Casting Design and Performance
Pages 133–138

Design Problems Involving Uniform Sections

IN MANY CASTINGS, functional requirements dictate that walls be uniform or nearly uniform in thickness. Many problems in producing castings having walls of uniform thickness are associated with the premature freezing of molten metal before all parts of the mold cavity have been filled. In other castings, it may be possible to fill the mold cavity completely, but centerline shrinkage or areas of porosity may be encountered because portions of the casting cannot be fed before the onset of freezing. In such castings, certain walls may be tapered by the addition of padding, which may be incorporated into the design, or ribs or webs may be added to provide feed paths.

The function of ribs or of sections of walls that have been enlarged in providing flow and feed paths for the molten metal as it fills the mold and cools is shown schematically in Fig. 1. In pouring a flat plate, Fig. 1(a), the metal enters the cavity and attempts to flow in all directions. If the distance from the gate to the extremities of the mold cavity is too great, the metal freezes prematurely, and misruns result. When ribs are added to the plate, Fig. 1(b), the metal flows readily to the extremities of the mold cavity, and successful castings are produced.

The same success is attained when the plate is enlarged at the gate and uniformly tapered to the extremities, as shown in Fig. 1(c). The metal flows into the mold cavity at the heaviest section, thus preventing an initial chilling of the metal by the mold, such as occurs with a small volume of metal. Because the molten metal in heavy sections retains more of its heat as it flows through the mold, it can more readily reach the extremities of the mold cavity.

A related problem is involved in the mechanics of cooling and freezing of molten metal and the attendant volumetric shrinkage. Referring to Fig. 1(a), let us assume that the metal is poured and fills the mold. For some castings where chilling of metal by the mold is possible, there is no assurance that freezing will start at points farthest from the gate and progress in an orderly manner to the gate so that the volume of metal lost because of shrinkage can be replaced from the reservoir (riser) intended for that purpose. In fact, a casting such as this may be expected to contain sections that are isolated from the feed source by metal that is closer to the gate. The metal nearer the gate freezes first and thus surrounds and isolates these molten pockets. Shrinkage of the molten metal in these isolated pockets creates voids or porosity.

With two risers feeding metal from opposite ends of the casting, more sound metal would be obtained in the plate, and with a riser feeding from each edge of the plate, a still greater percentage of sound metal could be obtained. However, risers add to the cost of producing a casting, and a method that minimizes the number of risers is more economical. This can sometimes be accomplished by providing feed paths within the casting configuration, as shown in Fig. 1(b). These paths permit the molten metal to flow easily to all sections of the cavity. If the enlarged sections are gradually tapered from the gate to the extremities, solidification follows an orderly progression through the casting and termigates in the riser. Compensation is provided for normal shrinkage throughout the casting, and sound metal is assured.

The same beneficial freezing pattern is obtained by tapering the plate, Fig. 1(c), provided the angle of taper is sufficient and the source of feed metal is at the heaviest section. Under these conditions, a favorable freezing pattern is assured because the metal that has flowed the farthest (and is therefore the coldest) is deposited in the thin section. In contrast to a heavy section, the thin section of molten metal has less heat to transmit to the mold before freezing starts. Thus, the direction of solidification can be predicted in tapered sections, provided the metal enters at the heavy end.

If the need for feed paths is anticipated in the early stages of the design of a casting, padding may be made a functional part of the casting, or it may be located so that its removal adds little or no cost.

Consider the two investment castings shown in Fig. 29 and 30 of Chapter 9 ("Design Problems Involving Thin Sections"). For successful production of the casting shown in Fig. 29, ribs were required on each of the legs. These provided feed paths that encouraged complete filling of the cavity and resulted in

