Feeding & Risering Guidelines for Steel Castings

Steel Founders' Society of America
2001

Index

1 PREFACE

In 1973, the Steel Founders' Society of America (SFSA) published *Risering Steel Castings* [1], a foundry handbook intended to provide risering guidelines for use in steel foundries. The guidelines contained in *Risering Steel Castings* were developed based on experimental casting work and supported by computer simulations. The steel casting industry has been well served by this handbook since its publication; following the guidelines generally results in sound castings. However, examples have surfaced in the last quarter of a century that indicate that the riser feeding distance rules contained in *Risering Steel Castings* are overly conservative in certain instances, especially where results have been extrapolated. Conservative feeding distance rules lead to the use of more risers than necessary on a casting, which in turn leads to a reduction in casting yield.

Beginning in the mid-1990's, a research effort was undertaken to develop a new set of risering guidelines [2, 3]. This research was based on an extensive set of low-alloy steel plate casting trials performed at various foundries throughout North America. A wide variety of plate dimensions were utilized in the trials, which produced castings ranging from radiographically sound to ASTM shrinkage x-ray level 5. Casting conditions (alloy composition, mold material, superheat, pouring time, etc.) were recorded by each foundry for each plate cast, and this information was then utilized to numerically simulate the casting of each plate, using modern casting simulation software. Once it was determined that there was good agreement between the casting trial results and their corresponding simulations, a large number of simulations were performed for geometries and/or casting conditions that were not used in the casting trials, thus producing a more complete data set. By analyzing all of this data, a new set of feeding distance rules for sound castings was developed. These new rules are presented in this publication.

Differences between this work and *Risering Steel Castings*:

- <u>Usually less conservative feeding distances</u>: The feeding distances calculated using the guidelines presented here are similar to those calculated using *Risering Steel Castings* in some instances, and less conservative in other cases. In general, the current distances become less conservative than those from *Risering Steel Castings* as the width-to-thickness ratio W/T of a casting section increases.
- <u>Consistent definitions of feeding distance</u>: The definitions of feeding distance for top risers with end effect, top risers with lateral feeding, and side risers are the same in this work, whereas different definitions were used in *Risering Steel Castings*.
- <u>Multipliers for different conditions</u>: Multipliers are provided to tailor feeding distances to different cast alloy compositions, mold materials, pouring superheats, and desired levels of casting soundness.
- <u>Soundness in terms of riser zones and end zones</u>: The information presented in Section 4 is intended to give the foundry engineer a physical understanding of the mechanisms involved in feeding solidification shrinkage with risers.

Things that have not changed from *Risering Steel Castings*:

- <u>Riser sizing procedures</u>: The procedures given in this work to determine riser size were written based on the information in *Risering Steel Castings*.

- Applicable text: The text from *Risering Steel Castings* that is still applicable to the current work has been transferred to this manual.
- High alloy risering guidelines: The work presented here is only valid for low alloy steels. Similar feeding distance rules will be developed for high alloy steels, but this is currently work in progress.

It is hoped the guidelines and rules presented in this publication will not only help to effectively riser steel castings and increase the casting yield, but will also provide increased insight into the basic physical phenomena of feeding. Although modern casting simulation software can be used, in place of actual casting trials, to detect feeding and risering problems in a steel casting, the present rules still serve several important purposes:

- Casting simulation does not provide the initial riser design for a casting; the present rules can be used to develop the first "trial" riser design.
- Casting simulation does not automatically optimize the risering; the present rules can be used to shorten the simulation iteration cycle by providing accurate information on the capabilities and limitations of a certain risering procedure (e.g., the maximum distance between risers), and how they change with the casting conditions and the desired soundness.
- Casting simulation is not used on the vast majority of steel castings for various reasons; then, the present rules represent the only means to rationally design the riser system for a casting.

The research leading to the new rules presented in this handbook was performed by R.A. Hardin, S. Ou and K.D. Carlson, under the guidance of Professor C. Beckermann at the University of Iowa. The SFSA would like to thank Professor Beckermann and his group for their research efforts. In addition, great appreciation is expressed to the foundries that participated in the casting trials, for their substantial time and resource investment.

This handbook was prepared with the support of the U.S. Department of Energy (DOE) Award No. DE-FC07-98ID13691. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors, and do not necessarily reflect the views of the DOE.

Malcolm Blair
Vice President – Technology

Carbon and Low Alloy Research Committee:
S. Kulkarni, *Chairman*
P. Bruno
J. Carpenter
G. Hartay
K. Murphy
A. See
B. Shah

2 RISERING BASICS AND TERMINOLOGY

Carbon steel experiences shrinkage of about 3% during solidification. Additional volume reduction occurs during the cooling of the liquid metal after pouring. These contractions will create internal unsoundness (i.e., porosity) unless a riser, or *liquid metal reservoir*, provides liquid feed metal until the end of the solidification process. The riser also serves as a *heat reservoir*, creating a temperature gradient that induces *directional solidification*. Without directional solidification, liquid metal in the casting may be cut off from the riser, resulting in the development of internal porosity. Two criteria determine whether or not a riser is adequate: 1) the solidification time of the riser relative to that of the casting, and 2) the feeding distance of the riser.

To be effective, a riser should continue to feed liquid metal to the casting until the casting has completely solidified. Thus, the riser must have a longer solidification time than the casting. Since the critical factor affecting solidification time is heat loss, minimizing heat loss from the riser is an important consideration. For a riser of fixed volume, a minimum amount of heat loss will occur when the riser geometry has the smallest possible surface area. A sphere represents the maximum volume-to-surface-area ratio (V/A, the *solidification modulus*), and therefore freezes at the slowest rate according to Chorinov's rule. However, spherical risers present molding problems. A cylinder with a height, H, equal to its diameter, D_R, is the typically recommended riser geometry, since it is a simple, easily moldable shape having a high volume-to-surface-area ratio. Various insulating or exothermic riser sleeves are available to reduce the heat loss from a riser. Regardless of its shape, the riser must be large enough to provide sufficient feed metal without the shrinkage pipe in the riser extending into the casting. As shown in Figure 1, there are two common riser configurations: the *top riser*, which is typically more efficient, and the *side riser*. The hemispherical bottom on the side riser prevents premature freezing of the riser/casting junction [1]. It is also recommended to gate the casting through the side riser for maximum effectiveness [1].

The *feeding distance* (FD) is the maximum distance over which a riser can supply feed metal such that the casting section remains relatively free of internal porosity. Hence, the feeding distance determines the number of risers needed. The feeding distance is always measured from the edge of the riser to the furthest point in the casting section to be fed by that riser. This is illustrated for a plate with a top riser in Figure 2, and for a plate with a side riser in Figure 3. When multiple risers are present, the feeding between the risers is called *lateral feeding*. The *lateral feeding distance* (LFD) is again the maximum distance over which a single riser can supply feed metal. If one would draw a line separating the casting section to be fed by a riser and the section to be fed by an adjacent riser, LFD is then the distance from the edge of the riser to the furthest point in the casting along this line. This is illustrated in Figure 4.

Another way to explain how feeding distances are measured is to draw a circle centered about the riser with a radius equal to the feeding distance plus the riser radius (see Figures 2 – 4). Then the casting section inside the circle is fed by that riser. For multi-risered castings (such as in lateral feeding), the circles must overlap such that all sections of a casting are inside these circles.

The feeding distance depends in part on the temperature gradient, which is the change in the temperature per unit length during solidification. Figure 5b illustrates how a steep temperature gradient facilitates the feeding of a casting [4]. The shape of the solid skin surrounding the liquid metal varies with the steepness of the temperature gradient during freezing. Steep gradients provide open, more accessible feeding passages. There exists a critical tapering angle for the liquid pool feeding the solidification shrinkage. For liquid pool angles smaller than this critical angle, centerline shrinkage will form in the isolated pools of liquid that are cut off from the feeding path. This is shown in Figure 5a. The feeding distance also depends on the cooling rate of the steel during solidification, and hence the section thickness. For large cooling/solidification rates (small section thicknesses), the feeding distance is smaller because the velocity at which the feed metal must flow to compensate for shrinkage is larger. Accompanying this larger feed metal velocity is an increased pressure drop along the feed path, which in turn promotes the formation of porosity. Since both the temperature gradient and the cooling rate are influenced by factors such as the section geometry, pouring conditions, steel type and molding material, the feeding distance will vary with all of these parameters. The feeding distances presented in the sections that follow were developed using the Niyama Criterion [5], which incorporates the effects of both the temperature gradient and cooling rate on porosity formation.

There are two terms that are important to understand when considering feeding distances: *riser zone* and *end zone*. Since the riser remains hotter than the casting section to be fed, it provides a temperature gradient that facilitates feeding. The length over which this *riser effect* acts to prevent shrinkage porosity is called the *riser zone length* (RZL). This is illustrated for a top riser in Figure 6. The cooling effect of the mold at the end of a casting section also provides a temperature gradient along the length of the casting section to be fed. This is called the *end effect*, and it produces a sound casting over the so-called *end zone length* (EZL). This is depicted in Figure 7. The feeding distances are functions of RZL and EZL; this is discussed in Section 4.

Sometimes methods are used to increase feeding distances. *End chills* create an additional temperature gradient and enhance the end zone length (and thus the feeding distance), but have no effect on the riser zone length. The lateral feeding distance can be enhanced by the use of *drag chills*. A drag chill does not increase the riser zone length, but rather it causes a temperature gradient that essentially creates an end effect between the risers. An open feed path is also promoted by a *taper*, where the section thickness continually increases toward the riser. In fact, a sufficiently large taper can result in an infinitely long feeding distance.

