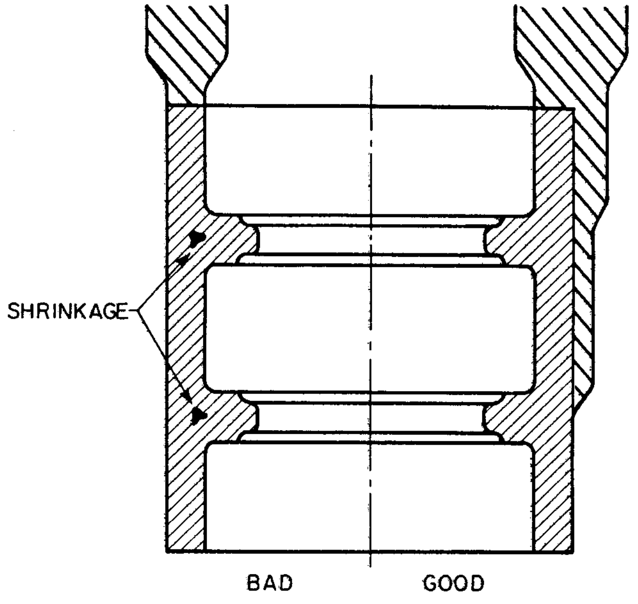
Fig. 4 Cross section of pressure vessel design showing added padding to feed an isolated heavy section (2).

Forcing the foundry engineer to resort to metal padding to eliminate shrinkage cavities in an isolated heavy section immediately raises production costs. First, the yield of good castings poured from a given heat of steel decreases since the padding metal is extraneous, and secondly, cleaning costs in processing the casting increase since the padding must be removed by arc-air washing and subsequent additional grinding time. Pad removal may also adversely affect surface appearance.

Illustrations of a cast design requiring the use of metal padding to eliminate shrinkage cavities are shown in Figures 4 and 5.

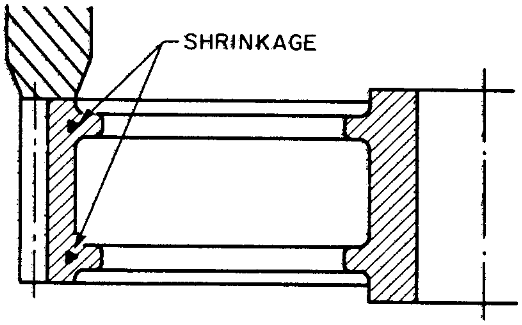
Chills

Chilling is another method used to reduce or eliminate shrinkage. In silica sand molds either chromite or zircon sand may be used as a chill for thinner casting sections. In addition to these materials metal chills are widely employed. Chills are designed to conform to the contour of the surface of the casting to be chilled. Metal chills are incorporated into the mold or into a core by ramming sand around the chill during molding or coremaking. Chills remove heat from the surface of the casting at a much faster rate than the surrounding mold wall. If the thickness of the chill is calculated correctly, the foundry engineer can impart directional solidification toward a riser from an adjacent heavier section and thereby eliminate the shrinkage cavity in the portion of the casting affected

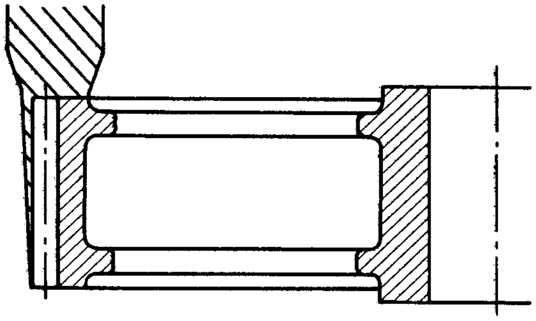


BAD GOOD

ROLL CASTING



BAD ARRANGEMENT



GOOD ARRANGEMENT

GEAR WHEEL

Fig. 5 Examples of padding for enhancement of riser feeding characteristics in roll casting and gear wheel (**2**).

by the chill. An illustration of this chilling effect on a boss is shown in Figure 6.

Joined Sections and Ribs

All steel casting designs are combinations of various geometric shapes, such as plates, bars, cubes, cylinders, etc. joined together in one continuous development to produce a functioning end product. One of the major advantages of designing with steel castings is the ability to place metal exactly where the designer wants it. However, as pointed out earlier in the text, wherever sections join together, an increase in mass occurs. These areas of largest mass must be fed by risers, or shrinkage cavities will occur in these areas. Conversely, the designer must attempt to design isolated masses out of his product, or at least minimize the occurrence of these isolated masses.

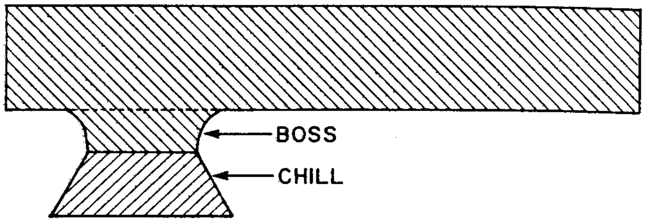


Fig. 6 Isolated boss-chill accelerates heat extraction.

The following paragraphs describe the methods to be used by the design engineer to *minimize heat concentration* in joining sections and ribs through the use of the inscribed circle method.

The increased mass at a joint can be estimated by the inscribed circle method shown in Figure 7. A general rule is that the increase in mass at the joint is proportional to the square of the ratio of diameters, $(D/d)^2$, and that this ratio *must be as small as possible.*

Tie-in members, ribs, or webs usually join the walls in a *T*-function.

As shown in Figure 8, the rib or web should be as thin as possible consistent with other requirements. If it is too thin, however, it may act as a cooling fin and upset the freezing and cooling of the casting. Figure 8 shows the proper proportioning of ribs and parent sections. Ribs should be staggered as shown in Figure 8 to avoid *X*-junctions.

A common use of brackets is shown in Figure 9. The heavy section flange at *A* would be hard to feed in some designs, so it is replaced with a thinner section, and reinforcing ribs are employed as shown in *B*.The sand at the junction of the rib, flange, and body is subjected to heat from three sides. To eliminate this hot spot, a cored hole is used as shown by Figure 10.

T, Y, and *X* Junctions

The rules for reducing hot spots described above for joined sections and ribs apply in principle to *T*, *Y*, and *X* junctions as shown in Figures 11 through 13. Referring to the inscribed circles, minimize the value of $(D/d)^2$ at all junctions to avoid unnecessary increases in mass.

The basic design rules for *T*-junctions are given in Figure 11 outlining the required relation between the thicknesses of the joining sections and the fillet radius at the junction to eliminate the foundry problems resulting from the *T*-junction construction.

Y-junctions are modifications of *T*-junctions, but *Y*'s present manufacturing difficulties which can be

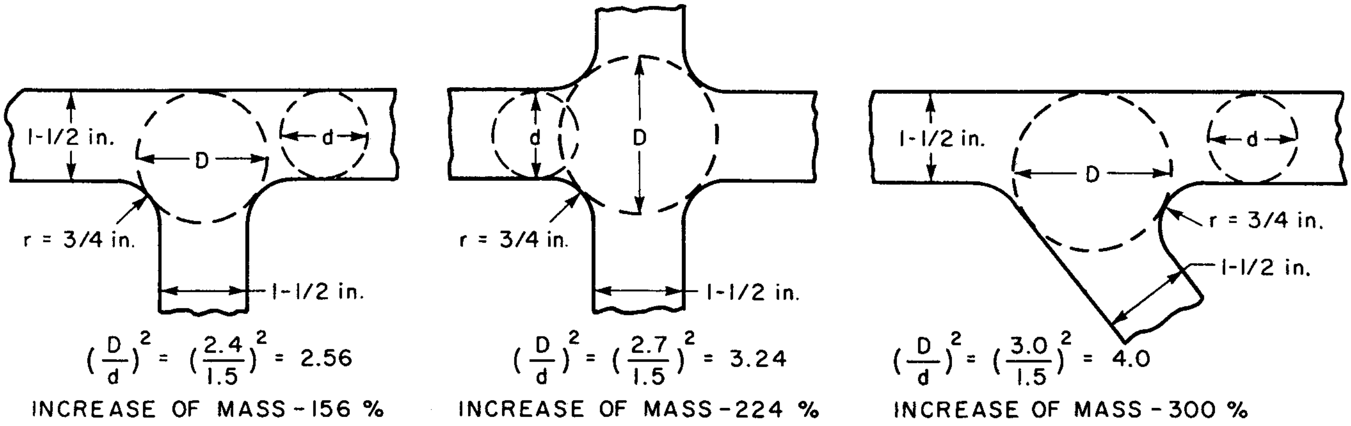


Fig. 7 Increase of mass resulting from joining sections.

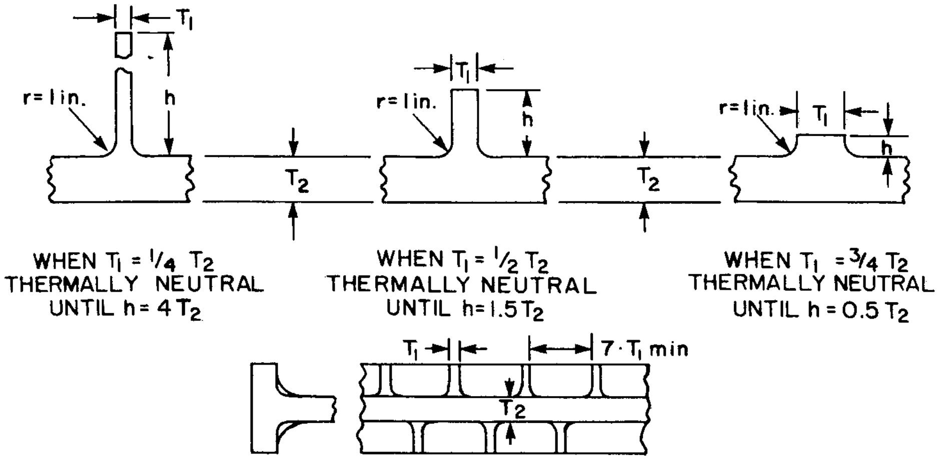


Fig. 8 Rib thickness for several *T*-junctions which are thermally neutral.

minimized if *Y*-junctions may be changed to *T*'s as shown at *B* in Figure 12. If a *Y*-junction must be used, it should be designed according to example A of Figure 12.

X-junctions are common in many designs but are especially difficult to cast sound and give rise to stress concentrations which may cause failure. If *X*-junctions must be used, the fillets should have a radius of 1 in. (25.4 mm). Good design practice takes advantage of the flexibility of the casting process to eliminate trouble-causing *X*-junctions where possible.

One method of improving the troublesome design of *X*-junctions is to core out the junction as shown in Figures 13 and 14. Another method is to offset the parts of one section to make two *T*-junctions. This is shown in Figure 15.

The *X*-junction is replaced here by a series of *T*-junctions and the design rules of Figure 11 must be observed for each junction.

A practical application of eliminating *X*-junctions in a commercial casting by the use of good casting design principles is shown in Figure 14. Figure 14A shows a grid designed with a number of *X*-junctions. The grid in Figure 14B does the same job but with *Y*-junctions instead of *X*'s.

For *X*-junctions, offset the two parts of one section as shown by Figure 15.

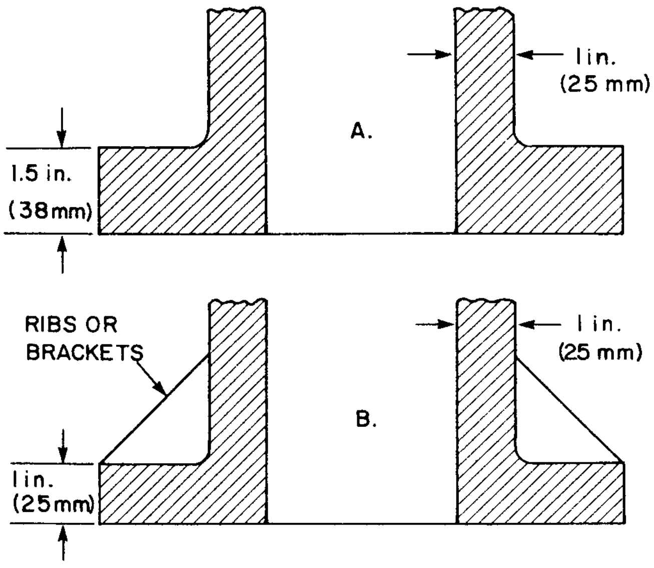


Fig. 9 Rib to increase rigidity and decrease weight.

Bosses, Lugs, and Pads

Bosses and pads increase the metal thickness, create hot-spots, and cause shrinkage. They should be blended into the casting by tapering or flattening the fillets. Bosses should not be included in the casting design

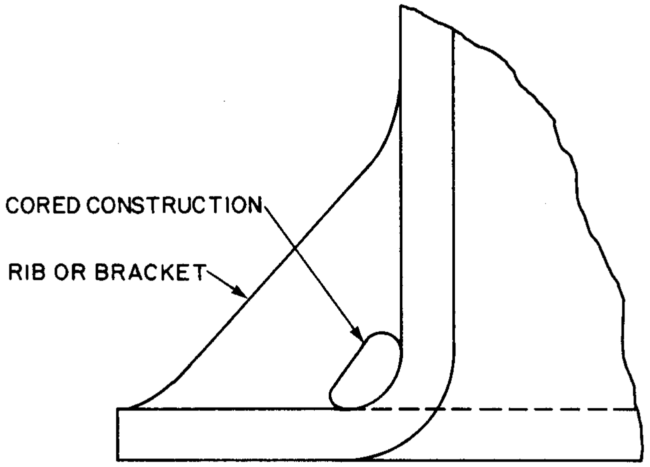
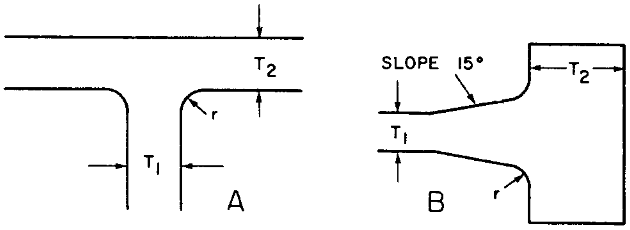
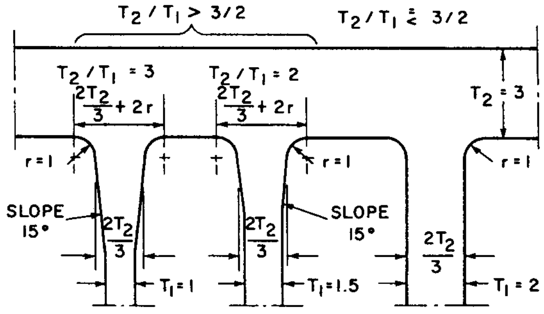


Fig. 10 Use of core to eliminate hot spot in rib design.