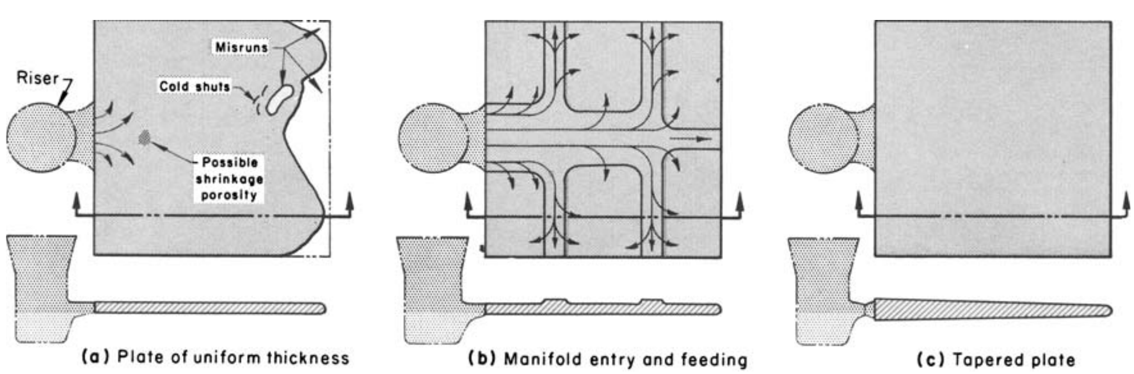

Fig. 1 Flat plates (a) are difficult to produce completely filled and with sound metal. By adding ribs (b), or tapering the plate (c), the problems are eliminated or substantially ameliorated.

sound castings. The casting shown in Fig. 30 of Chapter 9 was designed with each leg tapered. This permitted easy filling and feeding of the legs and induced a satisfactory freezing pattern. Although the addition of ribs to the first casting was satisfactory from a foundry point of view, removal of the ribs was necessary for the proper functioning of the part. In the second casting, the taper was satisfactory in terms of both production and function, because the casting was designed with this in mind.

In the magnesium casting shown in Fig. 19 of Chapter 9, the problem was to distribute metal efficiently to all flow channels and all parts of the mold before freezing, and to accomplish this objective with a minimum amount of metal. (This was an aircraft application, and no excess weight was permitted.)

The solution entailed greatly enlarging the two ends into which the metal was gated, thus allowing them to function as manifolds. Increasing their size kept the metal hotter and permitted unrestricted flow to each connecting member of the casting. As shown, ribs were added to each thin strut section, to provide a larger flow channel. Because of the larger mass, the rib and strut junctions developed hot spots in the mold and helped to prevent premature freezing. The heavy manifold ends were later machined off, but the small ribs remained intact.

Sand Castings

Produced in a dry sand mold, the steel elbow casting shown in Fig. 2 was originally designed with a uniform wall 1½ in. thick. This casting, intended for use at high temperature and high pressure, was produced with a rejection rate of 16%, because of shrinkage porosity caused by insufficient feeding of molten metal to all parts of the casting during solidification. ASTM class 1 radiographic soundness was specified for all areas except the unflanged end, where no defects whatever were permitted because of a subsequent welding operation for connecting the elbow to an adjacent member of the assembly. To overcome this feeding problem, the casting was revised by adding ½ in. to the wall thickness at the flanged end and tapering the wall uniformly to its original thickness at the opposite end. This change lowered the rejection rate from 16% to 6%.

The gate valve casting of Fig. 3 suggests another method for improving the flow of metal and feeding all sections adequately. These stainless steel castings were produced in sand molds and were intended for use in nuclear reactors, necessitating maximum attainable soundness. All castings were inspected radiographically, and any discernible defect was cause for rejection.

Although this casting was redesigned primarily to reduce the cost of producing it, addition of the 75 mm (¾-in.) webs also reduced the distance the metal had to travel as it cooled, and minimized shrinkage porosity caused by impeded feeding.

The webs functioned efficiently as manifolds to distribute molten metal to all parts of the mold cavity. Because they abutted the tubular sections, the webs reduced the distance the molten metal had to flow to reach the central portion of the casting. The webs also conducted metal to the flanges, which were used as flow paths to feed those parts of the casting nearest the flanges. These heavier sections then fed molten metal to the thinner sections. Although the webs were approximately the same thickness as the flanges, the webs were the last parts of the casting to freeze. The greater volume of metal that passed through the web-forming section of the mold heated it to a higher temperature than was reached in the flange-forming sections.