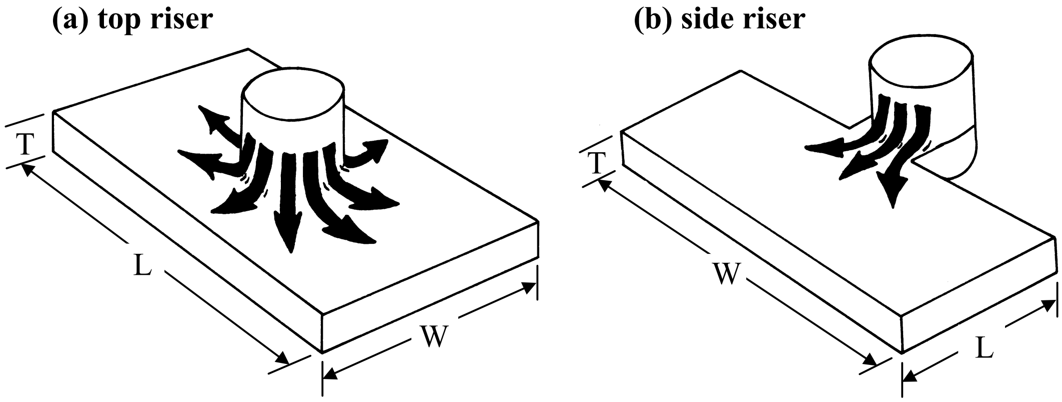


Figure 1 Dimensions for casting sections fed by (a) a top riser, and (b) a side riser (adapted from [1]).

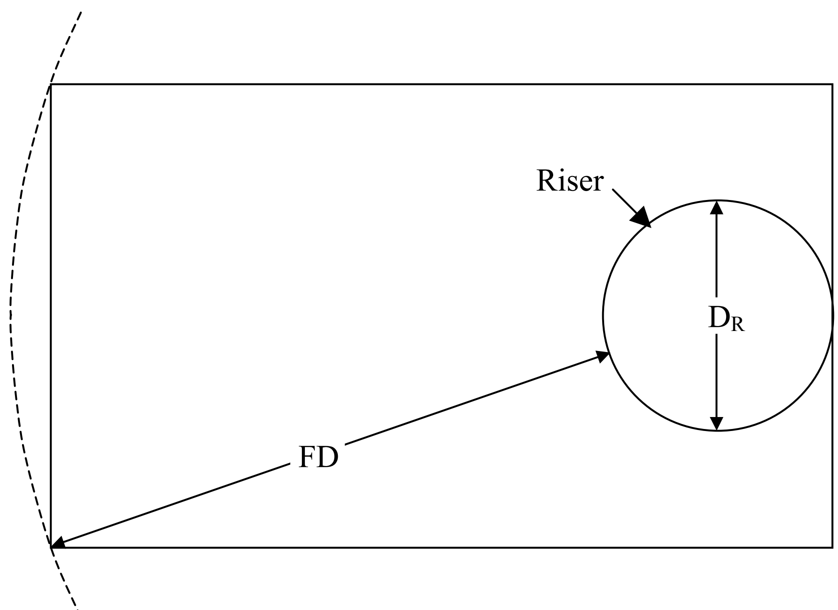


Figure 2 Illustration of the concept of a feeding distance FD; the feeding distance is always measured from the edge of the riser to the furthest point in the casting section to be fed by that riser.

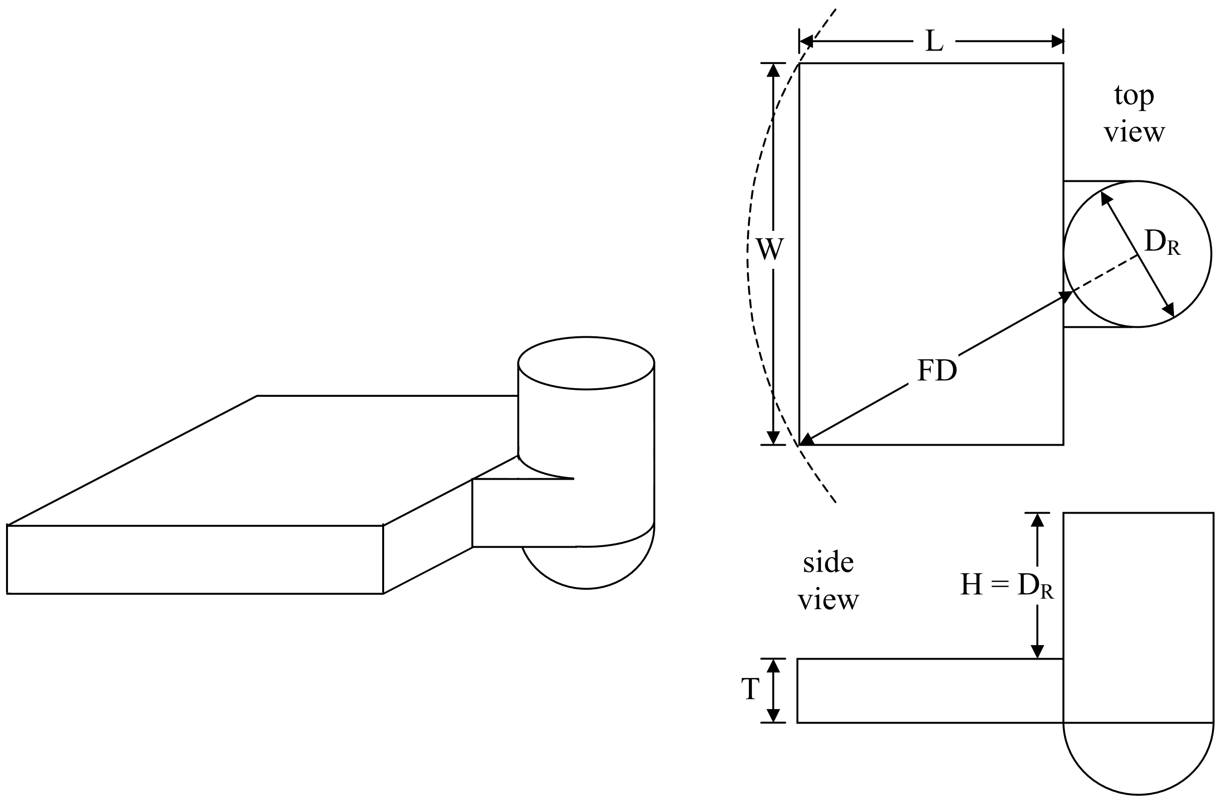


Figure 3 Definition of plate dimensions for a side-risered section with end effect.

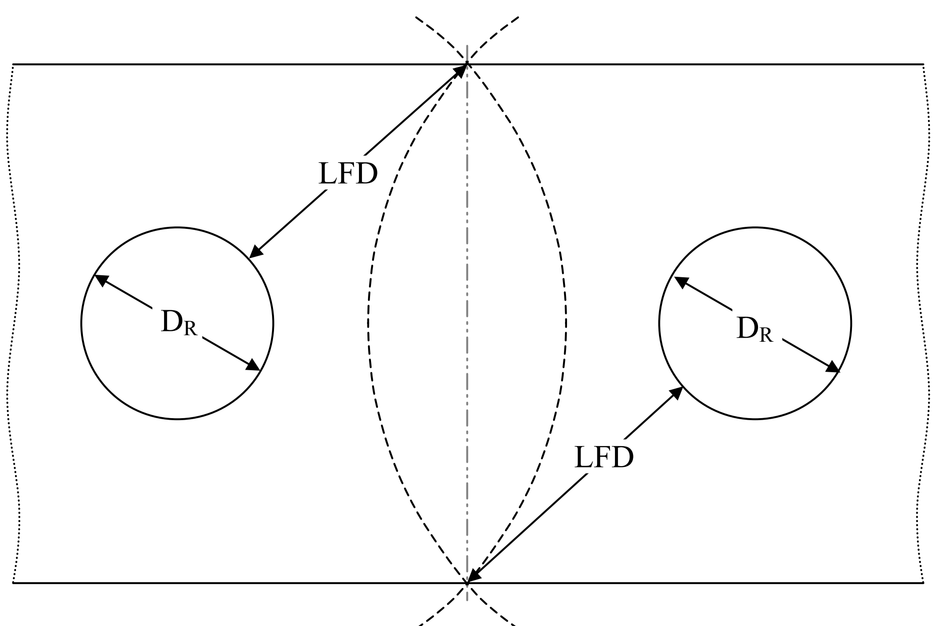


Figure 4 Illustration of lateral feeding between two risers; the lateral feeding distance LFD is measured from the edge of the riser to the furthest point in the casting section to be fed by that riser.

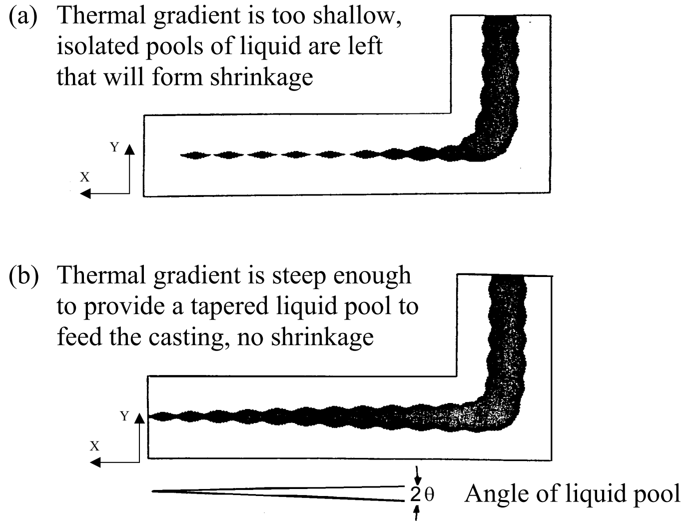


Figure 5 Illustration of a plate-like casting with (b) and without (a) an adequate thermal gradient to prevent formation of shrinkage porosity (adapted from [4]).