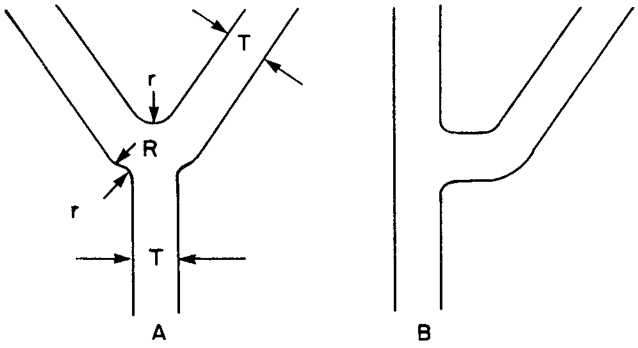


r = T_1, BUT NEVER LESS THAN 1/2 in. (13 mm) OR GREATER THAN
1 in. (25 mm) IF T_2 IS $< 1.5\ T_1$, THEN $r = T_1$ AS SHOWN IN SKETCH A
IF T_2 IS $> 1.5\ T_2$, THEN $r = T_1$ AS ABOVE WITH A 15° SLOPE
TO FIT THE RADIUS AS SHOWN IN SKETCH B
$T_2 - T_1$ = MINIMUM LENGTH OF SLOPE



T_2 MUST ALWAYS BE $\geqq T_1$

Fig. 11 Basic design rules for *T*-junctions.



r = 1.5 T BUT NOT < 1.5 in. (38 mm)
R = r + T
r = 1 in. (25 mm)

Fig. 12 *Y*-junction and *T*-junction arrangements.

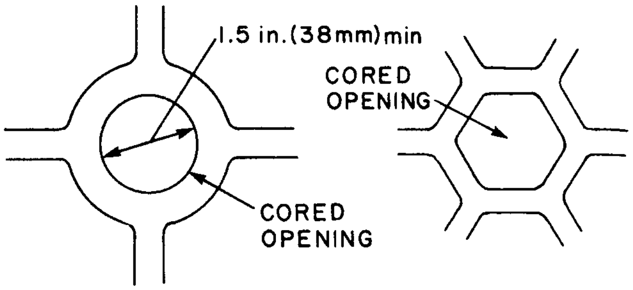
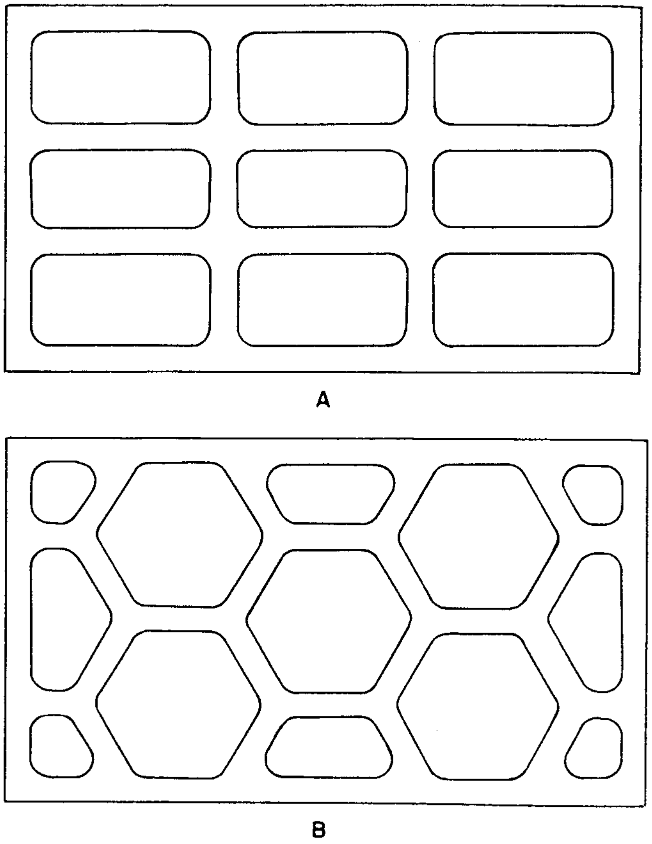


Fig. 13 Cored opening to improve *X*-junction.


A

B

Fig. 14 Grid design with and without *X*-junction.

when the surface to support bolts, etc., may be obtained by milling or countersinking (1).

When bosses and pads are required, their thickness should preferably be less than the thickness of the casting sections they adjoin, but thick enough to permit machining, without touching the casting wall (Figure 16). Where the casting section is light and does not permit use of this rule, Table 1 can serve as a guide for minimum recommended heights.

When there are several lugs and bosses on one surface (Figure 17), they should be joined to facilitate machining if possible. A panel of uniform thickness instead of many pads of varying heights simplifies machining (1). A continuous rib, instead of a series of bosses, also permits shifting hole location. An alternate design to heavy bosses is shown in Figure 18.

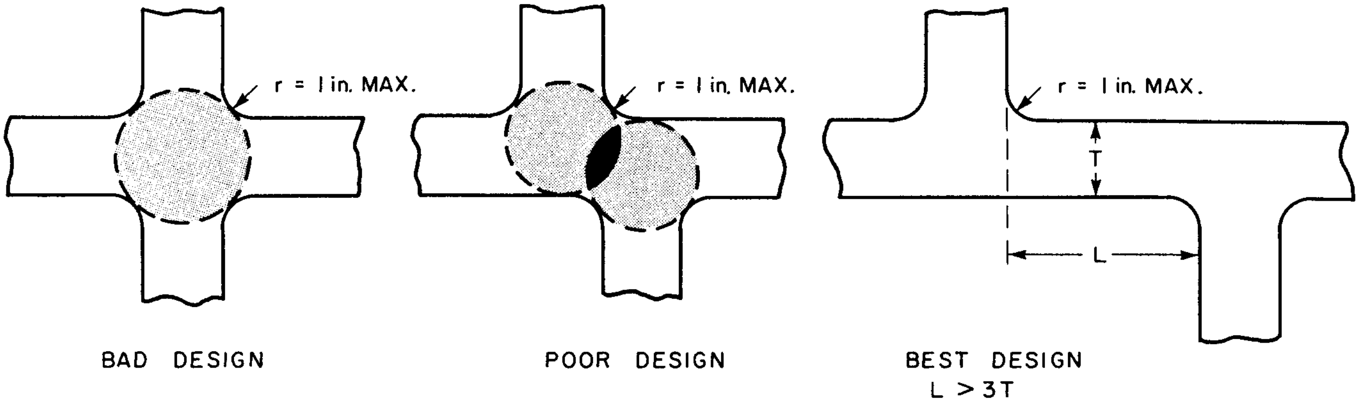


Fig. 15 Eliminate *X*-section where possible.

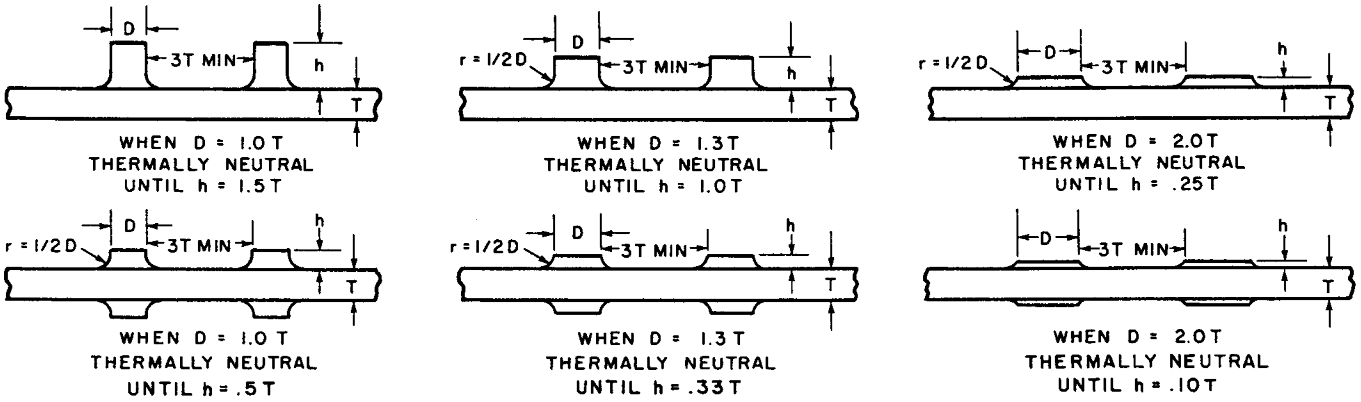


Fig. 16 Boss design.

TABLE 1 Height of Boss Versus Casting Length (1)

Approx. Casting Length		Height of Boss	
in.	(mm)	in.	(mm)
Up to 18	(up to 457)	0.25	(6)
18–72	(457–1830)	0.75	(19)
72–over	(1830–over)	1.00	(25)

Cored Openings

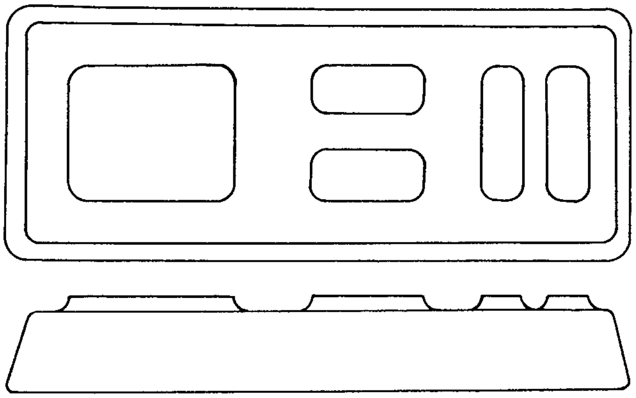
Isolated, heavy masses can often be redesigned to avoid occurrence of center line shrinkage by removing the center of a heavy mass through the use of a core.

This lightening technique changes the area of heavy mass to a more uniform section which can often eliminate the foundry engineer's problem of feeding this area. Illustrations of this approach are seen in Figures 10 and 18.

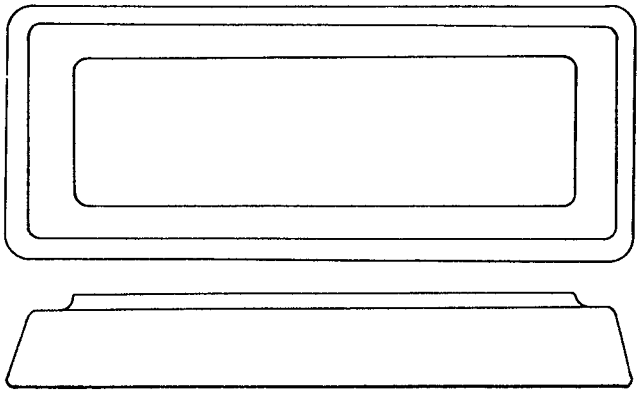
SURFACE INTEGRITY

In previous paragraphs, the problem of designing against the buildup of mass to eliminate or reduce the occurrence of shrinkage cavities has been dealt with. A parallel problem deals with the effect of manufacturing design on surface integrity of a steel casting, i.e. absence of surface discontinuities.

Cracks or hot tears tend to occur at changes in section or junctions unless proper design rules are followed. These areas represent hot spots and are



INCORRECT



CORRECT

Fig. 17 Redesign of numerous bosses (1).

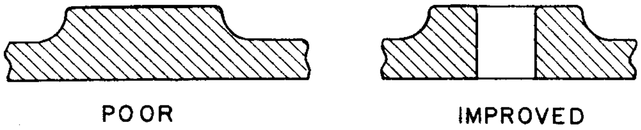
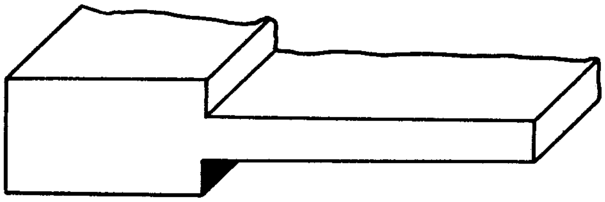
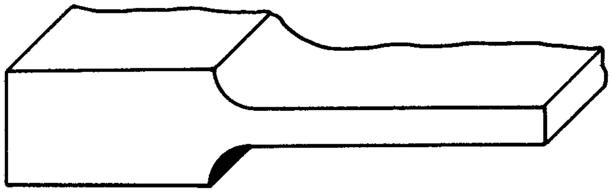


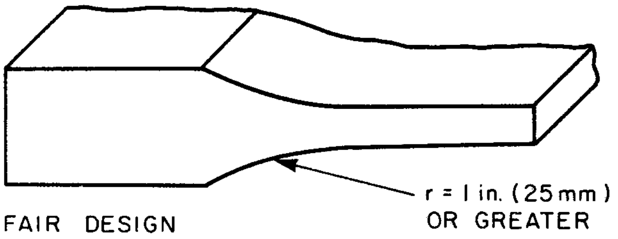
Fig. 18 Redesign of boss to cored opening.



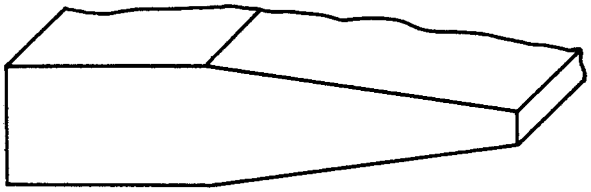
A. POOR DESIGN



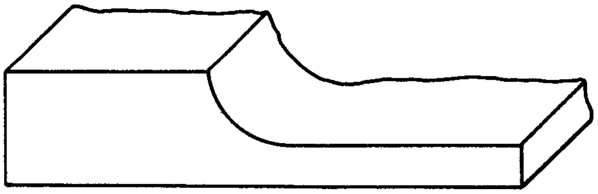
B. NOT RECOMMENDED



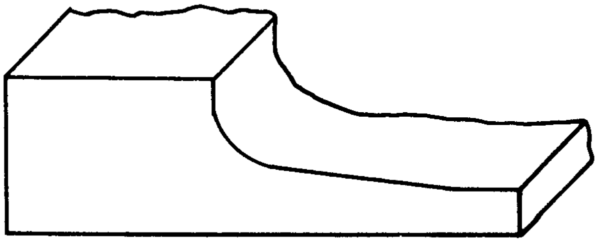
C. FAIR DESIGN



D. FAIR DESIGN



E. GOOD DESIGN - RECOMMENDED



F. GOOD DESIGN - RECOMMENDED

Fig. 19 Changing section thickness.

therefore particularly susceptible to hot tears because they solidify last and tear more readily than the adjacent sections when strain is imposed due to hindered contraction.