A related casting is shown in Fig. 4. These sand cast stainless steel fittings for a nuclear reactor also were revised to increase efficiency of production. The addition of the web reduced by one the number of risers required to obtain

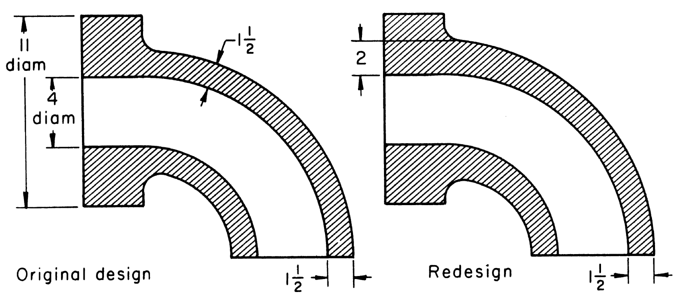

Fig. 2 As originally designed, with a constant wall thickness, this sand cast steel elbow fitting was producible only at a 16% rejection rate, because of shrinkage porosity due to insufficient feeding. Redesign, in which walls were increased at the flanged end and tapered, permitted more successful production; the rejection rate dropped to 6%. Dimensions in inches

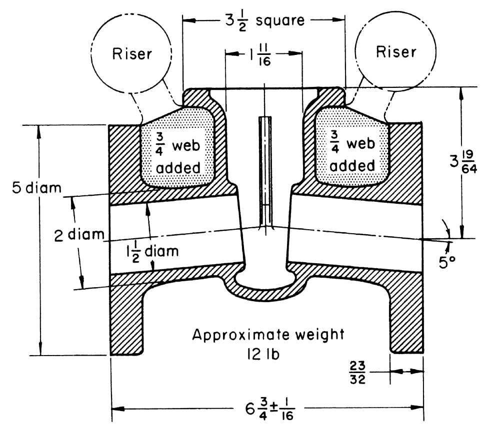

Fig. 3 The application of this sand cast stainless steel valve body required completely sound metal. The uniform walls were fed readily from the risers through the flanges and the webs. Webs were added to the original design.

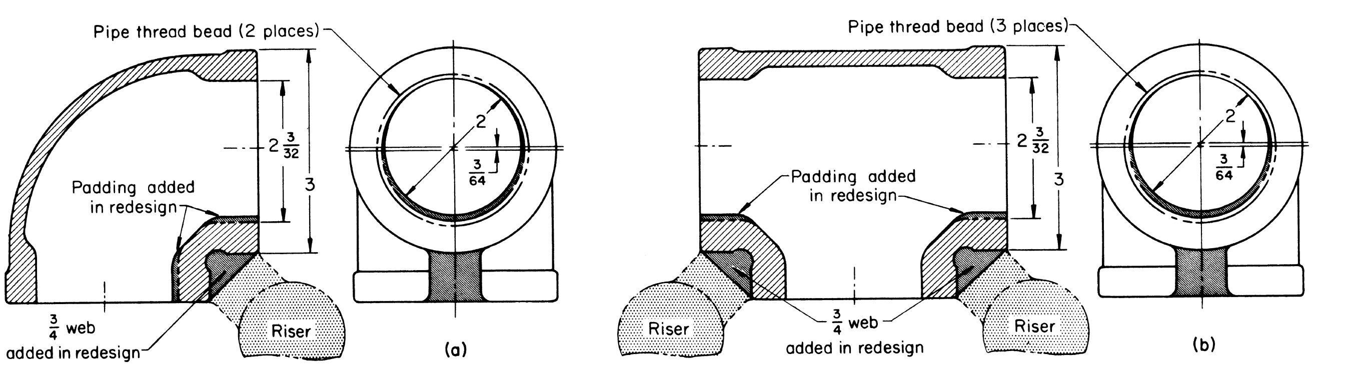

Fig. 4 Adding the webs and tapering the tapping beads in the elbow fitting (a) and the tee fitting (b) assisted in distributing the molten metal and created a favorable freezing pattern that permitted adequate feeding of all sections of these stainless steel sand castings during solidification.

sound metal. However, in these castings there were no flanges to assist the webs in the distribution of metal. Instead, internal padding of the thread beads provided the necessary flow and feed paths. As shown, the padding was tapered, with the heaviest part adjacent to the web and the thinnest part diametrically opposite—that is, at the point farthest from the webs.