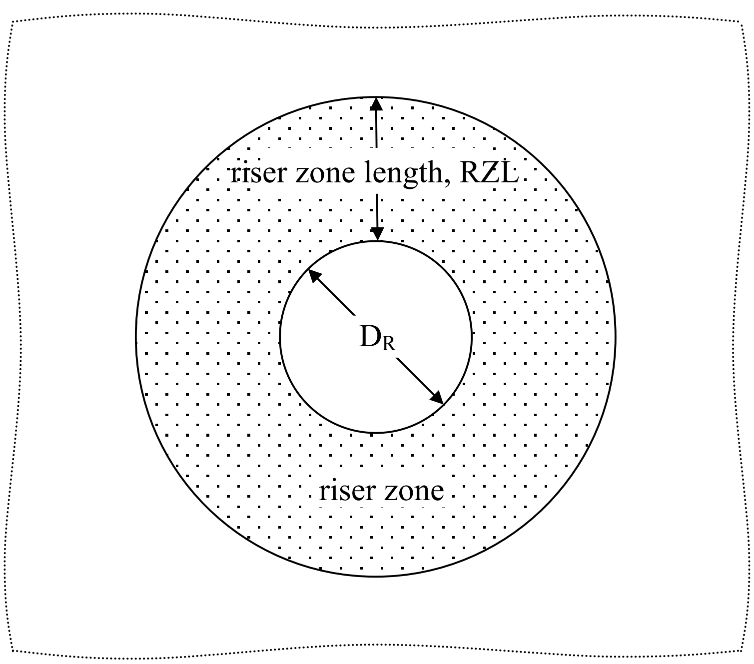


Figure 6 Illustration of the riser zone length RZL of a casting section without end effects; note that RZL is independent of the riser diameter D_R.

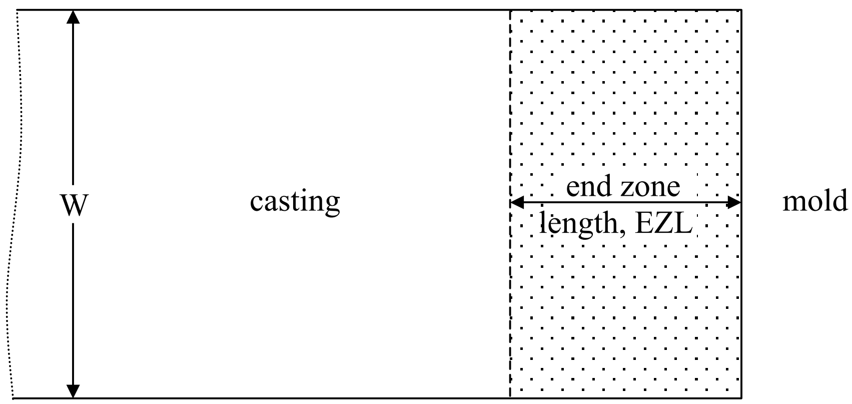


Figure 7 Illustration of the end zone length EZL of a casting section; note that EZL is a function of W for W/T<7.

3 RISERING PROCEDURE

The risering of steel castings should proceed in a systematic manner. The first step is to represent the casting as a collection of simple, plate-like sections. Representing the casting with simply shaped sections allows for the calculation of the solidification modulus (volume-to-surface-area ratio) for each casting section. As mentioned in Section 2, the larger the solidification modulus, the longer the solidification time. If a casting section has a larger modulus than all of the surrounding casting sections, it will still be solidifying after the surrounding sections are completely solidified. The last region to solidify in such a casting section is termed a *hot spot*. Once the hot spots in a casting are identified, a riser must be placed adjacent to each hot spot. This ensures that feed metal will be available to feed each hot spot until solidification is complete.

The reason that the collection of simple sections used to represent the casting should be plate-like is that the risering rules presented in this manual were developed for simple, plate-like shapes. Thus, it is necessary to use such shapes in order to apply these rules. Once this has been accomplished, edges of each casting section with and without the benefit of end effect must be identified. The feeding distance between a riser and an edge without end effect should be calculated as a lateral feeding distance (LFD), instead of as a regular feeding distance (FD). Examples of this process of representing a casting with simple plate-like shapes and identifying edges with and without end effect are shown in Figures 8 – 10.

Once the casting has been represented with a collection of plate-like shapes, the feeding zones of the casting must be identified. A *feeding zone* is a solidifying region of the casting that solidifies in such a manner that it must be risered separately from the rest of the casting (a region containing a hot spot is an example of a feeding zone). A feeding zone may require more than one riser to feed it, depending on the feeding distances involved. Feeding zones can be identified by their solidification moduli (V/A ratio). Sections with the smallest solidification moduli will solidify first, and might therefore divide the casting into distinct feeding zones. Sections having larger moduli will require feed metal until the end of solidification. Risers must be added to such sections to prevent shrinkage during the final stages of solidification. Feeding zones for simple castings might be the simple, plate-like parts that make up a casting. As shown in Figures 8 – 10, the plate-like parts make up distinct feeding zones that are easily identified. This is not always trivial for complex castings.

Once the feeding zones have been identified, a *feeding path* must be determined for each feeding zone. Regions of the casting where sufficient taper and directional solidification exist must be identified. Such regions need not be considered in determining the feeding distance. Also, for such cases, there is no end effect in determining the feeding distance. The principle of directional solidification should be considered in placing the riser. The feeding path should be identified so that it proceeds from the first region in the feeding zone to solidify to the last region to solidify. The riser should be placed at the last position along the feeding path to solidify. Ingates should be placed so that the metal enters below top risers, and always through side risers.

The final step prior to calculating feeding distances and riser sizes for each feeding zone is to define the feeding dimensions. The feeding dimensions of the section to be fed are the length

L, width W, and section thickness T. Two examples of a section with L, W, and T indicated are shown in Figure 1. As shown in this figure, a feeding zone and a feeding path must be identified in order to assign risering dimensions.

To summarize, the recommended procedure for risering steel castings is:

(a) Representation of the casting as a collection of simple, plate-like shapes
- **locate hot spots, and place a riser on each one**
- **for each plate-like shape, determine edges with and without end effect**

(b) Determination of feeding zones, feeding paths and feeding dimensions

(c) Determination of feeding distances (Section 5)

(d) Determination of riser sizes (Section 6)

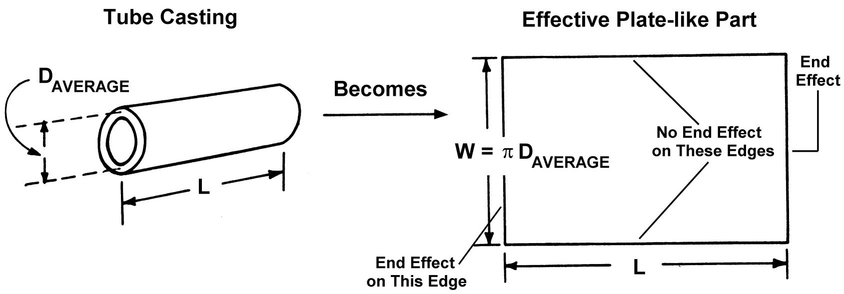


Figure 8 Tube casting represented as a plate having two edges with and two edges without end effect (from [1]).

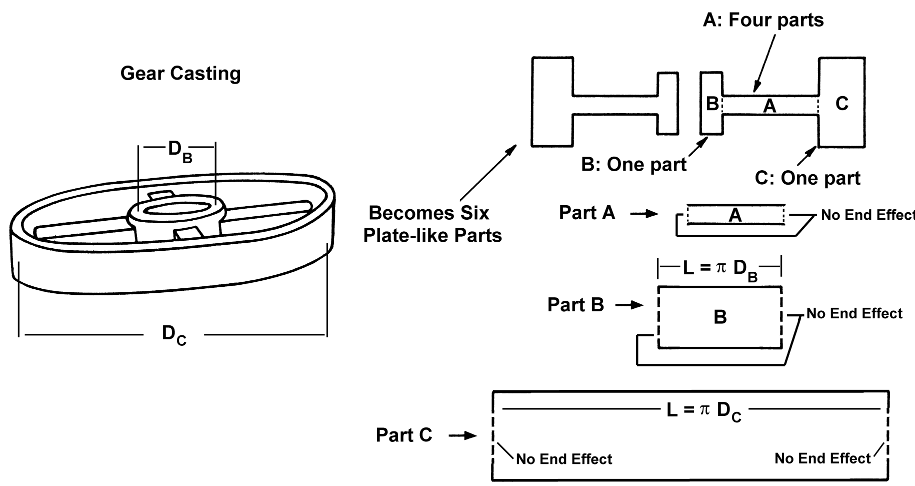


Figure 9 Gear casting represented as three different plate-like geometries (from [1]).