Failure to incorporate the design guidelines which follow can result in the formation of discontinuities, such as hot tears and cracks which cause costly removal, repair, and production delays. The repair may involve welding, weld dressing, further inspection, and finally a stress relieving heat treat cycle. Because all of these processing steps add considerably to the product cost, it is most advantageous for the customer to insist upon close cooperation between his designers and foundry staff in the design, prior to constructing the pattern. Joint designs may avoid these production problems, lower part costs, and often enhance visual appeal of the part and its functionality.

Changes in Section Size

While it is sometimes desirable that all sections in a part be designed with a uniform thickness, it is recognized that there are times when the designer has no alternatives and sections must incorporate relatively abrupt changes in thickness. Sharp corners and small radii at a change of section should be avoided whenever possible because they are responsible for stress concentration during solidification and also later in service.

The designer's use of the rules spelled out in the following paragraphs will aid the foundries in their quest to produce castings of high surface integrity at reasonable cost.

Changes in section thickness should be gradual. Figure 19 shows several designs for making changes in thickness of casting sections, according to the following rules:

Rule A. Sharp re-entrant angles or small fillets are not recommended (Figures 19A and B).

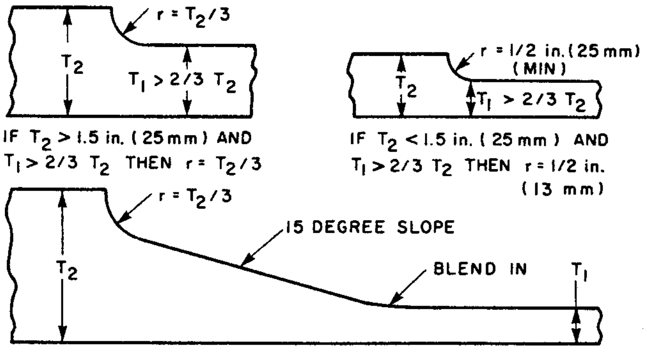
Rule B. A fair design results if both sections have a common center line provided they are joined by a 15° taper or by a radius of 1 in. (25.4 mm) or more (Figures 19C and D).

Rule C. The best design is one in which the change in section takes place entirely on one side of the thinner section (Figures 5-19E and F), and in which the junction is designed according to Figure 20.

Cylindrical sections of different diameters may be joined on a common axis under certain limitations. The following rules may be used where T_1 represents the thickness of the smaller section and T_2 the thickness of the larger section.

Rule A. If $T_1 = 1$ in. (25 mm), and $T_2 = 1\text{-}5/8$ in. (41 mm) then join with a 15° taper.

Rule B. If $T_1 = 1$ in. (25 mm), and $T_2 = 2$ in. (51 mm) then join with a fillet having a 1/2 in. to 1-1/2 in. (13 to 28 mm) radius.



IF $T_2 > 1.5$in. (38mm) AND $T_1 < 2T_2/3$, THEN $r = T_2/3$ WITH A 15 DEGREE SLOPE BETWEEN THE TWO PARTS. FOR EXAMPLE:
$T_1 = 1/2$ in. (13mm), $T_2 = 2$ in. (25mm), $r = T_2/3 = 2/3 = 7$ in. (18mm)
IN NO CASE MUST $r < 1.0$ in. (25 mm)
$T_2 - T_1$ IS THE MINIMUM LENGTH OF SLOPE

Fig. 20 Design rule for section thickness change.

Rule C. If $T_1 = 1/2$ in. (13 mm), and $T_2 = 1\text{-}5/8$ in. (41 mm) then do not join.

External Corners

High stress gradients develop when sharp external corners cool rapidly from high temperatures, particularly in the case of hardenable steel. The elimination of these high stress gradients by employing an external radius will do more than any other single step to prevent corner cracks. Rounded corners usually require an additional chamfering operation in any forming process other than casting.

An external corner radius of between 0.1 and $0.2T$ (T = section thickness) is necessary to avoid high thermal gradients.

Joined Sections and Ribs

The design rules for joined sections and ribs already presented on internal soundness apply equally in efforts to maximize surface integrity and reduce hot tears and cracks.

T, Y, and *X* Sections

The design rules on *T, Y,* and *X* sections already presented on internal soundness apply equally in efforts to maximize surface integrity and reduce hot tears and cracks.

Wave Construction

Wave construction is a design principle that should be mentioned in connection with the relief of internal stresses in cast structures. This design calls for the use of members which are slightly waved or curved.

A very good example of this type of construction is the use of curved spokes (Figure 21) in many classes of wheels. In such castings the rim, the hub, and the spokes may each cool at a different rate because of differences in their cross sectional areas, thus subjecting the casting to considerable internal stress. The use of the wave construction minimizes these internal stresses by allowing movement of the casting after solidification.

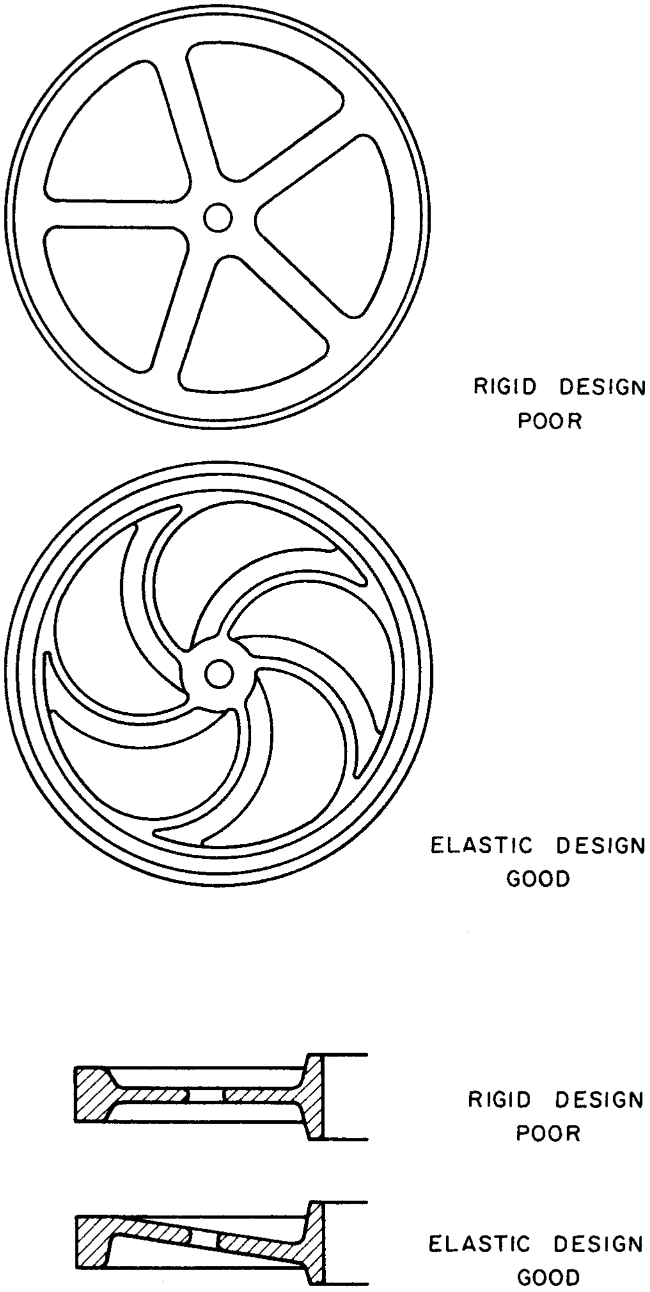


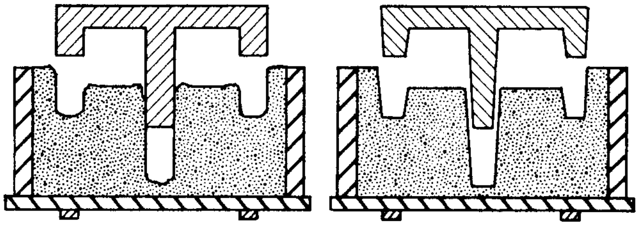
Fig. 21 Wave construction-elastic design.

DESIGN FOR MOLDING

Another aspect in designing steel castings, which the design engineer must consider, is the ability of the resultant shape to be molded economically.

The impact of proper design on molding and coremaking costs is significant. Such items as draft, undercuts, parting line, use of cores, and use of loose pieces all affect the direct labor cost in the foundry and the casting quality. The higher the quality level of the casting when it is shaken out of the mold, the lower the costs for cleaning, finishing, and upgrading to obtain a saleable casting.

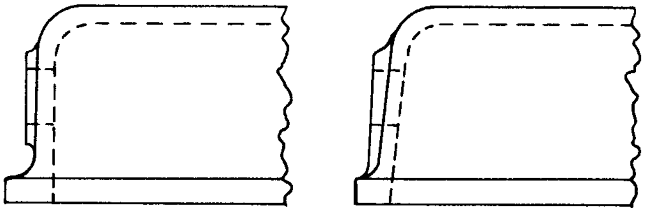
These items are considered in more detail in the following paragraphs.



WITHOUT DRAFT, MOLD PATCHING WILL BE NECESSARY

AMPLE DRAFT PERMITS EASY AND SAFE STRIPPING

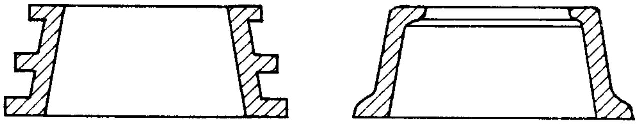
Fig. 22 Necessity for adequate draft (**1**).



INCORRECT A

CORRECT B

Fig. 23 Eliminate undercuts (1).



INCORRECT, OUTSIDE CORES A

CORRECT, NO CORES B

Fig. 24 Eliminate cores (**1**).

Draft

Draft is the amount of taper given to the sides of projections, pockets, and the body of a pattern so as to permit withdrawal from the mold without breaking the sand away. Draft should be added to the design dimensions but metal thickness must be maintained (see Figure 22) (**1**).

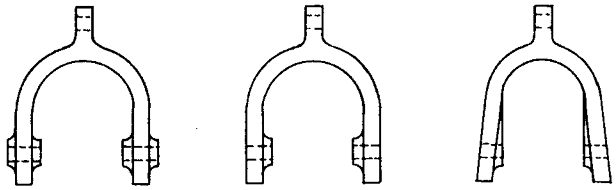
For general "one-off" or jobbing purposes, an average draft equals 1/16 in. per foot (about .5°). The specific draft to be employed depends upon the depth of the pattern in the flask and the manufacturing process. The selection of the draft should therefore be left to the foundry producing the part.

Undercuts and Loose Piece Patterns

Good casting design eliminates the need for loose pieces and outside cores. Undercuts, as shown by Figure 23A, involve the use of loose pieces or the use of cores. These increase costs and often serve no particular advantage. By eliminating the undercut as shown in Figure 23B, a much simpler and less costly molding procedure results (**1**).

The unnecessary use of ribs, lugs, and bosses increases costs. Engineers often place circular ribs around the outside of a casting to give strength, and to obtain a lighter structure as shown in Figure 24A. The external core work may be justified, but many times such ribbing may be redesigned to achieve substantial core cost reductions of 50% or more, as shown in Figure 24B and still achieve the desired structural requirements.

OMIT OUTSIDE BOSSES



INCORRECT, OUTSIDE & INSIDE CORES A

IMPROVED, INSIDE CORES B

CORRECT, NO CORES C

Fig. 25 Simplification of bosses (**1**).

Outside bosses which are not on the parting line require coring or use of loose pieces. Such designs as shown in Figure 25A increase molding or core costs. Pattern and molding or core costs can be reduced by omitting the outside bosses and leaving the inside bosses which require only a center core (Figure 25B). The design shown in Figure 25C is best in that it permits a straight draft and does not require the use of any cores or loose pieces (**1**).

Parting Line

Parting in one plane facilitates the production of the pattern as well as the production of the mold.

Patterns with straight parting lines, that is, with parting lines in one plane, can be produced easier and at lower cost than those with irregular parting lines.

Casting shapes symmetrical about one center line or plane readily suggest the parting. Such casting design simplifies molding and coring, and should be used wherever possible. They should always be made as "split patterns" which require a minimum of hand-work in the mold, improve casting finish, and reduce costs.

Designs necessitating the use of irregular parting involve more costly patterns and, unless machine molded, require more skillful molding.

Figure 26A shows a design which required an irregular parting line. By changing the design as shown in Figure 26B, substantial savings in production costs were achieved (**1**).

Cores

Number of Cores. A core is a separate unit from the mold and is used to create openings and cavities which cannot be made by the pattern alone. Every attempt should be made by the designer to eliminate or reduce the number of cores needed for a particular design to reduce the final cost of the casting.

A base plate where the original design was complicated, and involved the use of cores, is shown in Figure 27A. Figure 27B shows how, by a slight design change, cores were eliminated, thereby simplifying molding and reducing costs.

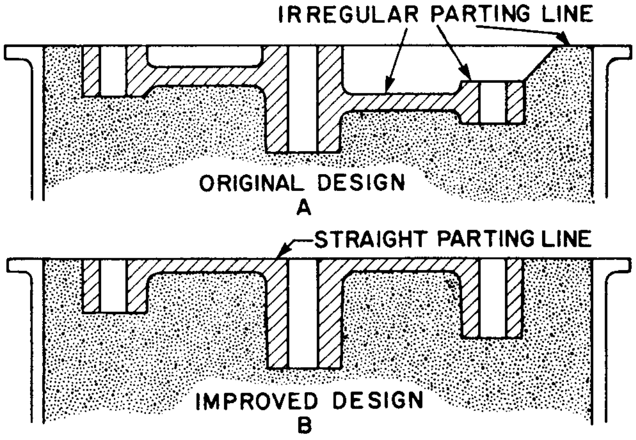


Fig. 26 Redesign for straight line parting (**1**).

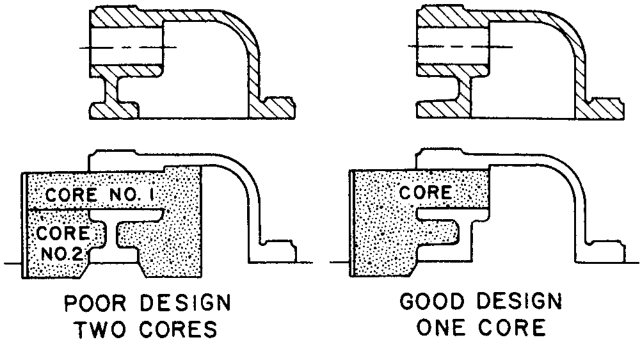


Fig. 28 Design illustrating reduction in number of cores.