The elbow castings, Fig. 2 and 4(a), and tee castings, Fig. 3 and 4(b), benefited from a more orderly solidification of molten metal as a result of redesign. Directional solidification was assured by the uniform temperature gradients in the molds, created by both the size of the casting sections and the flow path of the metal. Freezing of the metal started at the point farthest from the risers and progressed uniformly to the risers. All sections of the castings were adequately fed, and sound metal was obtained. The padding on the elbow and tee castings in Fig. 4(a) and (b) was machined away when the thread beads were bored to the desired diameter before being tapped.

The AZ91 magnesium casting of Fig. 5 illustrates a straightforward approach to padding. This casting was produced in dry sand molds. The minimum castable section thickness, arbitrarily established at 0.130 in., was heavy enough to provide the necessary strength. However, all castings produced were defective because of cold shuts and shrinkage.

The draft angle on the pattern was then increased from one degree to three degrees, and 0.125 in. was added to all wall thicknesses. With these revisions, all castings produced were sound. Although such a freehanded use of padding is not generally recommended, especially for aircraft castings, circumstances may occasionally warrant it. (The unwanted weight that was added to the casting shown in Fig. 5 was justifiable only because delivery of these castings was of utmost importance.)

Problems presented by walls of uniform thickness are not always attributable to the distance the metal must flow or be fed, but sometimes result from the way in which the walls are shaped. Figure 6(a), a section of a large aluminum sand casting for aircraft use, illustrates a tortuous configuration that caused turbulence as the metal flowed through the mold, resulting in the entrapment of oxides. Micro-shrinkage also occurred, and the rejection rate of this expensive casting was excessively high.

By relieving the sharpness of the angles of the casting walls, as shown in Fig. 6(b), free flow of metal was obtained. This eliminated both oxide inclusions and microporosity and resulted in the production of sound, acceptable castings.

Shell Mold Castings

As illustrated by previous examples, casting problems presented by uniform wall thicknesses are not always attributable to the distance metal must flow. Shape, too, exerts a strong influence. The casting shown in Fig. 7, a hollow spherical casting with a heavy flange, is an apparent exception to rules relating to feeding distance. Because the distance from the edge of the heavy flange to the bottom of the sphere is 4 in., it might be assumed that the casting could be fed satisfactorily from the heavy flange. However, as originally designed (Fig. 7a), it could not be. The total area of the thin section greatly exceeded that of the flange section from which it was to be fed, and feeding was inadequate; the part was unsound below points A, or about two thirds of the way down the wall of the sphere.

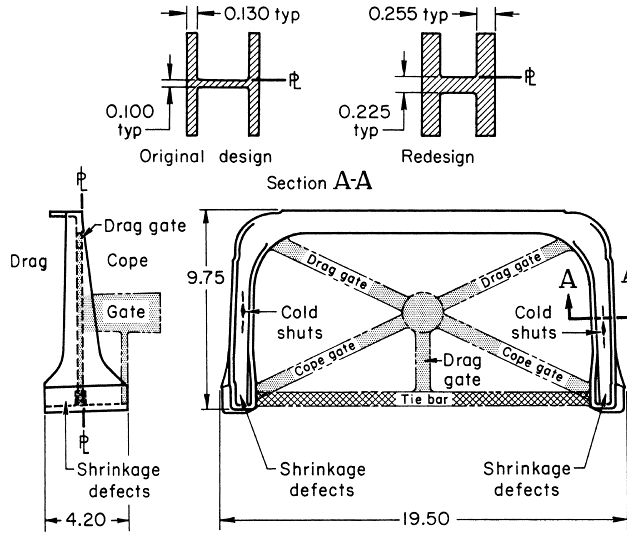

Fig. 5 In this sand casting as originally designed, excessively thin walls resulted in cold shuts and shrinkage. Overcorrecting by nearly doubling all wall thicknesses and by increasing the draft angle eliminated defects but added unnecessarily to the weight. Alloy was AZ91 magnesium