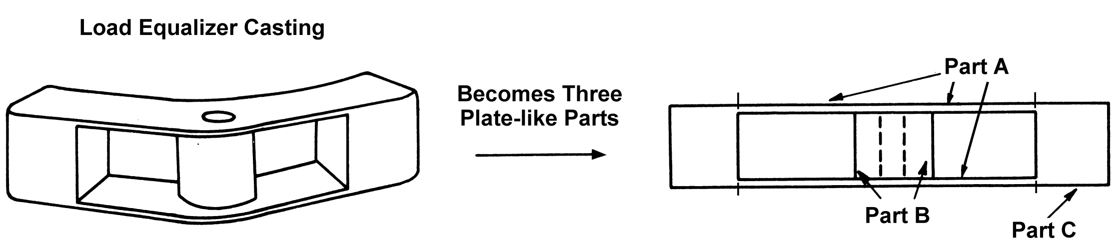


Figure 10 Load equalizer casting becomes three types of plate-like castings (from [1]).

4 CASTING SOUNDNESS IN TERMS OF RISER AND END ZONES

Riser zones and end zones are regions that are free of porosity because a thermal gradient exists in these regions that promotes directional solidification and facilitates feeding flow. The concepts of a riser zone and an end zone are illustrated in Figures 6 and 7, respectively. The size of a riser zone can be characterized by the riser zone length RZL, which extends radially outward from a top riser. The size of an end zone can be characterized by the end zone length EZL, which is measured normal to the end of a casting section.

Figure 11 shows the normalized riser zone length RZL/T and end zone length EZL/T as functions of the normalized section width W/T, where T is the section thickness. The curves in Figure 11 are valid for the casting conditions listed in the inset (see also Section 5). Notice that, as W/T increases from 1, both of these curves initially increase and then plateau at their respective maximum values at around W/T = 7. Fourth order polynomial curve fits of RZL/T and EZL/T for W/T < 7 are given in the Appendix. Considering first the EZL/T curve, the thermal gradient created by the mold for large W/T (i.e., W/T > 7) extends a distance EZL/T = 4.2 into the casting. As W/T decreases below 7, however, EZL/T begins to decrease. This can be explained by considering that there are actually three end zones acting on the casting section shown schematically above the EZL/T curve in Figure 11. The end zone shown extends from the right edge of the casting, but there are also end zones extending from both sides in the width direction. The directional solidification created by these side end zones causes solidification fronts to move from the sides into the casting, just as the right end zone causes a solidification front to move from the right edge into the casting. As W/T decreases below 7, the solidification fronts extending from the sides begin to meet at the centerline before the solidification front extending from the right edge can travel the entire end zone length. When the side fronts meet, they cut off feeding flow to the right end zone, and effectively reduce the size of that end zone. This causes the decrease seen in EZL/T as W/T approaches 1. The decrease in RZL/T can be similarly explained: for small W/T, the end zones extending from the sides in the width direction of the casting section meet at the centerline and effectively reduce the size of the riser zone. For W/T > 7, the riser zone length is simply given by RZL/T = 3.05, which is independent of the riser diameter.

By utilizing the riser zone and end zone concepts, it is possible to determine whether or not a casting section fed by a riser will be sound, as well as where porosity will form if the casting section is not sound. This is shown in the following subsections for (1) a top riser feeding a casting section that ends in the mold, (2) lateral feeding between top risers, and (3) a casting section fed by a side riser.

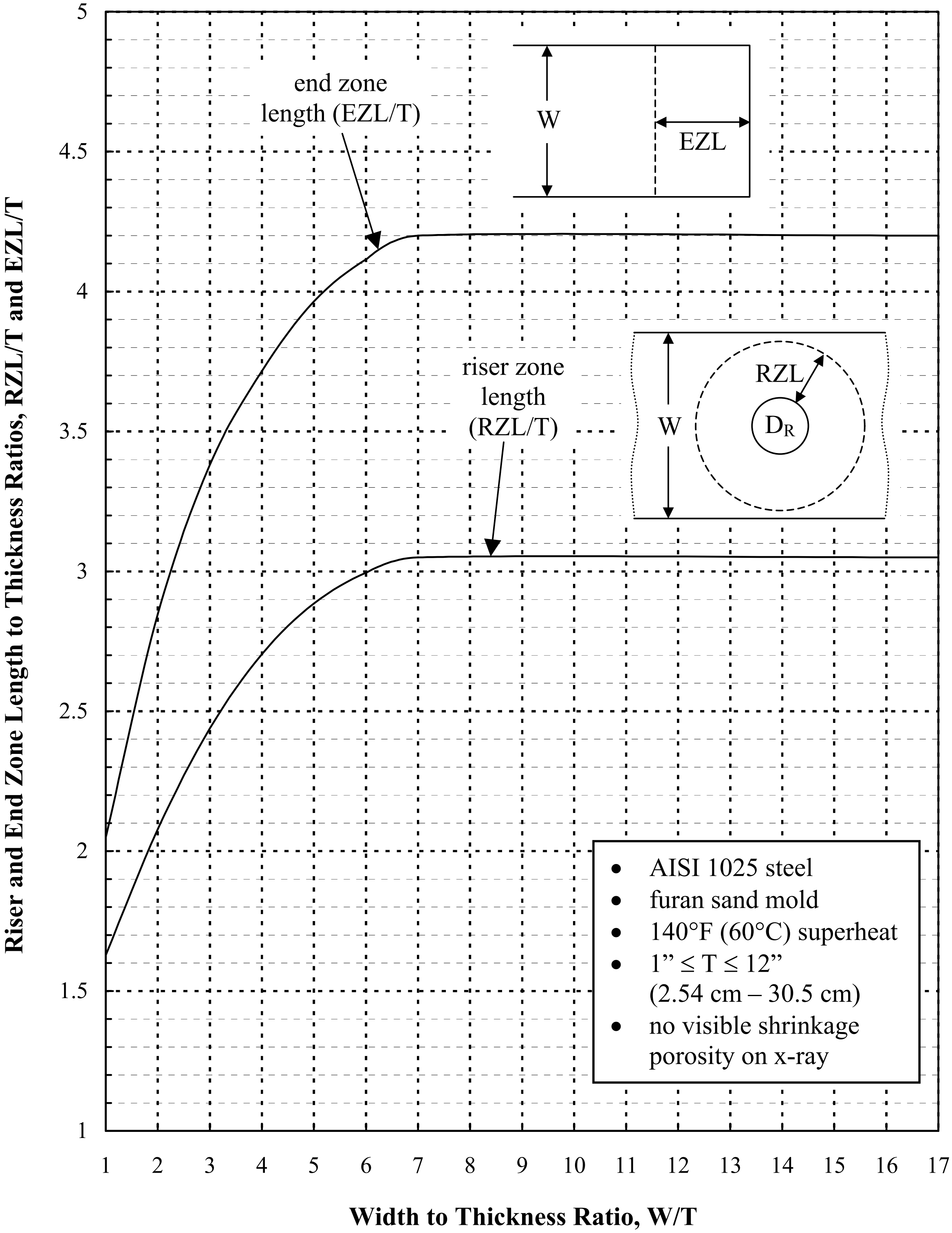


Figure 11 Riser zone length and end zone length as a function of width and thickness.

4.1 Top-Risered Casting Section Ending in the Mold

Figures 12 and 13 illustrate two different situations involving a top riser feeding a casting section that ends in the mold. Figure 12 depicts the case when the casting section width W is less than or equal to twice the size of the end zones extending from the sides in the width direction of the casting section (i.e., $W \leq 2EZL_2$). It should be noted that the end zone lengths EZL_1 and EZL_2 can be different, because they are functions of the length of the casting-mold interface from which they originate. Thus, EZL_1 is a function of W, and EZL_2 is a function of the length of the side edges of the section shown (not labeled). Figure 12a shows a sound casting section. The only regions of this casting section that do not lie within either the riser zone or the end zone extending from the right edge of this casting section (i.e., EZL_1) are the regions between the dashed lines (one above the centerline and one below). But these regions lie within the end zones extending from the side edges in the width direction of the casting section. Hence, the entire casting section not beneath the riser is covered by a riser zone or an end zone, and the casting section is sound. Figure 12b shows that, if the distance between the riser and the right edge of the casting section is increased, shrinkage porosity will result along the centerline between the riser zone and the end zone extending from the right edge of the casting. It may seem that this casting section should be sound, because the entire section lies within either the riser zone, the end zone extending from the right edge, or the end zones extending from the side edges. However, due to the directional solidification caused by the end zones extending from the side edges of the casting section, solidification fronts will advance from the side edges toward the centerline. These fronts will meet at the centerline, and feed metal from the riser zone to the end zone extending from the right edge of the casting section will be cut off. This will result in the centerline shrinkage porosity shown in Figure 12b.

Figure 13 illustrates the case when the width W of a casting section is greater than twice the size of the end zones extending from the side edges of the casting section shown (i.e., $W > 2EZL_2$). Figure 13a depicts a sound casting. Again, the entire casting section not directly beneath the riser lies within a riser zone or an end zone. Figure 13b shows the onset of shrinkage porosity as the distance from the riser to the right edge of the casting section increases beyond the maximum distance for a sound casting shown in Figure 13a. Note that, when $W > 2EZL_2$, the shrinkage porosity begins to form in the two small regions not covered by an end zone or riser zone, rather than along the centerline as in the case where $W \leq 2EZL_2$. Figures 13c and 13d show how the shrinkage porosity regions grow and eventually merge into one region as the distance between the riser and the right edge of the casting section continues to increase. An important difference between the cases depicted in Figures 12 and 13 can be seen by comparing Figures 12a and 13c. Note that these two figures are similar, since the end zone extending from the right edge of the casting is tangent to the riser zone in both figures. However, due to the difference in casting section width W in these two figures, Figure 12a results in a sound casting, while Figure 13c results in shrinkage porosity.