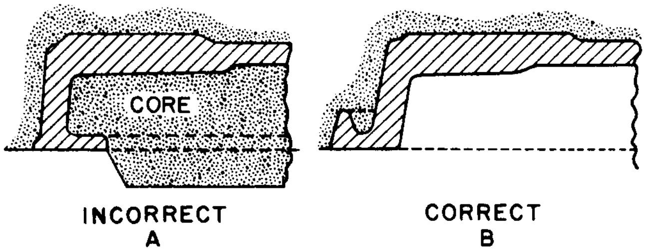


Fig. 27 Simplification of a base plate design to eliminate a core (**1**).

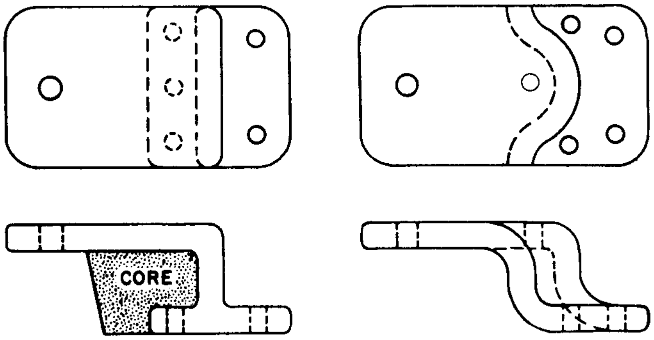


Fig. 29 Omega section design is applied in redesign of bracket to eliminate core and decrease stress problems.

Figure 28 shows how a change in a flange can affect the shape of cores, reduce the number of cores, and reduce the cleaning time for the casting.

Another example of eliminating a core by redesign is illustrated in Figure 29. Application of the Omega section design to the bracket casting decreased the stress concentration and at the same time eliminated a core.

Core Support and Core Strength. The minimum diameter of a core which can be successfully used in steel castings is dependent upon three factors: 1) the thickness of the metal section surrounding the core, 2) the length of the core, and 3) the special precautions and procedures used by the foundry. The adverse thermal conditions to which the core is subjected increase in severity as the metal thickness increases and the core diameter decreases. This, of course, is the result of an increasing amount of heat to be dissipated from the heavier metal sections, and reduced ability of the core to absorb and dissipate this heat as its diameter decreases. As the severity of the thermal conditions increases, the cleaning of the casting and core removal become much more difficult and expensive.

The thickness of the metal section surrounding the core, and the length of the core, both affect the bending stresses induced in the core by buoyancy forces and, therefore, the ability of the foundry to obtain the tolerances required. If the size of the core is large enough, rods can often be used to strengthen the core. Naturally, as the metal thickness and the core length increase, the amount of rodding required to resist the bending stresses also increases. Therefore, the minimum diameter core must also increase to accommodate the extra reinforcing.

The curves shown in Figure 30A indicate the recommended minimum core diameters to be used in cylindrical or boss sections in steel castings as a function of the metal section thickness and the core length.

Thus, the minimum core diameter recommended for normal foundry practice in a particular application can be determined by locating the point at which the curve representing the desired core length crosses a vertical line that represents the section thickness involved. These curves were prepared for cores placed in the horizontal plane only. Minimum core diameters determined from these curves can be reduced by 25% if the core is to be used vertically. A similar curve for cores in plate sections of steel castings is also shown in Figure 30B.

It is important to realize that these curves represent the minimum core diameter recommended for normal steel foundry practice. It is possible to use smaller diameter cores but it will involve the use of special practices and may increase cleaning cost. Applications which require smaller cores than those recommended here should be discussed with the producing foundry.

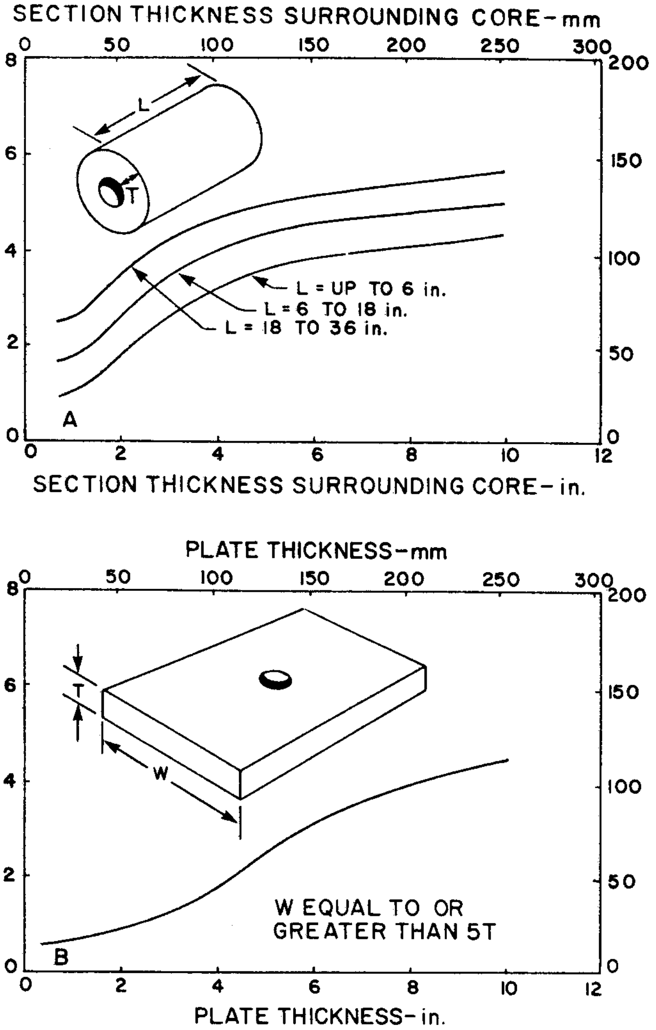


Fig. 30 A. Recommended minimum diameter for horizontal cores supported at ends only, in cylindrical or boss sections of steel castings. For vertical cores the minimum diameters can be reduced by 25%. B. Recommended minimum core diameter for plate sections in steel castings.

DESIGN FOR CLEANING

While major emphasis is placed on designing a cast component to obtain maximum internal soundness, surface integrity, and an economical molding design, consideration for subsequent cleaning and finishing operations is extremely important. The various finishing operations are discussed in more detail in Chapter 12*, and these operations are essentially labor intensive. Every effort to reduce the finishing time necessary to remove gates and risers, to simplify the core removal process, and to reduce the necessity to grind and snag off fins and padding ultimately lowers the price of the casting.

The cost of removing cores from casting cavities may become prohibitive when the areas to be cleaned are inaccessible. The casting design should provide for openings sufficiently large to permit ready access for the removal of the sand core. Figure 31A shows a casting which was uneconomical to produce because internal coring was difficult. The design was further complicated by the need for external cores. As redesigned in Figure 31B the casting was of uniform thickness, weighed less, and was stronger; a savings of 30% in patternmaking and production costs resulted. The cleaning time was reduced appreciably by eliminating the outside ring core and the inside core.

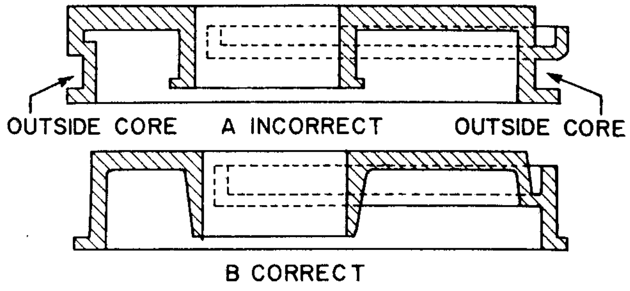


Fig. 31 Redesign to obtain uniform sections and eliminate core.

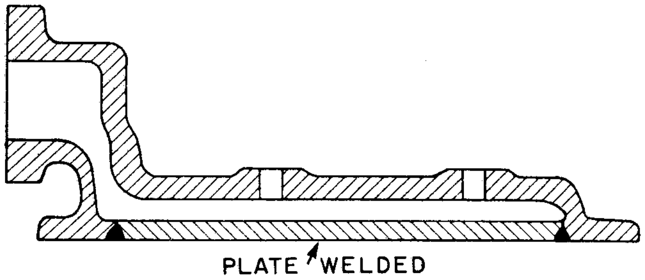


Fig. 32 Cast-weld design replaces a costly cored design that is difficult to clean.

Accessibility

An example of a common design for a steam ring is shown in Figure 32. The core for this casting is reinforced with metal rods to give the necessary strength. However, the openings through the ports are small and provide little access for removal of the core and to further clean the internal surfaces by shotblasting and grinding. The removal of the core and rods through these openings, therefore, results in high cost. The alternative design which incorporates the Omega design presents a steam chamber which can reduce costs by as much as 25%. A simple cut plate for a cast-weld construction is welded into the casting to produce the final steam ring design.

The original design of another example in Figure 33A provides six small holes at the top and one opening on the side for core removal causing extremely high cleaning costs. An improved design provides for substantially larger areas for core removal through the bottom as evident in the section A–B of Figure 33B. A plate is then added to close off the cylinder chamber.

The schematic illustration of a steam chest housing with an outer chamber in Figure 34 represents a complicated design from the core removal standpoint; it is more economically produced as a cast-weld construction where three separate castings are produced and welded together to develop the final design.

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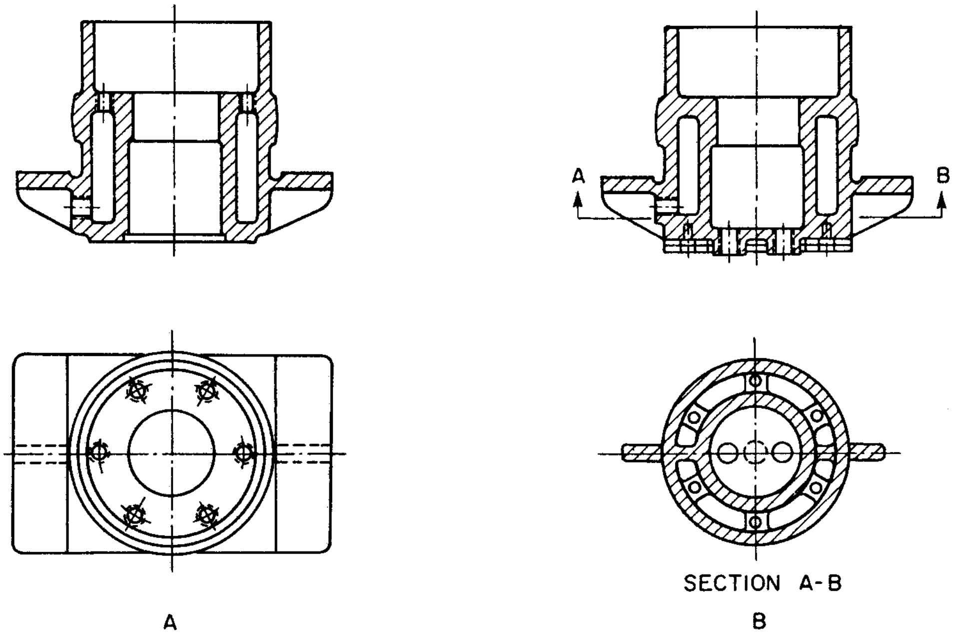

Fig. 33 Jacketed design for easier cleaning (3).

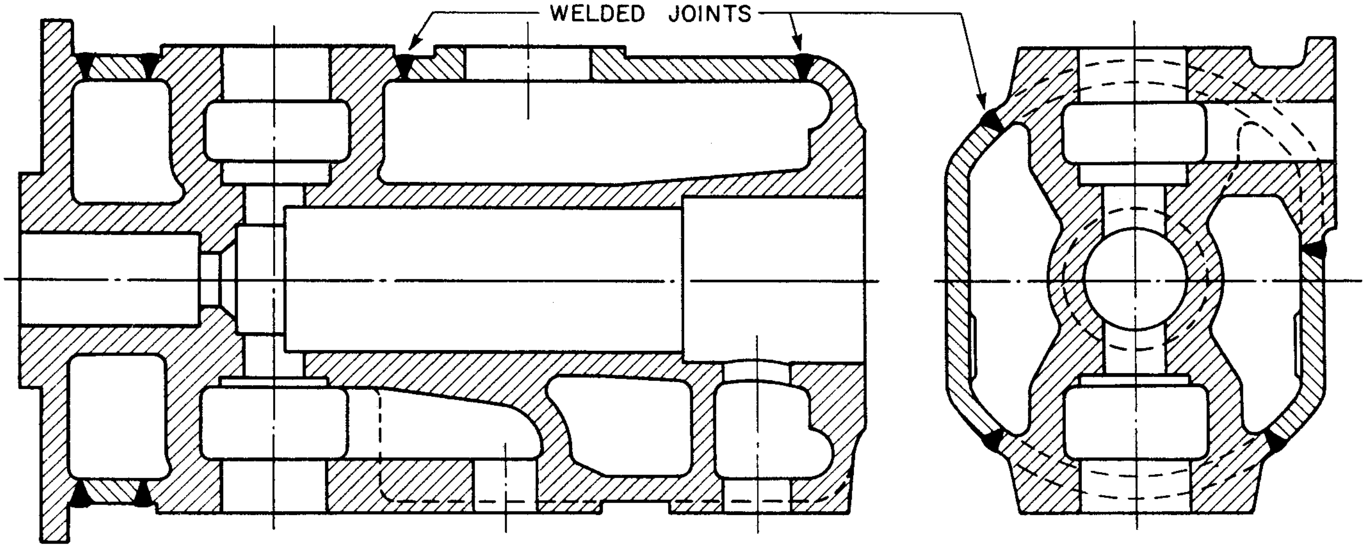

Fig. 34 Complicated cored design, best produced as a cast weld unit (3).

Cored Openings

The box or tubular section is efficient for complex loading as discussed in Chapter 4*. There are, however, three objections to these designs:

1) a core is required to form the section which adds to the cost,
2) inner surfaces increase the difficulty of inspection, and finally,
3) the cleaning costs are substantial for internal surfaces.

All of these objections can be overcome by employing the *U*-section of Figure 35C and D. Open-side sections do not give the properties about both axes that are obtainable in the box section, but the values are equivalent to the I-beam section in one position (Figure 51). In the other position the *U* is superior to the I-beam. The *U*-section can be designed with the radius equal to the wall thickness or with a radius to 1 in. (25.4 mm).

A variation of the *U*-section is the Omega section of Figure 36. This design is useful singly or in series. It is used to replace ribs and stiffening brackets and is the web design of tractor and trailer wheel centers. The design proportions of Omega are discussed in Table 3c.