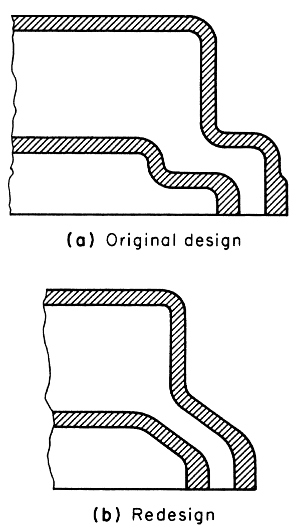

Fig. 6 A partial section of a large, intricately shaped aluminum casting in whose original design (a) sharp bends retarded metal flow and created turbulence. The resulting inclusions and porosity caused a high rejection rate. Revised design (b), in which bends were eliminated or were made less acute, was producible without defects.

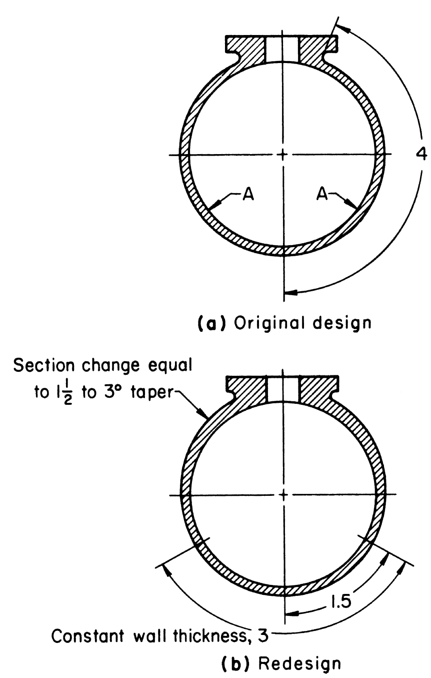

Fig. 7 In this flanged spherical casting as originally designed (a), feeding was restricted a short distance from the riser, resulting in unsoundness below points A. Tapering the walls, as shown in (b), provided adequate feeding. This alloy steel casting was produced in a shell mold.

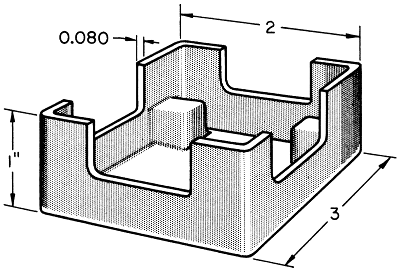

Fig. 8 Walls of uniform thickness did not deter successful production of this casting, because it was designed so as not to exceed the capabilities of the metal (magnesium alloy AZ63A) or the process (shell molding) that was used in producing it. Rejection rate was less than 5%

To assure soundness, this wall had to be tapered from the top to a point not more than 1½ in. from the bottom of the sphere, as indicated in Fig. 7(b). Such a taper should be no less than 1½°; a taper of 3° would virtually guarantee soundness. When a large sphere is cast it is usually necessary to provide risers at various points around the sphere in order to feed from lower wall sections as well as from the top.

Not all castings require padding or the addition of ribs to obtain sound metal. When the normal capabilities of metal and process are not exceeded, uniform walls are practical and do not defy successful production. A good example of a successfully produced casting with walls of uniform thickness is shown in Fig. 8. This AZ63A magnesium part, 3 in. long, 2 in. wide, and 1 in. high, with 0.080-in.-thick walls, was produced in shell molds with a rejection rate of less than 5% for all causes.

Permanent Mold Castings

Castings produced in metal molds have an advantage, in one respect, over those produced in sand or ceramic molds. Water lines can be incorporated in the mold to create a planned chilling effect on specific sections of the casting. By adjusting the rate of water flow, the degree of chilling can be controlled accurately. This permits some leeway in the variation of wall thicknesses that can be incorporated in a single casting. This possibility of chilling the casting should not be used as a substitute for good design. Regardless of the casting process, a well designed casting can be produced more easily and more economically than one of unfavorable design, even though the unfavorable design does not tax the capabilities of the process.