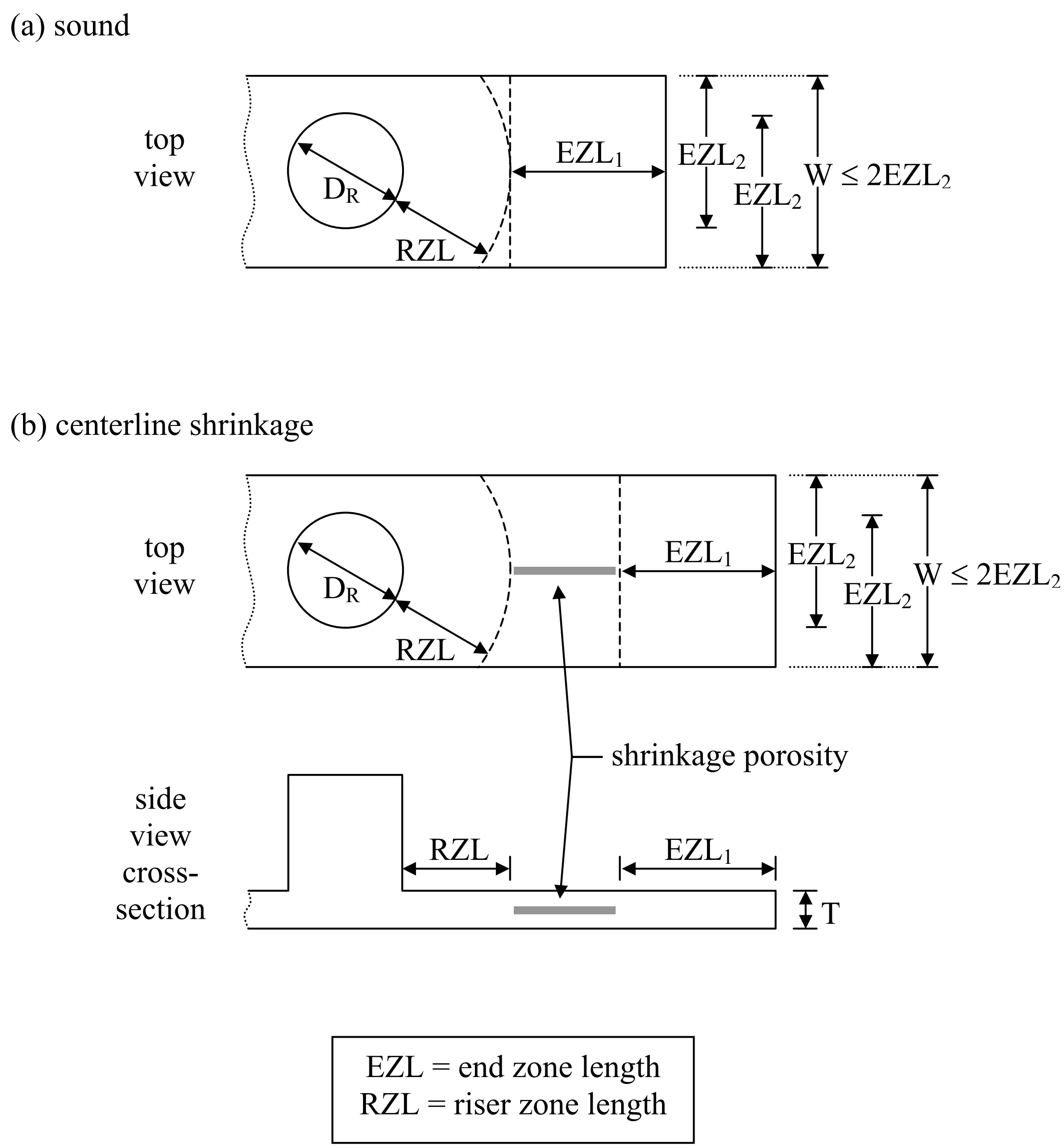
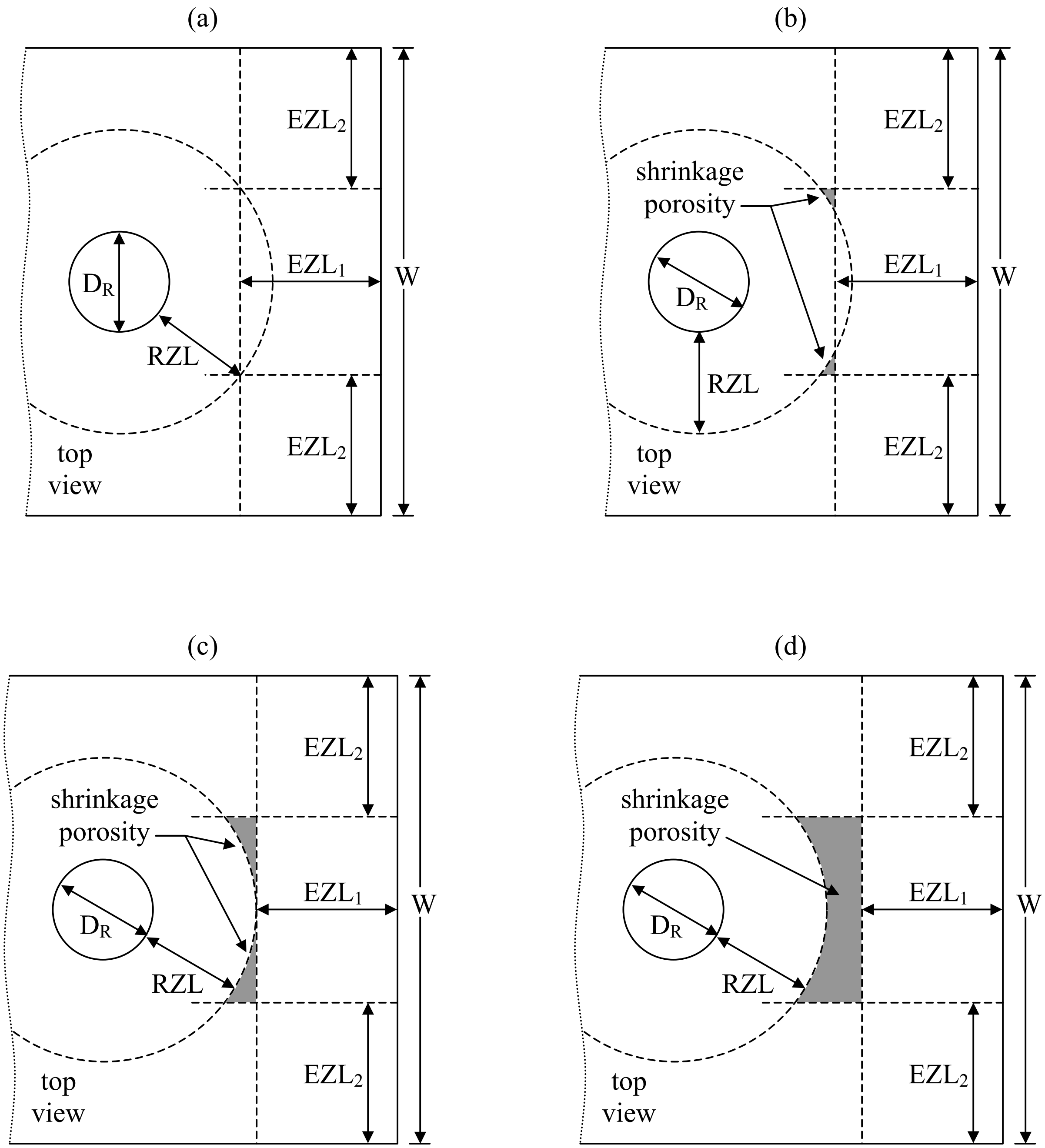


Figure 12 Top-risered plate with end effect for plates with width $W \leq 2EZL_2$. (a) The plate is sound if the riser zone and the end zone extending from the right edge of the casting section are tangent (as shown) or overlap. (b) The plate has centerline shrinkage between these zones if they do not meet.



EZL = end zone length
RZL = riser zone length

Figure 13 Top-risered plate with end effect for plates with width $W > 2EZL_2$. (a) The plate is sound if the intersections of the end zones lie within or intersect the riser zone. (b) – (d) show where porosity forms as the plate length increases.

4.2 Lateral Feeding in a Top-Risered Casting Section

Different examples of top-risered lateral feeding are presented in Figures 14 – 16. Figure 14 illustrates the case when the casting section width W is less than or equal to twice the size of the end zones extending from the side edges in the width direction of the casting section (i.e., W ≤ 2EZL). Figure 14a shows a sound casting. The riser zones are tangent to each other, encompassing all of the casting section except for the areas between the dashed lines. These areas fall within the end zones that extend from the side edges of the casting section shown in Figure 14a. When the distance between risers increases, as in Figure 14b, the riser zones do not intersect. Similar to the situation shown in Figure 12b, the solidification fronts advancing from the side edges of the casting section in Figure 14b meet at the centerline, and cut off feeding from the riser zones. This results in the centerline shrinkage shown in Figure 14b. Figure 15 depicts the case when the width W of a casting section is greater than twice the size of the end zones extending from the side edges of the casting section shown (i.e., W > 2EZL). Figure 15a shows a sound casting. Again, the entire section lies beneath a riser, or in a riser zone or an end zone. When the distance between the risers is increased, shrinkage porosity begins to form in the casting in the regions not covered by riser zones or end zones. This is illustrated in Figure 15b. Analogous to Figure 13, the regions of shrinkage porosity grow and merge as the distance between risers continues to increase, as seen in Figures 15b – 15d. Note that Figures 14a and 15c are similar, since in both figures the riser zones are tangent to each other. However, due to the difference in widths, the casting in Figure 14a is sound, while the casting in Figure 15c has shrinkage porosity. Figure 16 shows the case when there are no end effects in the region of interest. In order for the casting to be sound, the casting section between all of the risers must lie within one or more riser zones. This is shown in Figure 16a. Figures 16b and 16c show where shrinkage porosity first occurs, and how this region grows as the risers are placed further apart.