DESIGN FOR MACHINING

Some types of castings are used in the entirely unmachined condition. A small percentage of the castings produced require a single machining operation or perhaps several, using the simpler machine tools and relatively inexpensive tooling set-ups. A much larger number of castings require a range of machining setups that present a large variation in machining costs

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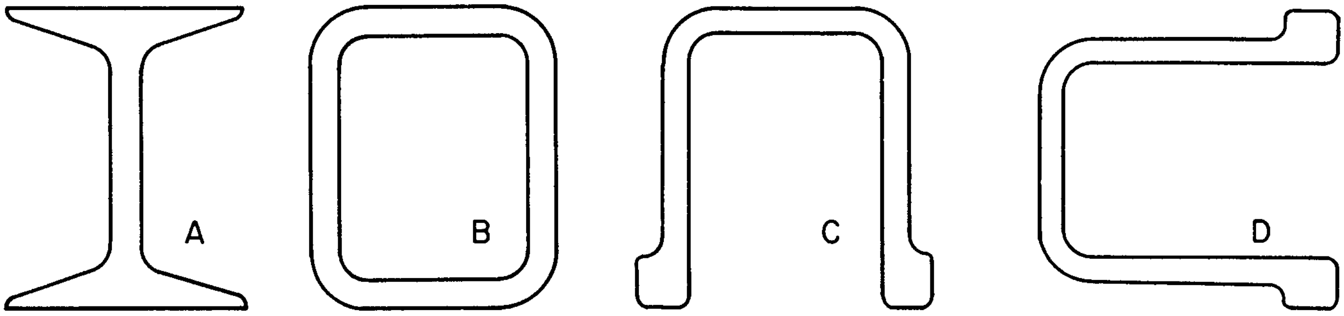

Fig. 35 Comparison of I-beam, box, and *U*-section designs.

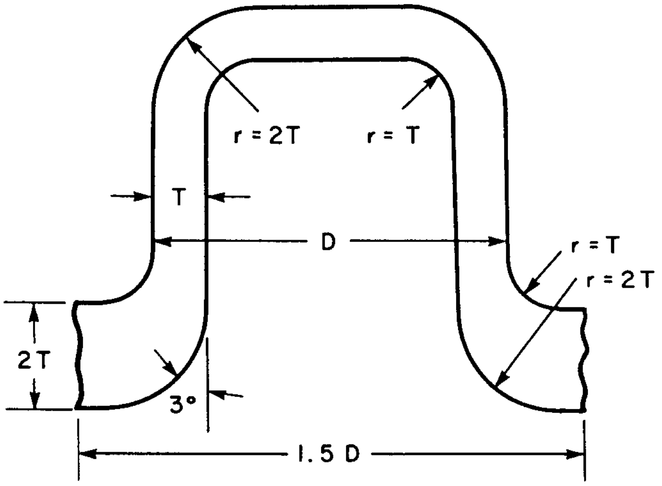

Fig. 36 Omega section design.

from a fractional percentage of the casting cost to a component design that is machine-cost intensive.

In the final analysis the foundry engineer is responsible for giving the designer a cast product that is capable of being transformed by machining to meet the specific requirements intended for the function of the part. To accomplish this goal a close relationship must be maintained between the customer's engineering and purchasing staff and the casting producer. Jointly and with a cooperative approach, the following points must be considered: (2)

1. The molding process and its limitations.
2. Machining stock allowance to assure clean-up on all machined surfaces (tolerance).
3. Design in relation to clamping and fixturing devices to be used during machining.
4. Selection of material specification and heat treatment.
5. Quantity of parts to be produced.

Layout

It is imperative that every casting design, when first produced, be checked to determine whether all machining requirements called for on the drawings may be attained. This may be best accomplished by having a complete layout of the sample casting to make sure that adequate stock allowance for machining exists on all surfaces requiring machining. For many designs of simple configuration that can be measured with a simple rule, a complete layout of the casting may not be necessary. In other cases, where the machining dimensions are more complicated, it may be advisable that the casting be checked more completely, calling for target points and the scribing of lines to indicate all machined surfaces. The illustration in Figure 37 represents one approach that may be used where a reasonably complicated casting is checked in reference to the three dimensioning planes, A, B, and C and the bosses which represent target points which are adjustable by grinding.

DESIGN FOR FUNCTIONALITY AND REDUCED WEIGHT

Valves and Fittings

Pressure vessels such as valves, fittings, and casings for turbines and various pumps must be designed with special attention to wall section thickness, the amount of pressure which the vessel must hold, and the relationship between the heavy sections that join adjacent walls.

The cast elbow in Figure 38 is used for high temperature and high pressure service. The original design with a uniform wall resulted in a 16% rejection rate. Redesign with adequate taper from the heavy flange substantially decreased the rejection rate, at the same time it yielded castings of high internal integrity that met required radiographic quality standards.

Figure 39 represents a fitting design that frequently is an integral component of valves and more complicated pressure vessels. The use of taper and rounded corners, internal as well as external, improves the quality and is recommended for pressure casting requiring nondestructive examination such as magnetic particle testing.

Indiscriminate use of stiffening ribs on pressure vessels can cause considerable trouble with leakage unless the ribbed sections can be arranged to be properly fed through a risering system or chilled to eliminate internal shrinkage.

A design containing *X* and *T* junctions is shown in Figure 40. The *X* junctions can be eliminated

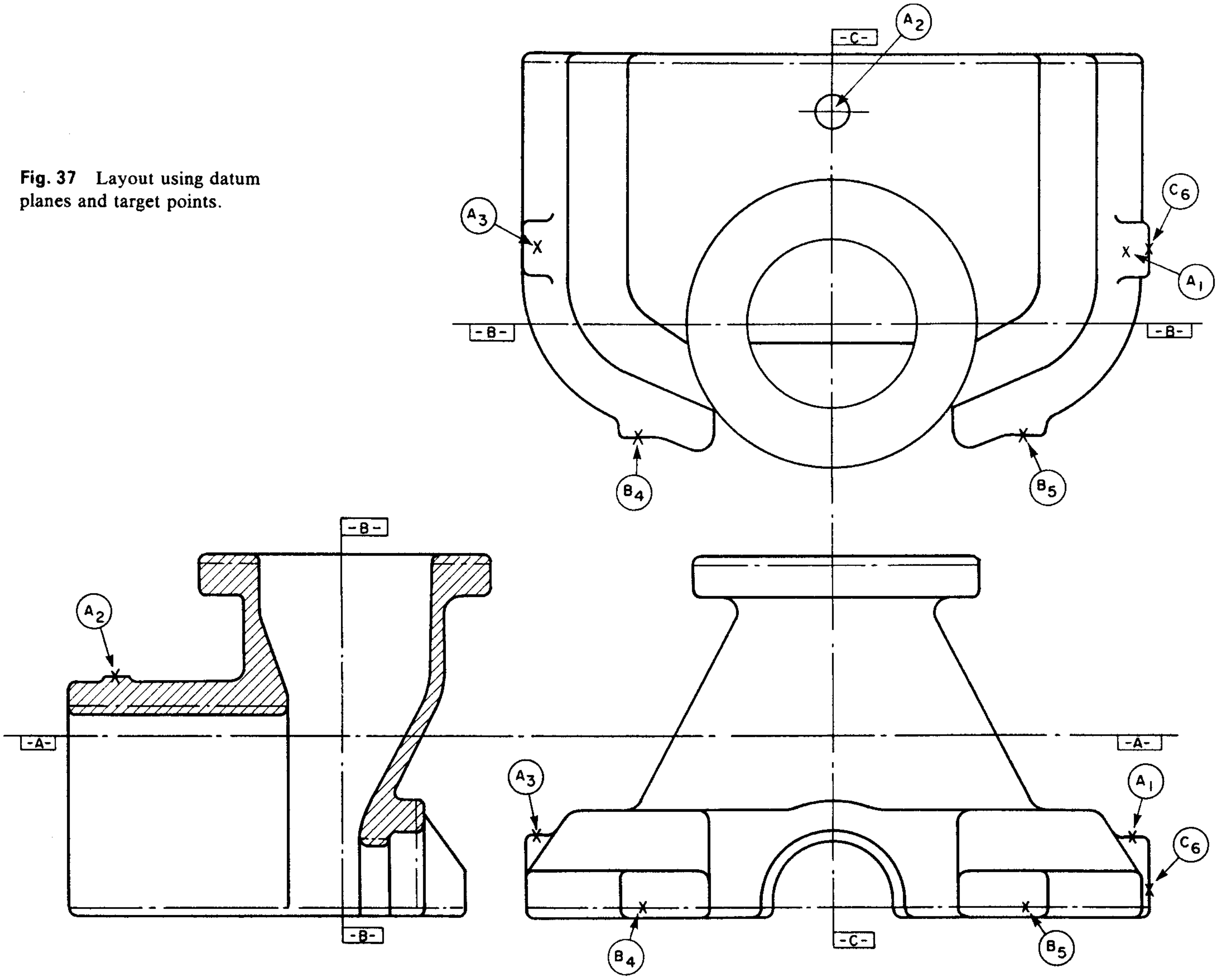

Fig. 37 Layout using datum planes and target points.

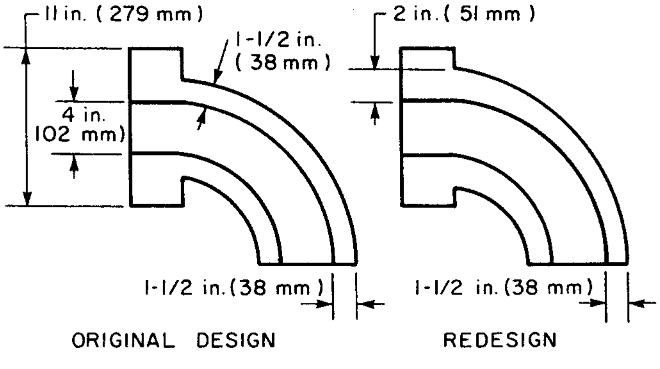

Fig. 38 Use of taper and radii to improve internal integrity of elbows.

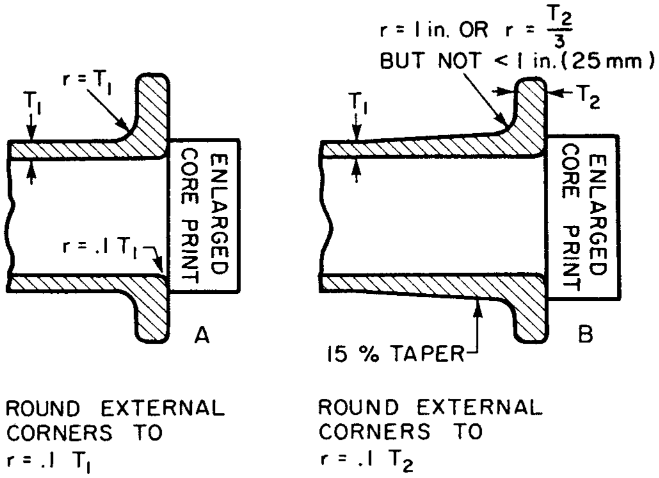

Fig. 39 Use of taper and radii to improve internal and surface integrity of fittings.

by producing staggered *T* sections. However, both *X* and *T* junctions can be replaced by using Omega sections repeated as corrugated sections. The section modulus is increased and the *T* junctions eliminated. The corrugated design will not affect the operation of the gate valve, since there is no liquid or gas flow through this part of the casting.

Padding and tapers properly placed by the foundryman may be necessary for casting production to improve internal integrity. If weight is not a considera-

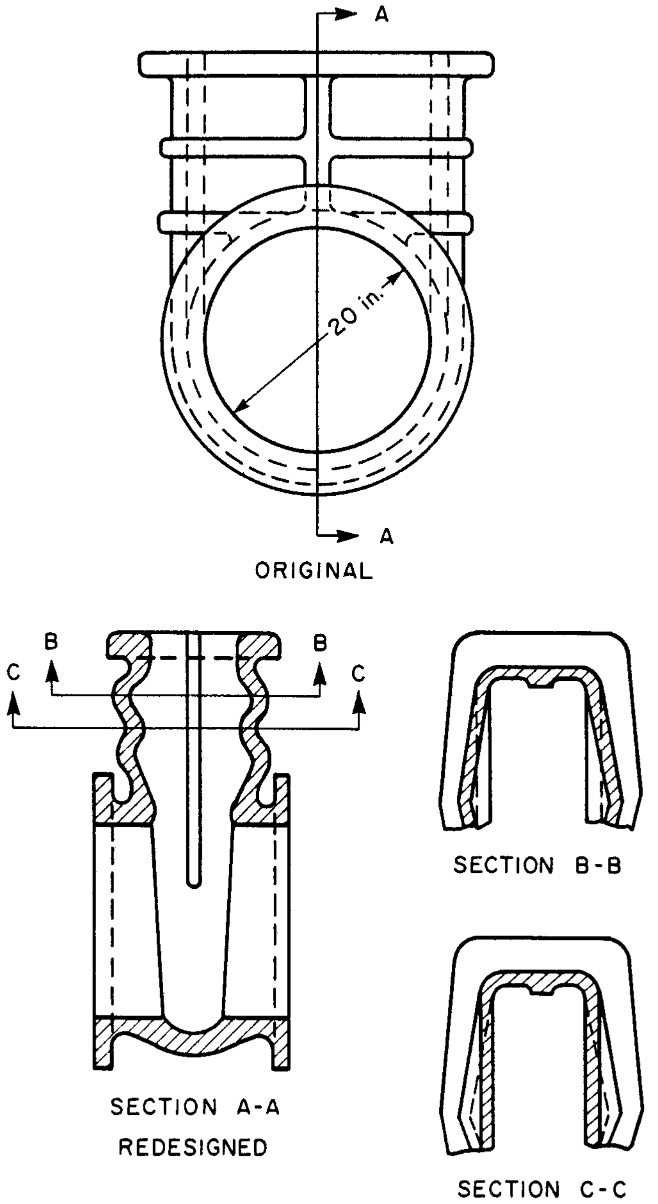

Fig. 40 Corrugated section substituted for intersecting ribs in valve casting. Section A-A with corrugated bonnet port walls.