The permanent mold casting shown in Fig. 9 was structural in use and required radiographic quality. The inner wall was designed to have minimum thickness, to save weight. Because of the taper required for molding, ribs were heavier at the junction with the inner wall than was functionally necessary. Eliminating shrinkage areas and cracks at these junctions was a problem.

Two of the ribs at the parting line were still heavier, because of their being used for the attachment of gates and risers. These ribs were insulated with extra mold coating, because smoothness of the as-cast surface was not mandatory. By water-cooling the inner steel core to obtain some chilling of the metal, the casting was made to good quality. The design of this casting could have been improved by increasing the thickness of the inner wall to equal that of the heavier adjoining ribs. This uniformity of wall thickness would have eliminated the shrinkage defects.

Size can determine whether a casting design incorporating uniform walls is practical or impractical. The effect of large areas of uniform wall thickness on producibility can be illustrated with reference to the casting shown in Fig. 10. This casting was relatively easy to produce to the dimensions indicated. However, if it had been several times larger, with no change in wall thickness, progressive solidification would have had to be induced by varying the thickness of the mold coating, even if a wall thickness of 4.06 mm (0.160 in.) were otherwise adequate. Such practice is difficult, time-consuming and expensive. An alternate method would be to incorporate a taper in the walls to help produce the necessary solidification pattern.

Investment Castings

Uniform walls in an investment casting are readily produced if the casting is not too large, in relationship to wall thickness, and if gates

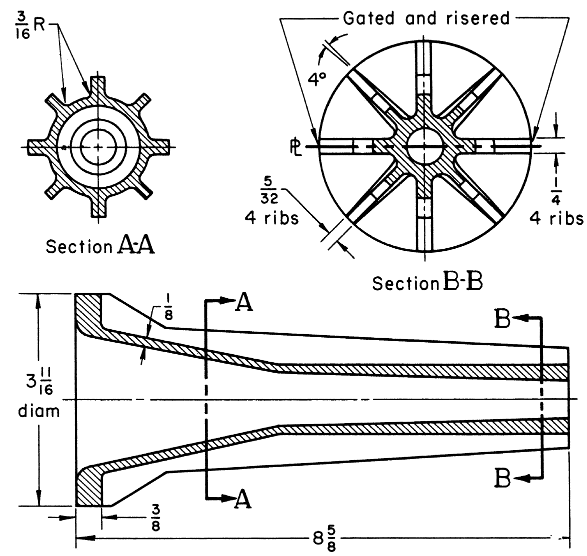

Fig. 9 In this permanent mold casting, functioning of heavier ribs with thin walls induced hot tears and shrinkage at the junctions. Uniformity of wall thickness would have eliminated these defects.

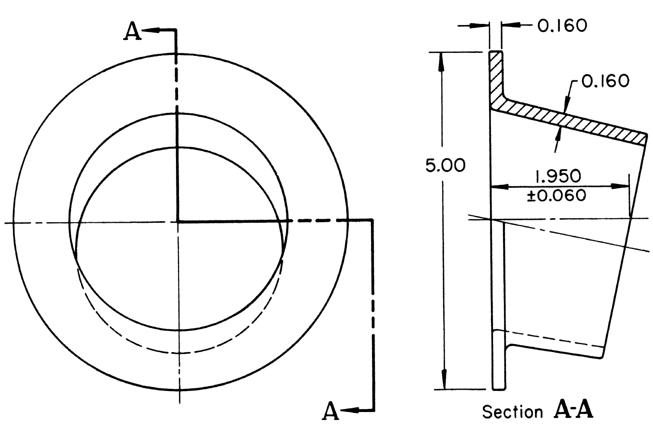

Fig. 10 This casting was easy to produce in a permanent mold to the dimensions indicated. However, if all dimensions other than wall thickness were increased proportionally, this casting would be difficult to produce. The enlarged casting would require tapered walls or controlled variation in the thickness of the mold coating, in order to permit efficient production.