Based on the cases presented in Figures 12 – 16, it can be stated that a casting section will be sound provided that ALL THREE of the following conditions are met:

(1) The entire casting section not directly beneath a riser must lie within either a riser zone or an end zone.

(2) If two or more end zones intersect, their point(s) of intersection must lie on or within the boundary of a riser zone.

(3) If two or more riser zones intersect and end effects are present in the region, the point(s) of intersection of the riser zones must lie on or within the boundary of an end zone.

For example, consider Figure 12. The end zones extending from the side edges of this casting section meet at the centerline (not shown). Hence, these end zones share a common boundary, which is the centerline of the casting section. The intersection between this boundary and the boundary of the end zone extending from the right edge of the casting section is the midpoint of the vertical dashed end zone boundary line shown in Figure 12. In Figure 12a, this intersection is the point where the riser zone and the end zone extending from the right edge meet. Hence, conditions (1) – (3) listed above are satisfied, and the casting section is sound. In Figure 12b, the intersection of the end zones is outside the riser zone. Condition (2) is violated, and shrinkage porosity develops.

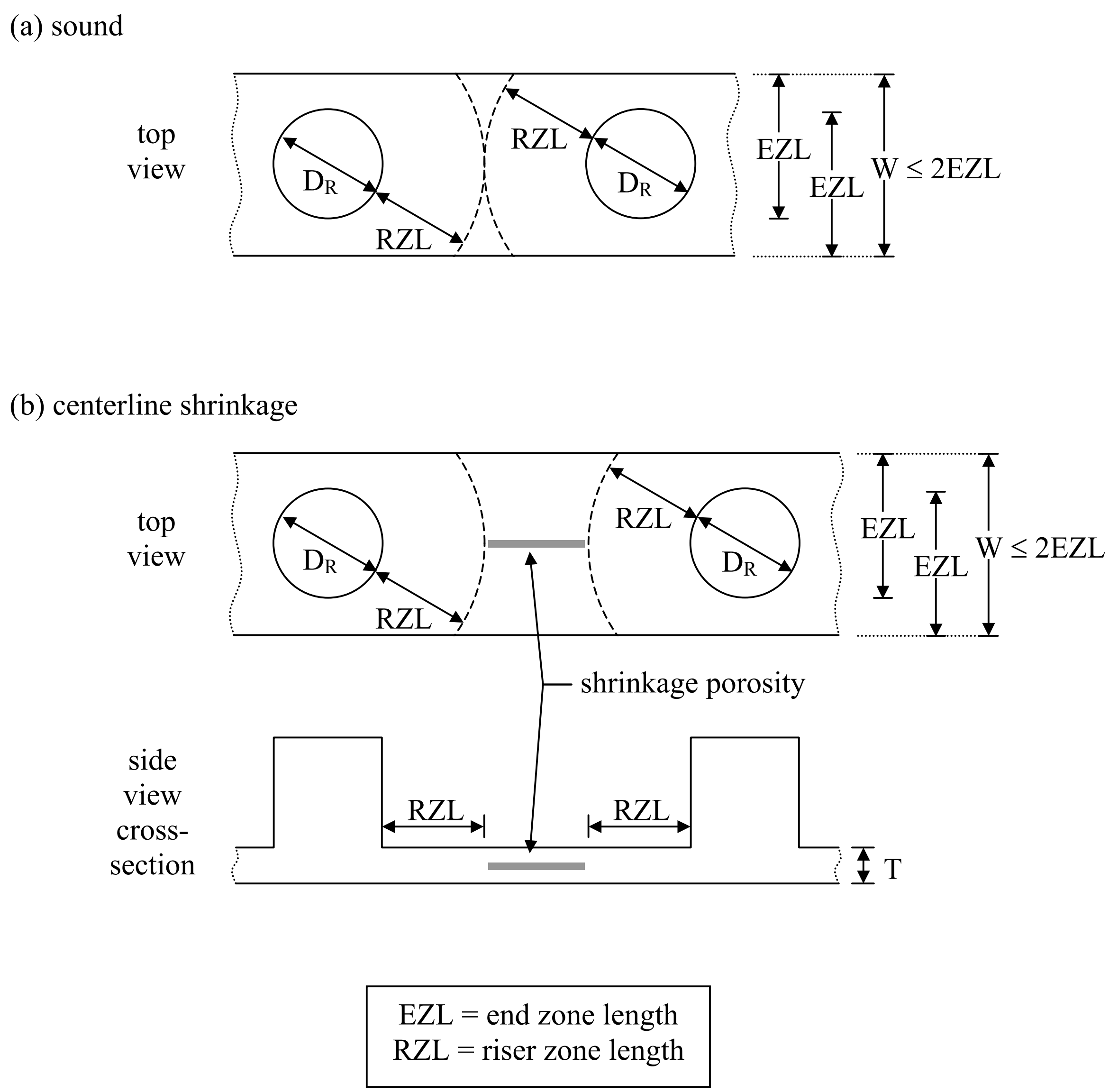


Figure 14 Top-risered plate with lateral feeding for plates with width W ≤ 2EZL. (a) The plate is sound if the riser zones are tangent (as shown) or overlap. (b) The plate has centerline shrinkage between the riser zones if they do not meet.

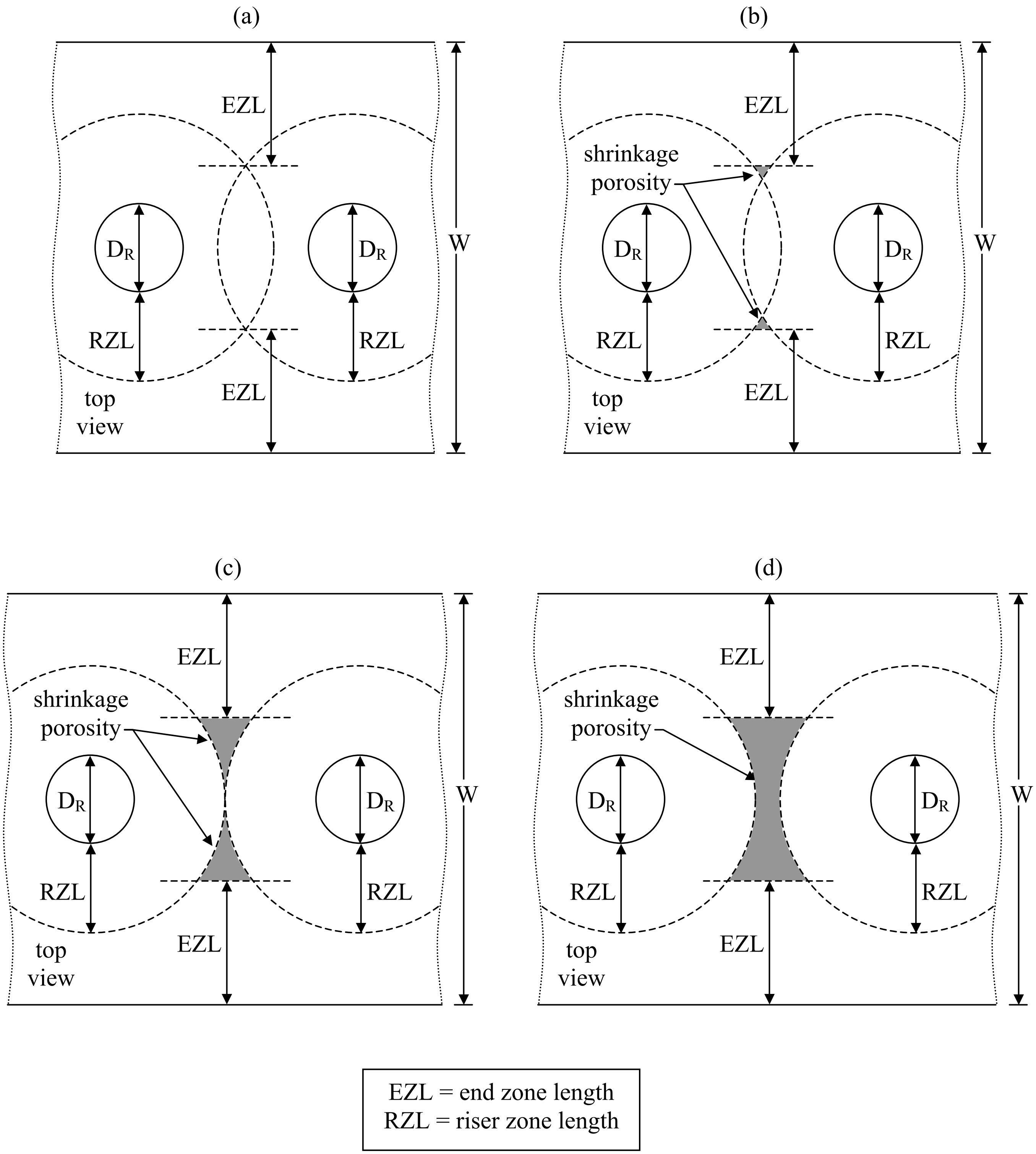


Figure 15 Top-risered plate with lateral feeding for plates with width W > 2EZL. (a) The plate is sound if the end zone lines lie within or intersect the riser zones. (b) – (d) show where porosity forms as the distance between risers increases.