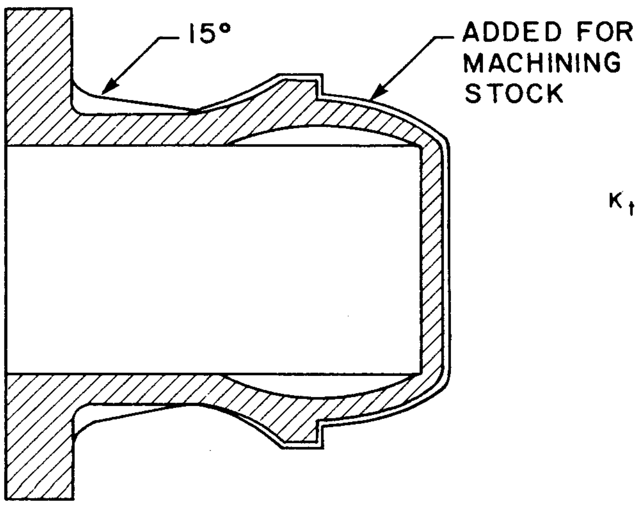

Fig. 41 Application of padding and tapers for improved casting production and internal integrity.

tion, the padding could be permitted to remain. An illustration of the use of properly placed padding is shown in Figure 41. The walls are tapered in two areas to enhance the internal integrity of the casting. This example is included to indicate how certain steel casting designers, working with foundry engineers, can design castings with sections that taper toward riser positions to permit higher degrees of solidity not always possible in uniform sections.

STRESS CONCENTRATION FACTORS

The stress distributions in structures are significantly modified by section changes, grooves, holes, and so on, so that high stresses may occur locally. The stress concentration factor, K_t, for these stress raisers is obtained mathematically or experimentally, typically by means of photoelastic or strain gage studies. Extensive stress concentration data have been published in the open literature (4). The following section, therefore, will cite some of these stress concentration data and illustrate the unique advantages which designers may gain by designing components as castings to achieve low stress concentrations economically.

Reinforced Holes

Reinforcement of holes to reduce their stress concentrations is readily achieved when components are designed as castings. Figure 42 illustrates the effect of the reinforcement thickness and width, as well as the fillet radius on the stress concentration factor of a circular hole in a flat plate in tension.

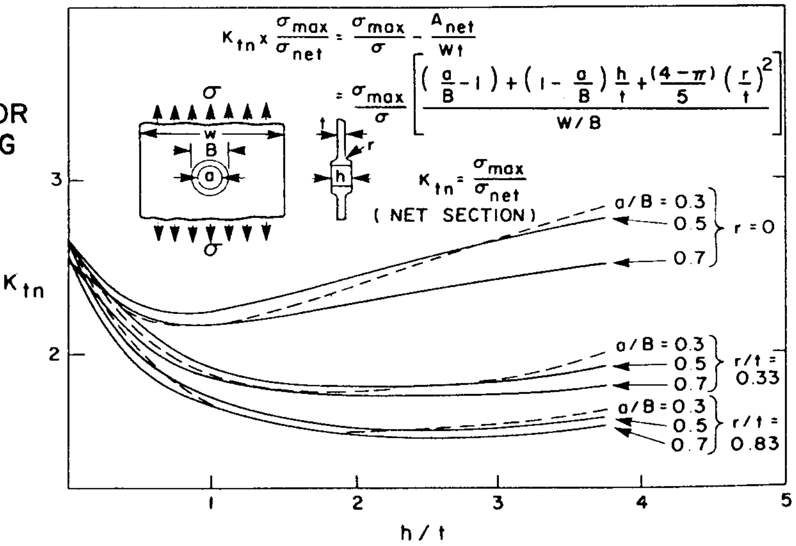

Fig. 42 Stress concentration factor, K_{tn}, for reinforced hole in a plate in tension, $w/b = 4$, $B/t = 5$ **(4)**

Fillets

Important reductions of stresses are obtained by generous fillets in areas where sections join. These fillets are cast readily, and also improve structural integrity of the casting as pointed out beginning on page 7.

Examples of stress concentration factors, for round bars and shafts in bending and torsion are illustrated in Figures 43 to 46 as a function of fillets radius and the thickness. Similar data are presented in Figure 47 for angle and box sections in torsion.

Fillets and Corners of L Junctions

Stress concentration factors in bending for various corner designs (Figure 48) are shown in Table 2. Actual tests of cast steel junctions (Figure 49) for static loads to failure as well as the fatigue life in bending indicate comparable performance in fatigue for designs 1, 2, and 3 (Figure 50). The corner design 2 performed best in terms of static strength and fatigue. Design 3, however, is superior from the foundry production point of view, yielding good fatigue properties in bending and 80% of the strength in static loading compared to design 1 with a larger corner cross-section.

SECTION MODULUS, MOMENT OF INERTIA

Designing with castings offers significant advantages relative to obtaining rigidity of components and minimum fiber stresses because the cross-section of a component can be chosen in accordance with service loads. Design with rolled components, in contrast, is limited by the available standard sizes. Forged

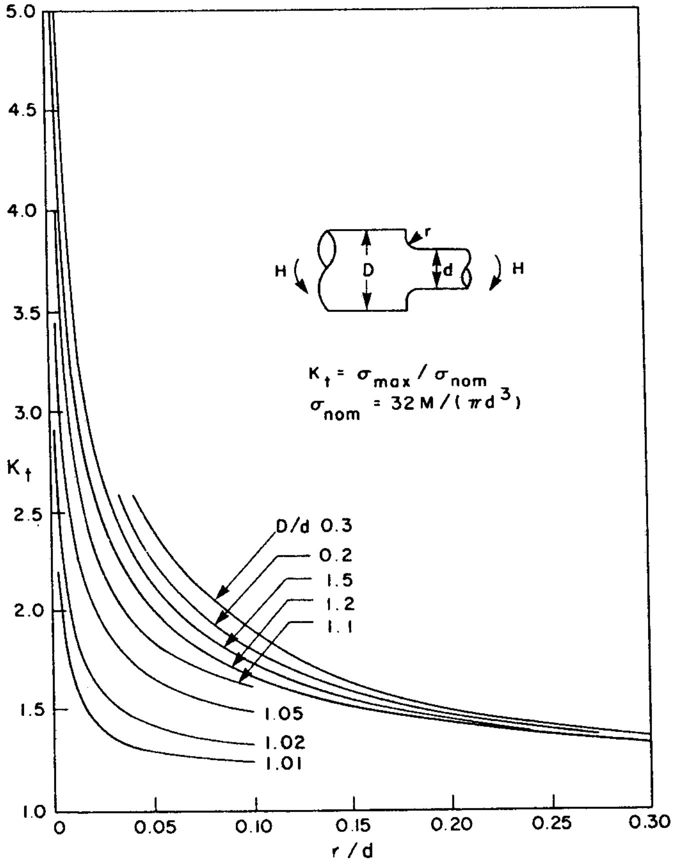

Fig. 44 Stress concentration factor, K_t, for bending of a stepped round bar with a shoulder fillet **(4)**

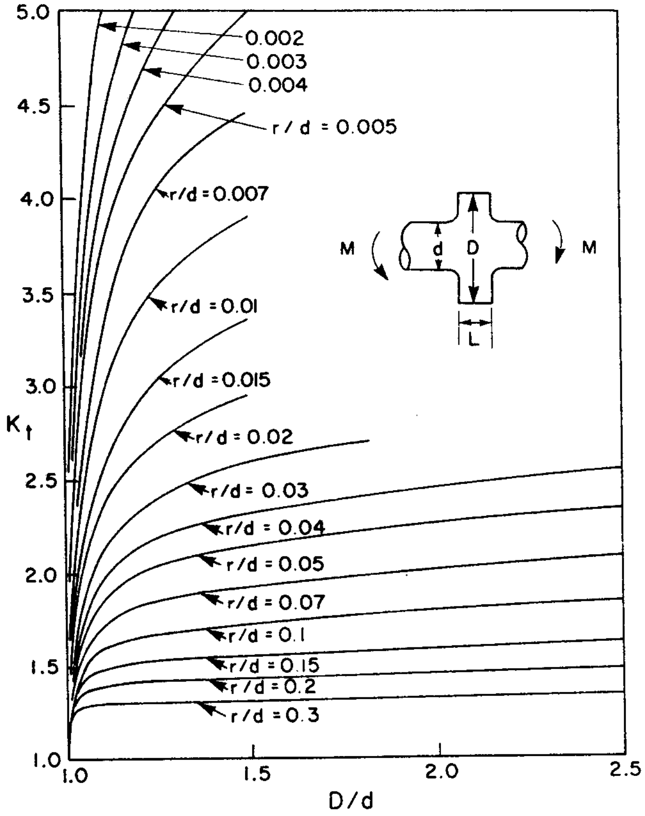

Fig. 43 Stress concentration factor, K_t, for bending of a stepped round bar with a shoulder fillet **(4)**

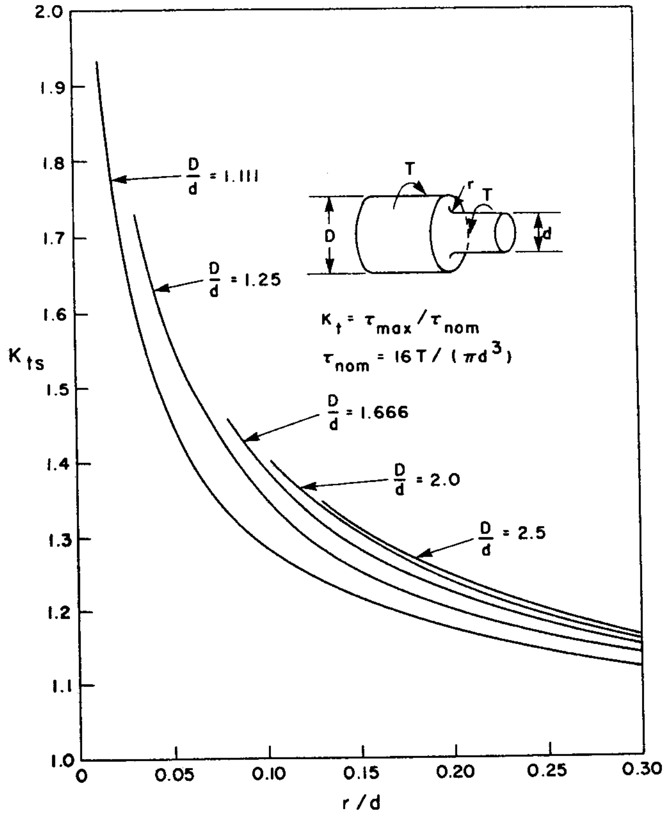

Fig. 45 Stress concentration factor, K_{ts}, for torsion of a shaft with a shoulder fillet **(4)**

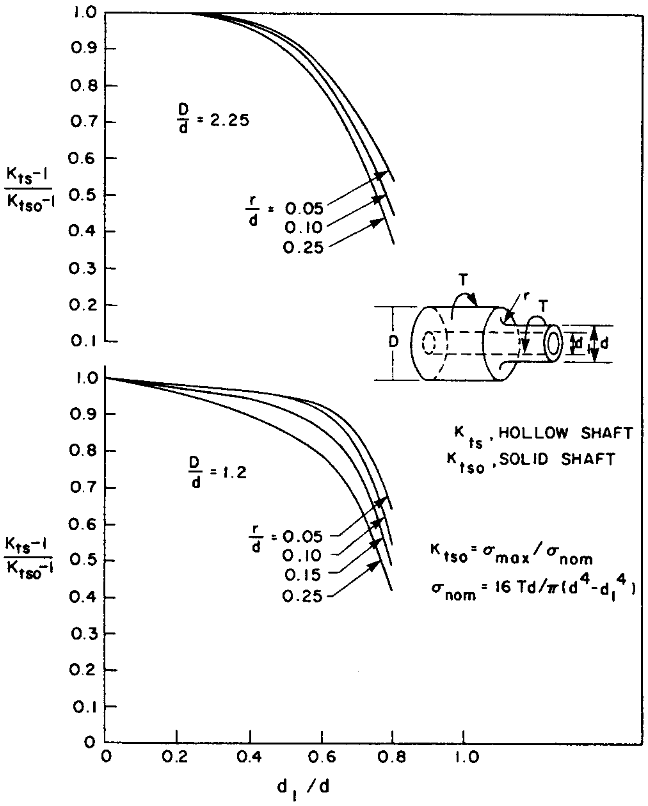

Fig. 46 Effect of axial hole on stress concentration factor of a torsion shaft (4)

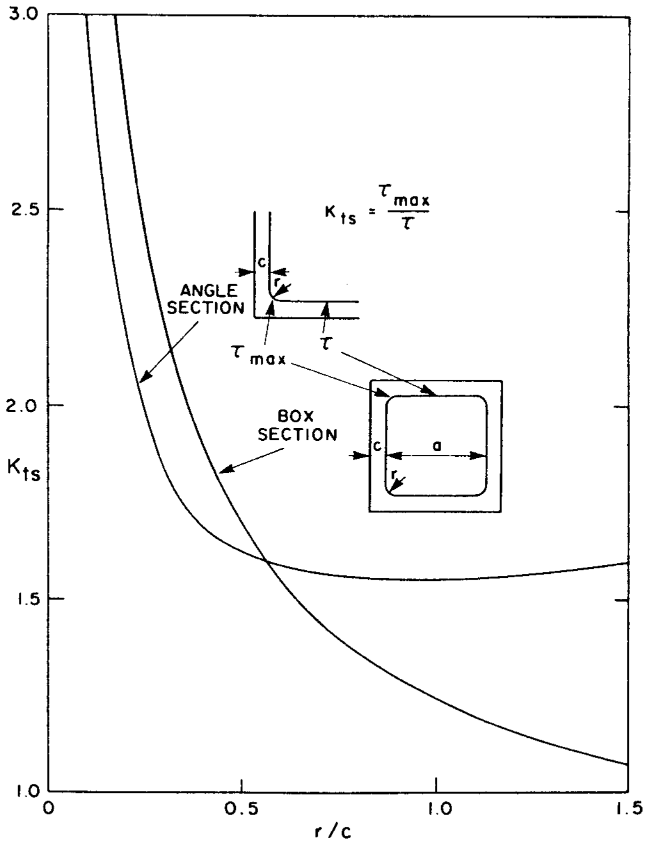

Fig. 47 Stress concentration factor, K_{ts}, for angle and box sections in torsion (4)

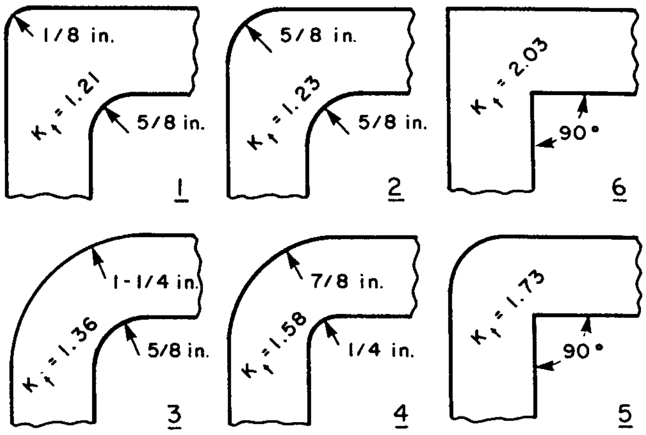

Fig. 48 Corner type designs for cast steel L specimens t = 5/8 in (15.9 mm) (58). Conversion: 1 in. = 25.4 mm

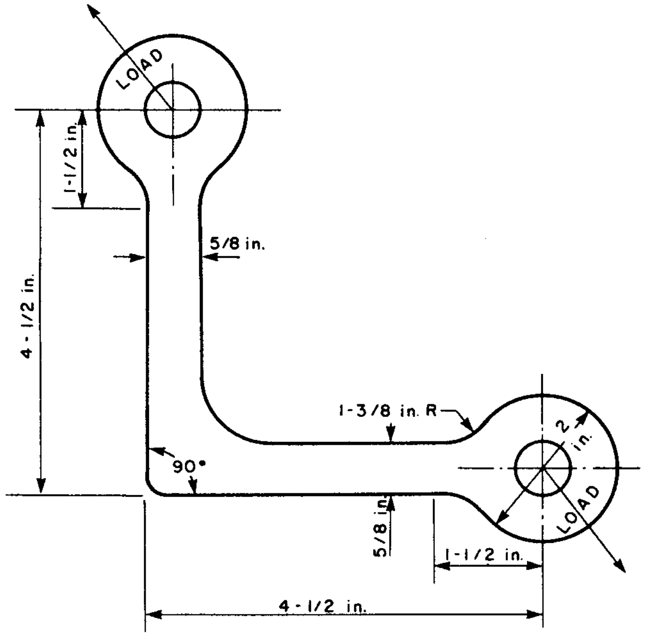

Fig. 49 Dimensions of cast steel L specimens tested. Section depth = 1 in. = 25.4 mm.

components offer greater design flexibility than wrought products. Compared to casting the design flexibility of forged parts is limited, however, due to the manufacturing considerations (die design) and the high cost of design changes for forgings.