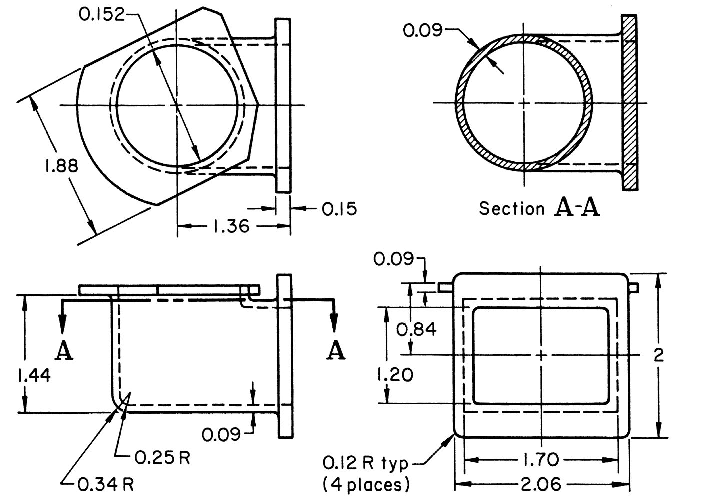

Fig. 11 A well-designed aluminum investment casting, incorporating uniform walls and - efficient gating areas

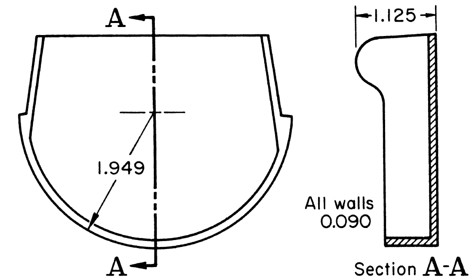

Fig. 12 This 356 aluminum alloy casting, produced in a centrifuged plaster-base investment mold, represents minimum wall thickness for the shape, alloy and process.

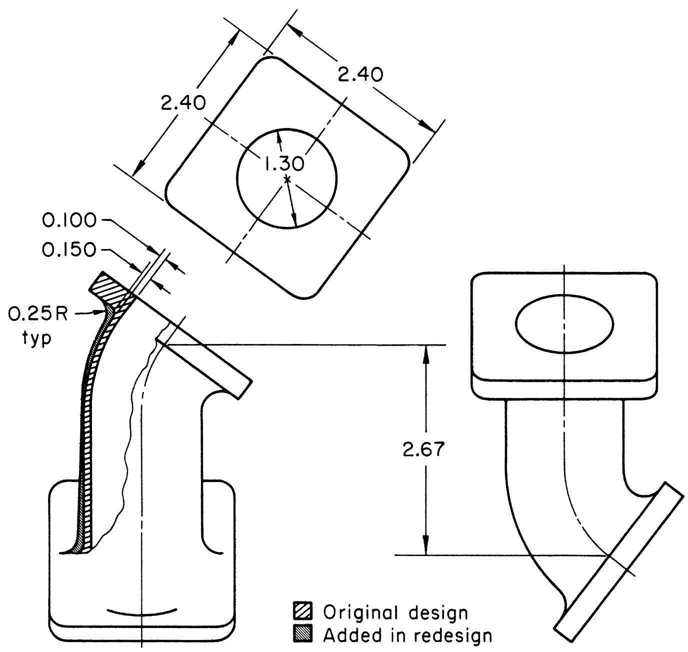

Fig. 13 A critical application necessitated class 1A quality for this type 347 stainless steel investment casting. Hot tearing at the junctions and porosity in the body, which resulted from too-rapid solidification within the uniform wall of the tubular section, were eliminated by tapering the body toward each flange and increasing the fillet radii at the junctions.

can be placed at desirable locations. The body of the aluminum investment casting illustrated in Fig. 11 incorporates a uniform wall thickness of 0.09 in. throughout, even at the point where the wall changes direction. The irregularly shaped flange also is maintained at this same thickness. The rectangular flange (3.8 mm, OR 0.15 in. thick) is just enough heavier to permit efficient gating and transfer of metal to all sections. This part was easy to produce, and virtually no defects were encountered.