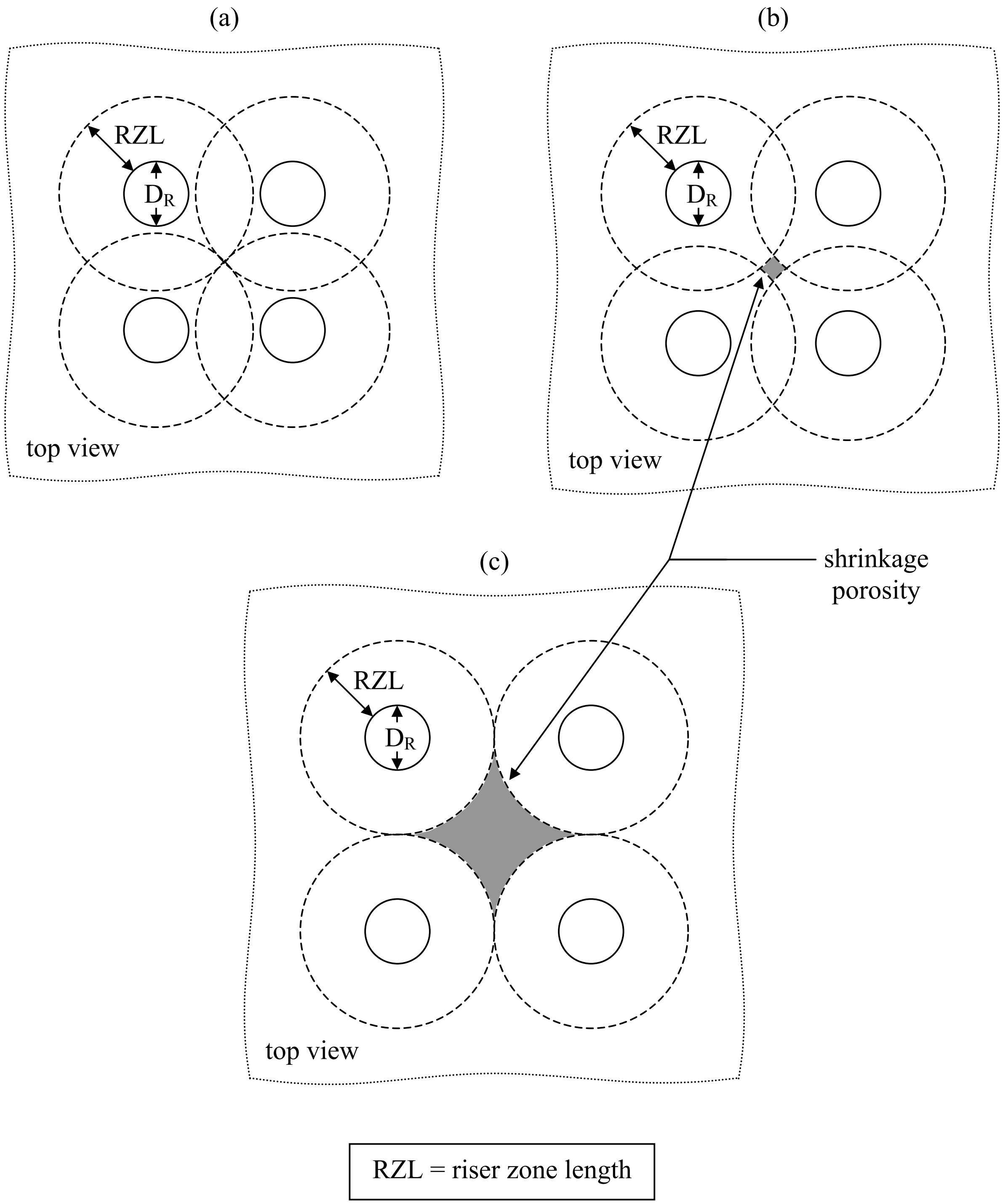


Figure 16 Top-risered plate with lateral feeding for a plate section without end effects. (a) The region of the plate between the risers is sound if it is completely contained within one or more riser zones. (b) and (c) show where porosity forms as the distance between risers increases.

4.3 Side-Risered Casting Sections

Although the discussion of riser zones and end zones to this point has been limited to top-risered sections, these concepts can also be considered in terms of side risers. The concept of end zones is the same as for top risers, because end zones are only a function of the casting/mold interface, and not of risers. The concept of a riser zone is slightly different, because side risers do not feed radially in all directions as do top risers, and there are competing effects of the riser zone and the end zones adjacent to the riser. Figure 17 shows an example of a casting that is fed with a side riser. This casting has at least part of all four of its sides in contact with the mold, so there are four end zones present. The end zones extending from the right and left sides in Figures 17a and 17b are functions of the length L, and the end zones extending from the upper and lower sides are functions of the width W. The riser zone drawn in Figures 17a and 17b is approximate. As mentioned above, side risers do not feed the casting in the same manner as top risers. With side risers, some of the feed metal entering the casting moves radially (as with top risers). However, feed metal also has to turn the corners to feed the casting on the right and left sides of the riser contact. In addition, the thermal gradient created by the hotter metal in the riser is competing with the cooling effects of the mold on the edges of the casting near the riser contact. Due to these differences between side riser feeding and top riser feeding, the riser zone can only be approximated as a circular arc, as shown in Figure 17. However, the basic concepts are still useful and valid.

The casting section shown in Figure 17a is sound. The intersections of the end zones fall on the riser zone, and the entire casting is covered by a riser zone or an end zone. Thus, the three conditions listed in Section 4.2 are satisfied. Figure 17b shows that as the width W is increased, the intersections of the end zones move outside of the riser zone. As in Figures 12 and 14, shrinkage porosity forms along the horizontal centerline between the riser zone and the intersections of the end zones.

Analogous to Section 4.1, a wide range of geometries can be considered for side risers as well, using the same procedures demonstrated thus far in this section. When considering the soundness of side-risered casting sections in terms of RZL and EZL, the curves given in Figure 11 can be utilized, but the values of RZL should be considered approximate.

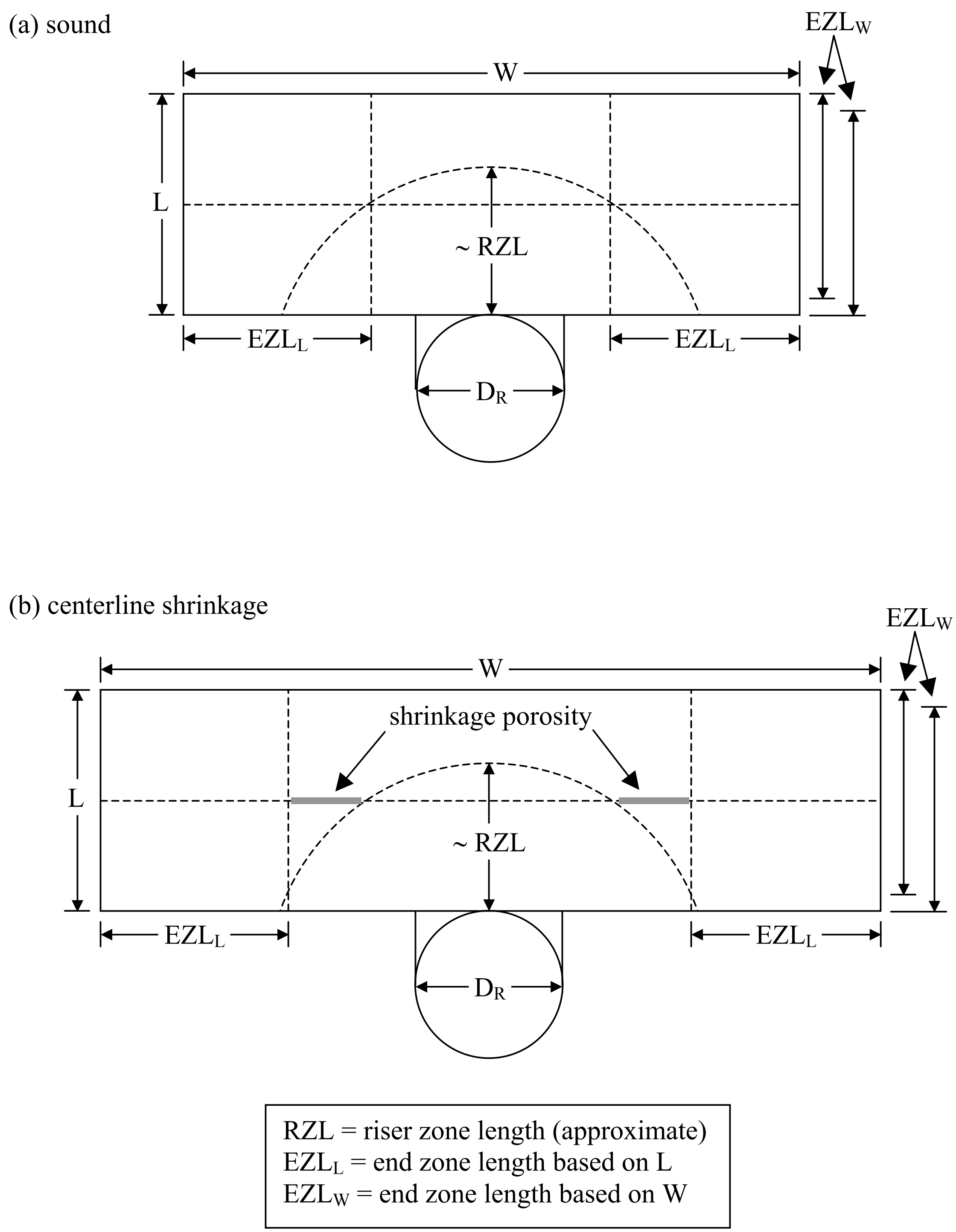


Figure 17 An example of the application of riser zone and end zone concepts to a side-risered plate. (a) The plate is sound if the intersections of the end zones fall in or on the boundary of the riser zone. (b) Shrinkage porosity develops between these intersections and the riser zone if they do not meet.