The section modulus, S, is important in consideration of maximum fiber stress. Given the service load and the allowable stresses in the chosen grade of steel, the designer can compute the required section modulus and then choose a cross-section that satisfies the section requirement. The equation illustrates this for a cantilever beam in one point loading at the free end:

$$S = L \cdot l/\sigma_a$$

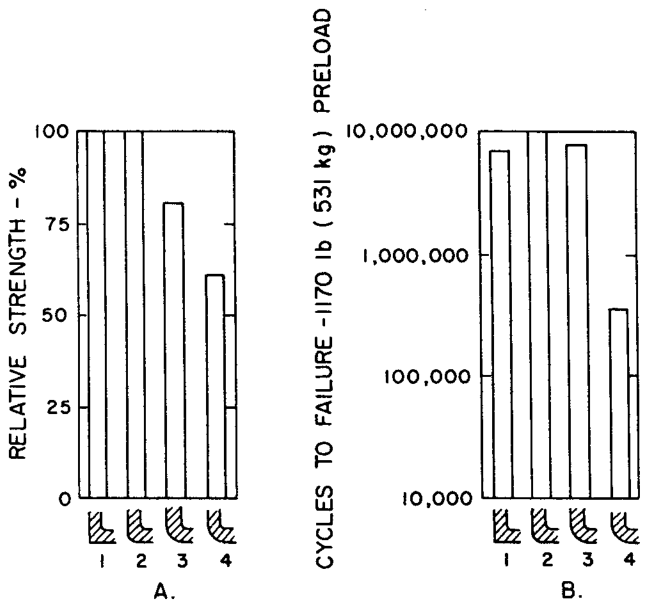

Fig. 50 Property comparison of L design castings, UTS = 70–75 ksi (483–517 MPa)

a) Relative bending strength of casting designs

b) Limited life fatigue tests in bending of steel castings at a constant preload of 1170 lb (531 kg) (58)

TABLE 2 Stress Concentration Factors of Steel Casting L Designs (5)

Corner Design	Fillet r/w	Outside Corner R/w	Stress Concentration factor-Kt Photo-elasticity	Stress Concentration factor-Kt Strain Measurement
1 L	1	0.2	1.21	1.17
2 L	1	1.0	1.23	1.22
3 L	1	2.0	1.36	1.33
4 L	0.4	1.4	1.58	1.60
5 L	0	1.0	1.73	—

TABLE 4 Design Data for Different Lever Shapes in Figure 51 (6)

Design	Moment of Inertia (in.^{4}) I_x	I_y	Section Modulus (in.^{3}) S_x	S_y	Max. fiber stress for 21,000 lb Load ksi	(MPa)
A. Oval	2.9	1.2	1.9	1.2	100	689
B. I-beam	12.1	1.9	5.5	1.4	34	234
C. C-section	10.5	1.3	4.8	0.7	39	269
D. Box section	11.2	4.6	5.1	3.4	37	255
E. U-section	9.1	6.2	4.2	5.0	44	303

Conversion: 1 in.^{4} = 4.16 × 10^5 mm^4
1 in.^{3} = 1.64 × 10^4 mm^3
1 lb = .454 kg

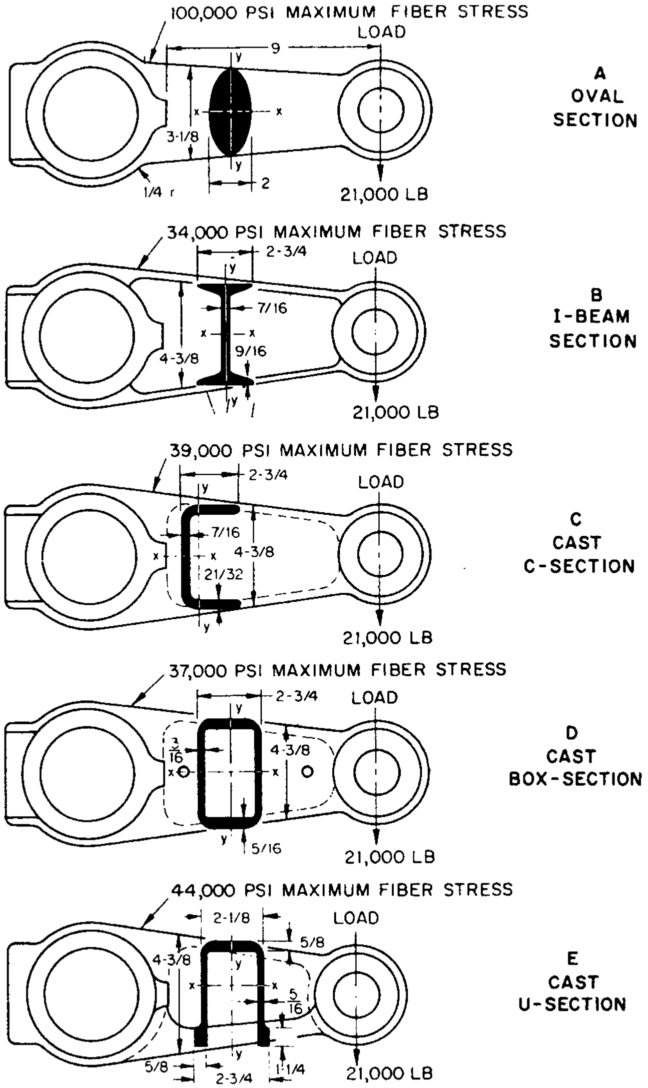

Fig. 51 Comparison of designs affecting the stresses and load-carrying ability of lever arms (6). Conversion: 1 in. = 25.4 mm, 1000 psi = 6.89 MPa

The term L represents the load acting on the beam of length, l. The term σ_a represents the allowable stress for the grade of steel chosen.

The moment of inertia, I, is considered in deflection, i.e. ridigdity of a component. This equation illustrates its use for the deflection, d, of the cantilever beam discussed above:

$$d = \frac{L \cdot l^3}{3E \cdot I}$$

where the term E represents the modulus of elasticity.

Values of section modulus, moment of inertia and radius of gyration are listed in Table 3 for box, C, Omega, and U sections of different sizes. These data are presented for the convenience of the designer. Additional values can be calculated for any design by applying the usual equations from mechanics. The use of these data, and the advantages of selecting suitable cross-sections for production by the casting process are illustrated for lever arms by the following comparison of oval and I-beam sections with cast C-, box-, and U-sections (Figure 51).

The oval cross-section results in the highest maximum fiber stresses and is not a recommended casting design. The maximum fiber stresses are substantially reduced by the alternate cross-sections (Table 4). The I-beam section is a very efficient design. The C, box, and U section designs are readily cast and support significant side thrust or torsion loads.

Box and tubular sections are cast readily but cost somewhat more than open sections (C, U, and Omega) due to core production, core removal, and more complex inspection and repair of internal surfaces.

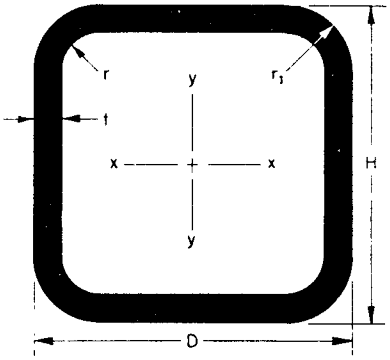

TABLE 3a Properties of Tubular Sections (7)

I = Moment of Inertia **S = Section Modulus** **R = Radius of Gyration**

Dimensions					X Axis			Y Axis				
D in.	H in.	t in.	r in.	r_1 in.	I in.^{4}	S in.^{3}	R in.	I in.^{4}	S in.^{3}	R in.	Area in.^{2}	Weight per lineal inch
1	1	3/16	3/16	3/8	0.6	.12	.35	.06	.12	.35	.48	.13
2	2	3/16	3/16	3/8	.63	.63	.71	.63	.63	.71	1.3	.35
3	3	1/4	1/4	1/2	3.3	2.2	1.1	3.3	2.2	1.1	2.5	.71
4	4	1/4	1/4	1/2	9.0	4.5	1.6	9.0	4.5	1.6	3.5	.98
4	6	1/4	1/4	1/2	23.5	7.8	2.3	12.0	6.0	1.6	4.6	1.3
4	8	1/4	1/4	1/2	46.1	11.8	2.9	15.2	7.6	1.6	5.6	1.6
6	6	1/4	1/4	1/2	30.6	10.2	2.3	30.6	10.2	2.3	5.6	1.6
4	5	3/8	3/8	3/4	18.2	7.3	1.8	13.0	6.5	1.5	5.8	1.6
5	6	3/8	3/8	3/4	35.5	10.8	2.2	27.8	11.1	1.9	7.4	2.1
6	8	3/8	3/8	3/4	90.0	22.5	3.0	60.0	20.0	2.5	9.8	2.7
4	4	1/2	1/2	1	12.2	6.0	1.4	12.1	6.0	1.4	6.4	1.8
4	6	1/2	1/2	1	35.3	11.8	2.0	18.0	9.0	1.4	8.6	2.4
4	8	1/2	1/2	1	74.8	18.7	2.7	24.3	19.2	1.5	10.4	2.9
6	6	1/2	1/2	1	49.2	16.4	2.2	49.2	16.4	2.2	10.8	3.0

Conversion: 1 in. = 25.4 mm
$1 \text{ in.}^2 = 645 \text{ mm}^2$
$1 \text{ in.}^3 = 1.64 \cdot 10^4 \text{ mm}^3$
$1 \text{ in.}^4 = 4.16 \cdot 10^5 \text{ mm}^4$

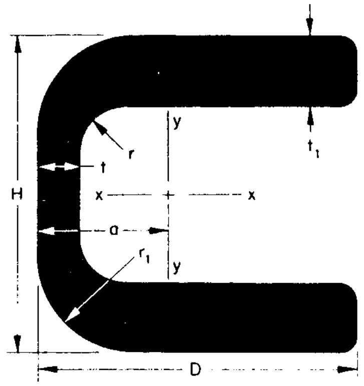

TABLE 3b Properties of C-Sections (7)

I = Moment of Inertia **S = Section Modulus** **R = Radius of Gyration**

Dimensions						X Axis			Y Axis					
D in.	H in.	t in.	t_1 in.	r in.	r_1 in.	I in.^{4}	S in.^{3}	R in.	I in.^{4}	S in.^{3}	R in.	a in.	Area in.^{2}	Weight per lineal inch
1	1/2	3/16	9/32	3/16	3/8	.02	.05	.23	.02	.07	.23	.23	.37	.10
2	1	3/16	9/32	3/16	3/8	.37	.37	.65	.06	.09	.26	.39	.87	.24
3	2	1/4	3/8	1/4	1/2	2.9	1.9	1.2	.62	.52	.55	.80	2.05	.57
4	2	1/4	3/8	1/4	1/2	5.3	2.7	1.5	.66	.51	.53	.70	2.32	.65
4	4	1/4	3/8	1/4	1/2	10.3	5.2	1.7	5.3	2.2	1.2	1.61	3.79	1.1
4	6	1/4	3/8	1/4	1/2	27.0	9.0	2.5	5.7	2.3	1.1	1.48	4.47	1.25
6	6	1/4	3/8	1/4	1/2	38.0	12.7	2.6	18.2	5.0	1.8	2.35	5.80	1.60
5	6	3/8	9/16	3/8	3/4	34.0	13.6	2.1	28.5	9.1	1.9	2.85	7.80	2.2
4	4	1/2	3/4	1/2	1	15.2	7.6	1.5	7.8	3.5	1.1	1.77	7.2	2.0
4	6	1/2	3/4	1/2	1	43.0	14.3	2.3	9.2	3.8	1.1	1.6	8.5	2.5
4	8	1/2	3/4	1/2	1	85.6	21.4	3.1	8.6	3.3	.9	1.43	9.2	2.6
6	6	1/2	3/4	1/2	1	63.1	21.0	2.4	33.1	9.4	1.7	2.5	11.2	3.1
6	9	1/2	3/4	1/2	1	92.0	30.6	2.5	82.5	15.7	2.4	3.78	14.8	4.1

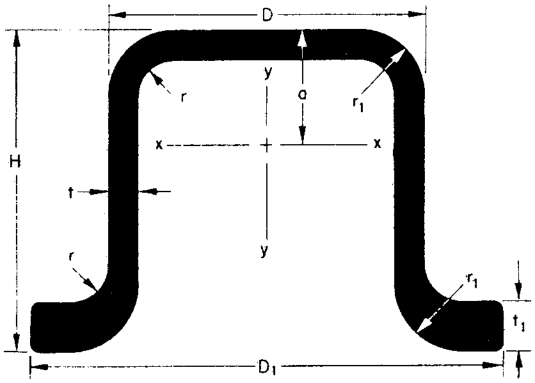

TABLE 3c Properties of Omega Sections (7)