The 356 aluminum alloy part illustrated in Fig. 12 was produced in a centrifuged mold and heat treated to the T6 condition. This casting is part of the leading-edge assembly of an aileron; all walls are 0.090 in. thick. The foundry considered the 0.090-in. wall to be of minimum practical thickness for this configuration. Decreasing thickness below 0.090 in. would result in rejected castings, and the rejection rate would increase with decreasing wall thickness.

By centrifuging the mold, pressure is exerted on the molten metal, forcing it rapidly into all parts of the mold cavity. Centrifugal action is often used to produce castings with uniform or thin walls that cannot be produced with static pressure alone.

Lack of favorable directionality of freezing was a problem with the type 347 stainless steel investment casting illustrated in Fig. 13. This inlet by-pass valve adapter was intended to carry fuel close to a hot part of an airplane engine. Failure of the casting could cause a fire or explosion, with disastrous loss of the plane

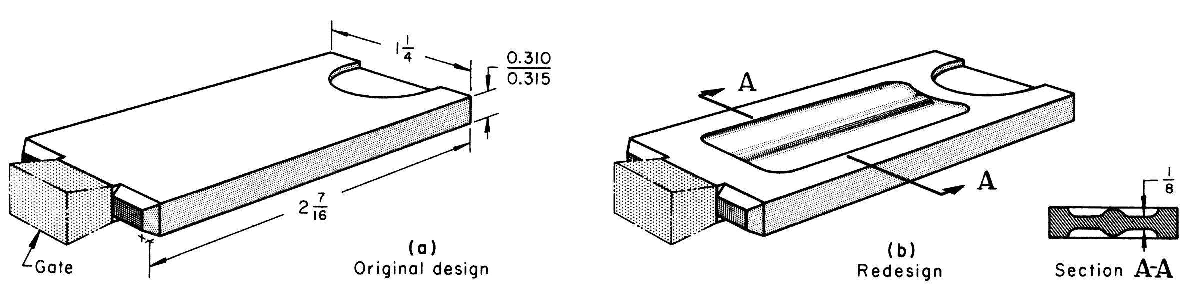

Fig. 14 The flat surfaces of this investment casting as originally designed (a) created problems of thickness tolerance and surface defects from cracking of the mold precoat. A redesign (b) eliminated the flat surfaces and the attendant defects.

and its occupants. Consequently, this part had to be produced to class 1A quality.

As originally designed, the casting did not lend itself to efficient production. The problem was not in filling the mold but in controlling solidification. With a uniform thickness of 0.100 in., the body of the casting solidified too fast for the fillet sections at the junctions of the body and the flanges to develop enough strength to withstand the contractive forces of the solidified body. There were hot tears at the junctions and porosity in the 0.100-in. walls.

To correct these defects, the casting wall was maintained at its original thickness (0.100 in.) at a point midway between the two flanges and was uniformly tapered to a thickness of 0.150 in. at each flange. Isolated sections were thus eliminated. To overcome hot tears, the fillet radii at the junctions were increased from 0.10 to 0.25 in. With a slight modification in processing, the redesign permitted acceptable castings to be produced, and rejections were few.

Although uniform walls are desirable in many castings, in one facet of production of investment castings, uniform walls create problems. The 4130 steel casting shown in Fig. 14(a) illustrates two such problems. The first involved cavitation, or contraction of heavy sections of the wax pattern. As a result of this pattern defect, the center of the casting was depressed below the permissible thickness variation. The second problem, although it appeared to be one of processing related to precoating of the mold, was basically one of design. On smooth, flat surfaces, a mold precoat is likely to crack when the molten metal is poured. If it cracks, but does not peel or wash, the result is a blemish on the surface of the casting where the molten metal fills the crack. Peeling or washing of the precoat causes larger areas of surface imperfections.

The solution to these problems lies in designing to avoid flat surfaces. Figure 14(b) shows how this was done successfully for this particular casting. The ¼-in.-diam riblike raised section along the center of the part acted as a flow channel to assure complete filling of the heavier section of the casting.