***I* = Moment of Inertia** **S = Section Modulus** **R = Radius of Gyration**

Dimensions							*X* Axis				*Y* Axis				
D in.	H in.	D_1 in.	t in.	t_1 in.	r in.	r_1 in.	I in.^{4}	S in.^{3}	R in.	a in.	I in.^{4}	S in.^{3}	R in.	Area in.^{2}	Weight per lineal inch
1	1	1-1/2	3/16	1/4	3/16	3/8	.06	.12	.35	.50	.09	.12	.42	.50	.14
2	2	3	3/16	1/4	3/16	3/8	.59	.59	.67	1.0	1.0	.67	.87	1.3	.37
4	4	6	1/4	1/2	1/4	1/2	7.8	3.8	1.5	1.8	12.5	4.2	1.8	3.7	1.0
4	6	6	1/4	1/2	1/4	1/2	13.5	5.4	1.8	2.9	14.8	4.9	1.9	4.7	1.3
4	8	6	1/4	1/2	1/4	1/2	45.5	11.4	2.9	4.0	20.5	6.8	1.9	5.6	1.6
6	6	9	1/4	1/2	1/4	1/2	30.2	10.1	2.3	3.1	47.1	10.5	2.8	5.8	1.6
3	5	4-1/2	3/8	3/4	3/8	3/4	14.2	5.7	1.7	2.5	8.9	3.9	1.3	5.1	1.4
4	4	6	3/8	3/4	3/8	3/4	10.0	5.0	1.4	1.9	17.3	5.8	1.8	5.1	1.4
4	4	6	1/2	1	1/2	1	11.5	5.8	1.3	1.9	23.6	7.9	1.8	6.9	1.9
4	6	6	1/2	1	1/2	1	34.5	11.5	2.0	3.0	30.4	10.1	1.8	9.0	2.5
4	8	6	1/2	1	1/2	1	75.8	19.0	2.6	4.1	36.3	12.1	1.8	10.9	3.1
5	5	7-1/2	1/2	1	1/2	1	24.5	9.8	1.7	2.5	46.0	12.3	2.3	8.5	2.4
6	6	9	1/2	1	1/2	1	46.9	15.7	2.1	3.0	83.4	18.5	2.8	10.3	2.9

Conversion: 1 in. = 25.4 mm
$1 \text{ in}^2 = 645 \text{ mm}^2$
$1 \text{ in.}^3 = 1.64 \cdot 10^4 \text{ mm}^3$
$1 \text{ in.}^4 = 4.16 \cdot 10^5 \text{ mm}^4$

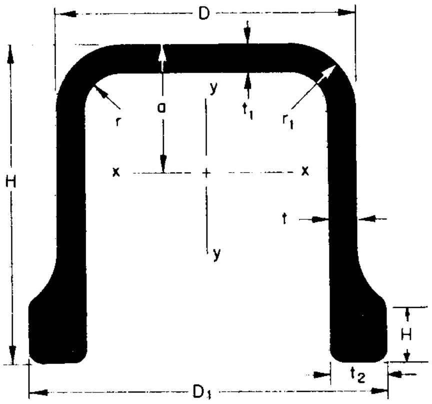

TABLE 3d Properties of U Sections (7)

***I* = Moment of Inertia** **S = Section Modulus** **R = Radius of Gyration**

Dimensions									*X* Axis*				*Y* Axis*				
D in.	H in.	D_1 in.	t in.	t_1 in.	t_2 in.	h in.	r in.	r_1 in.	I in.^{4}	S in.^{3}	R in.	a in.	I in.^{4}	S in.^{3}	R in.	Area in.^{2}	Weight per lineal inch
1	1	1-3/16	3/16	3/16	9/32	3/8	3/16	3/8	.06	.12	.35	.50	.09	.12	.35	.50	.14
2	3	2-1/2	1/4	1/4	1/2	1/2	1/4	1/2	2.1	1.4	1.0	1.5	1.5	1.2	.85	2.1	.59
3	4	3-1/2	1/4	1/4	1/2	3/4	1/4	1/2	5.1	2.6	1.3	1.8	5.0	2.9	1.3	3.1	.87
5	8	5-1/2	1/4	3/8	1/2	1	1/4	1/2	42.0	10.5	2.6	3.7	26.3	9.6	2.1	6.2	1.7
6	10	6-1/2	1/4	3/8	1/2	1	1/4	1/2	87.0	17.4	3.4	4.5	52.2	16.1	2.6	7.7	2.2
4	6	4-3/4	3/8	9/16	3/4	1	3/8	3/4	24.7	8.2	1.9	3.0	19.5	8.2	1.7	6.8	1.9
4	4	5	1/2	1/2	1	1	1/2	1	10.3	5.2	1.3	2.0	18.3	7.3	1.7	6.4	1.8
4	6	5	1/2	1/2	1	1	1/2	1	32.0	10.7	1.9	3.0	24.7	9.9	1.7	8.6	2.4
4	8	5	1/2	1/2	1	1	1/2	1	68.1	17.1	2.6	4.0	30.7	12.3	1.7	10.4	2.9
6	6	7	1/2	5/8	1	1-1/2	1/2	1	40.7	13.6	2.0	2.7	70.0	20.0	2.6	10.4	2.9

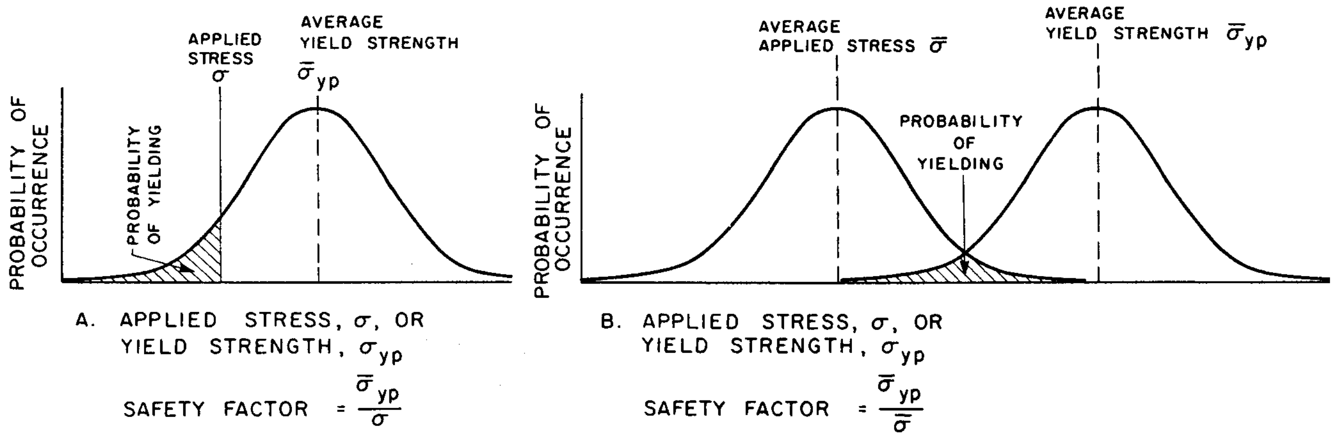

Fig. 52 Schematic diagrams of probability of occurrence of applied stress and material yield strength

GENERAL CONSIDERATIONS OF SAFETY FACTORS

The need for safety factors arises from uncertainties in the design input parameters and sometimes necessarily approximate design techniques. The principal areas of uncertainty are:

Adequacy of Postulated Service Loads
Adequacy of Postulated Service Environment
Adequacy of Analytic Techniques
Scatter in Material Property Data
Scatter in the Discontinuity Population

A full treatment of the uncertainties in the design process requires an analysis of the probability of successful service performance. The answer is simply not yes or no. A rigorous probability analysis requires more information than is typically available for common design problems, therefore, the safety factor approach is adopted.

Part of the significance of the safety factor approach can be explained through a simple probability analysis. If we consider the yielding of a tensile bar, the deterministic approach predicts that yielding will occur when we exceed the yield strength of the material, σ_{yp}. The difficulty with this concept is that a large number of tensile tests will show scatter in the measured values of σ_{yp}.

If enough tests are conducted, a plot showing the probability of obtaining a given yield strength from a randomly selected tensile specimen can be constructed. Figure 52 schematically illustrates the probability of occurrence versus yield strength value. The area under the curve is unity since the yield strength for any test must lie somewhere under the curve. If the applied stress is known to be a certain value, σ, the probability that this stress will lead to yielding of a randomly selected bar is given by the shaded area of Figure 52a. There is a small but finite probability that the selected bar will have a strength less than the applied stress. A safety factor may be considered as the ratio of the average yield strength, $\bar{\sigma}_{yp}$ to the applied stress, σ. As the safety factor increases, the vertical line moves to the left, the area under the tail of the probability curve decreases and thus the probability of yielding decreases.

In a real design problem the applied load is not known with absolute certainty. There is some chance service loads will be higher or lower than expected. Hence, service stresses can be expressed in terms of the probability of occurrence. The probability of failure as shown in Figure 52b now is related to the area of overlap of the distributions of applied stress and material strength. The relationship of factors of safety to probability of failure depends sensitively on the shape of the applied stress and material strength probability curves. Figure 52b refers to applied stress and material yield strength. We could equally well consider applied cyclic stress and the fatigue limit stress, applied K and K_{Ic} fracture toughness and other failure parameters. For a more refined treatment the reader is referred to references **8** and **9**.

The variations in material property data and expected service environment are not the only sources of uncertainty. Safety factors are also used to account for the fact that approximate design techniques may be in error. For example, in some applications a sophisticated creep analysis may not be economically feasible. A simple approximation may be used instead and a safety factor included to offset errors associated with the approximate approach. Indeed, for very complex loading situations even the most sophisticated failure criteria are clearly deficient and factors of safety must be used.

The commonly used safety factors cited in the previous sections reflect both the probabilistic approach to failure and successful service experience. They are offered as guidelines rather than hard and fast rules.

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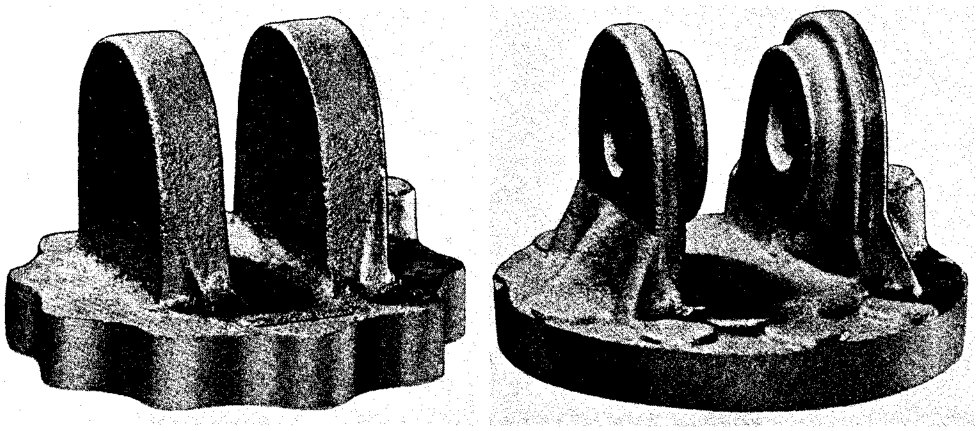
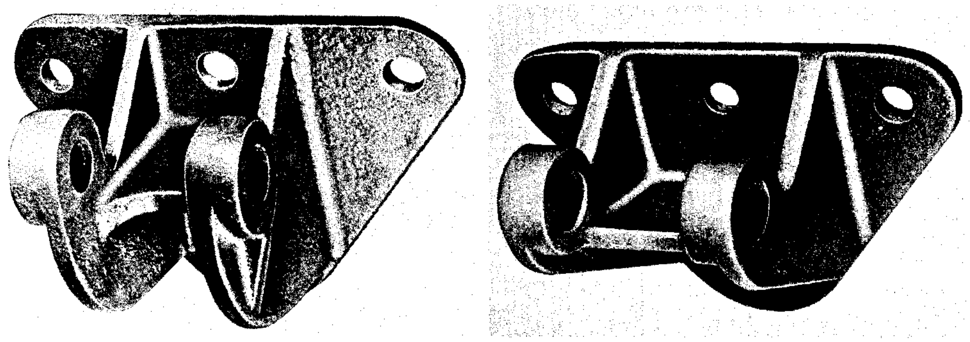
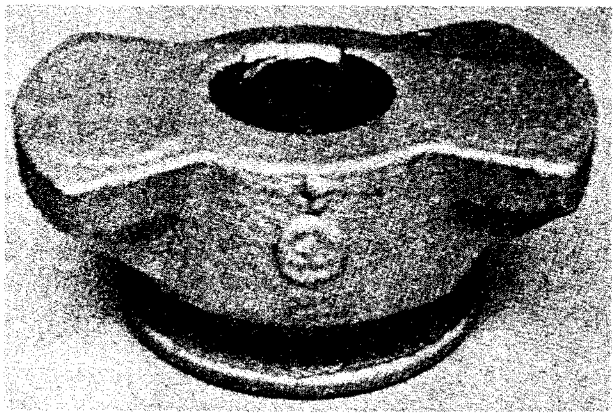


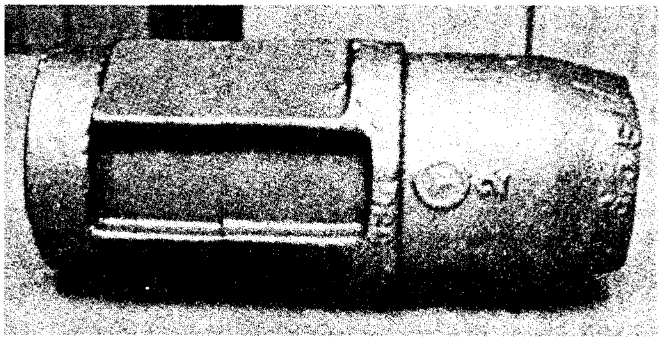
Cylinder head casting. Original design, left, and redesign for quality improvement.*



Hinge butt casting. Original design left, and casting after redesigning with a cost saving of 15.9%.*



A 4 lb. (2 kg) winch clutch part converted from malleable iron to a low alloy cast steel to prevent failure.*



Oil well drilling casting converted from nodular cast iron to a Cr-Mo steel casting because of field failures.*

**Taken from Chapter 7—Steel Castings Handbook—5th edition.*