5 CALCULATION OF FEEDING DISTANCE

The feeding distance, measured from the edge of a riser to the furthest point in the casting section, indicates the length of a casting section that can be fed by that riser ***without developing visible shrinkage defects in radiographic testing*** (i.e., *better* than ASTM shrinkage x-ray level 1). As shown in Figures 2 – 4, the concept of a feeding distance is most easily applied by drawing a circle centered about a riser, with a radius equal to the feeding distance plus the riser radius. Then, the casting section inside this circle is fed by that riser.

The feeding distance rules presented in this section were developed for casting sections with thickness, T, ranging from 1” to 12” (2.54 cm to 30.5 cm). For thin casting sections [i.e., less than 1” (2.54 cm) thick], the feeding distance becomes highly dependent on the filling process. If a thin section is gated through the riser, feeding distances up to twice as long as those predicted with the present rules have been reported [1]. Bearing the effects of filling in mind, the feeding rules provided here can be used for thin sections, but they will give an overly conservative estimate of the feeding distance in many instances.

Sections 5.1 to 5.6 provide equations and charts that can be used to calculate the feeding distance for a casting section with given dimensions. Top risers, side risers, sections with a taper and different end cooling conditions (regular end effect, lateral feeding, and chills) are considered. The feeding distances discussed here are valid for the following base casting conditions:

- AISI 1025 steel,
- PUNB (furan) sand mold,
- 140°F (60°C) pouring superheat.

Application of these feeding distances to sections cast with different alloy compositions, molding materials, and pouring superheats, as well as to other soundness levels (e.g., higher ASTM shrinkage x-ray levels), is explained in Section 5.6. As with the RZL/T and EZL/T curves in the previous section, fourth-order polynomial curve fits are provided in the Appendix for the curves shown in this section.

5.1 Top Riser With End Effect

Feeding distances for top-risered sections (Figure 2) are given graphically by the curve in Figure 18, where FD/T is plotted against W/T. By dividing FD and W by the thickness T (the dimension into the page for the casting sketch shown in Figure 18), a single curve can be used to represent the feeding distances for all section thicknesses. The feeding distance curve for end effect terminates at a W/T value of about 15. For larger W/T, the width of the section becomes larger than its length (for a standard riser diameter), and the two can be switched around.

It was mentioned in Section 2 that the feeding distance is related to riser and end zone lengths. This can be seen by comparing Figures 11 and 18. Consider, for example, W/T = 1. For small W/T, the largest sound casting section corresponds to Figure 12a, where the riser zone is tangent to the end zone. Because W is small, FD is approximately equal to the distance along the centerline from the riser edge to the right edge of this casting, which is simply RZL + EZL. The values for RZL/T and EZL/T at W/T = 1 from Figure 11 are 1.65 and 2.05, respectively.

Their sum is 3.7, which is about the value of FD/T for W/T = 1 in Figure 18. As W/T increases, RZL/T and EZL/T increase until about W/T = 7, when they reach their maximum values and then remain constant. FD/T increases slightly faster than the sum of RZL/T and EZL/T from W/T = 1 to W/T = 7. Beyond W/T = 7, FD/T continues to increase with W/T, even though RZL/T and EZL/T remain constant. This is because FD/T is the diagonal distance from the riser to the furthest corner of the casting section, and since W/T continues to increase, so does FD/T. Once W/T is larger than $2(EZL_{max}/T) = 8.4$, the largest sound casting section corresponds to Figure 13a. Again, as W/T continues to increase, so does FD/T. This occurs until about W/T = 15, where FD/T reaches its maximum value of about 9.0.

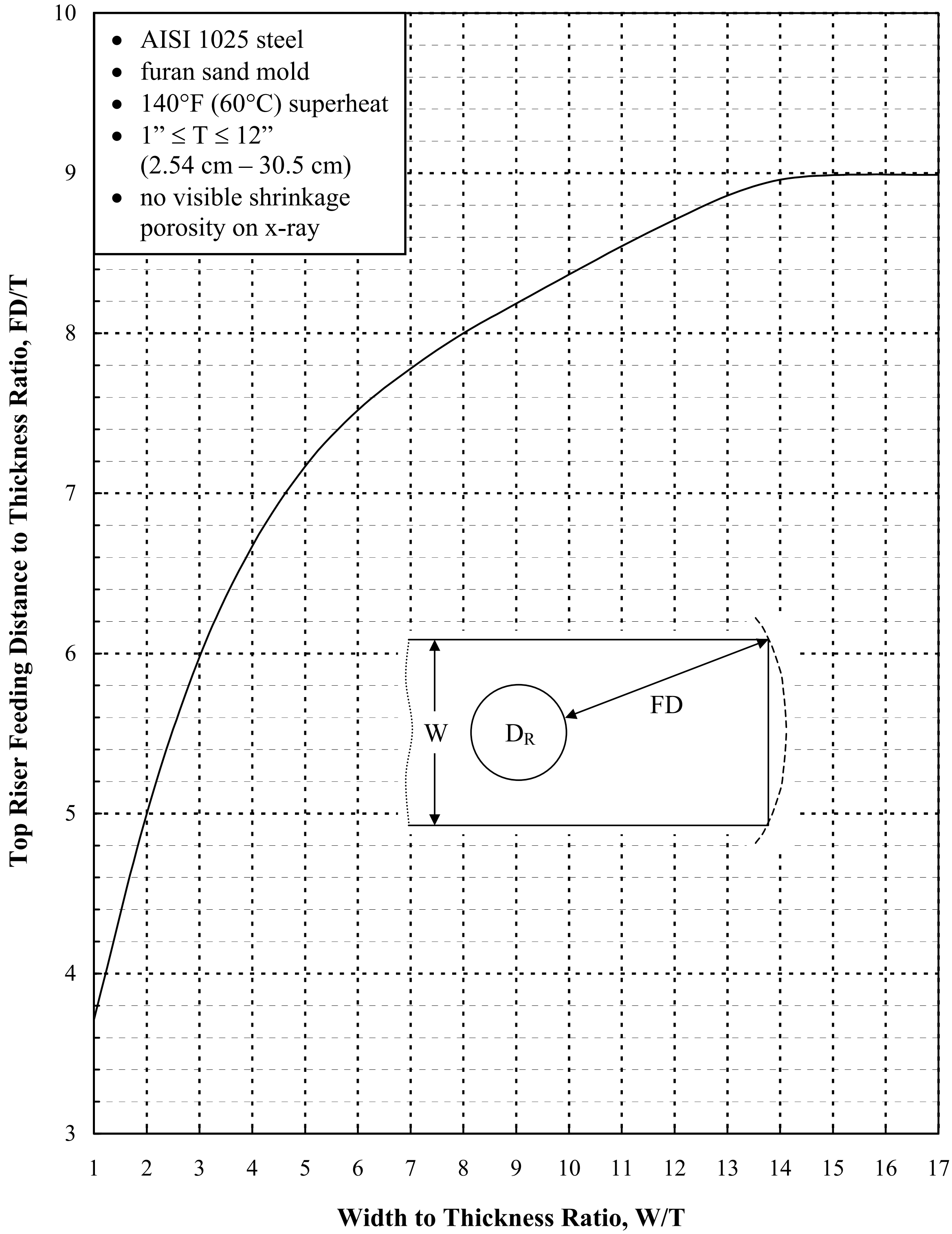


Figure 18 Feeding distance (FD) as a function of width and thickness for top-risered sections.

5.2 Lateral Feeding (Feeding Between Top Risers)

The normalized lateral feeding distance LFD/T for top risers (Figure 4) is plotted as a function of the width-to-thickness ratio W/T in Figure 19. For relatively small values of W/T, the lateral feeding distance is equal to about 48% of the end effect feeding distance, i.e.

$$\frac{\text{LFD}}{\text{T}} = \left(\frac{\text{FD}}{\text{T}}\right)_{\text{lateral}} \approx 0.48\left(\frac{\text{FD}}{\text{T}}\right)_{\text{end effect}} \qquad \text{, for W/T} \leq 7 \tag{1}$$

This equation is approximately valid to up to about W/T = 7. Note that division by the thickness T in the above equation is not necessary, since T cancels out. It is simply included to make the multiplier easier to use with the various equations and figures where FD/T is correlated or plotted. It should be noted that there is a slight riser diameter dependence in the LFD/T curve shown in Figure 19. The effect is small up to about W/T = 7. But for larger values of W/T, this curve can be in error by a few percent, depending on the riser diameter. When there are no end effects in the lateral feeding region under consideration (for example, see Figure 16, with four risers), the width W is not relevant. For this special case, the lateral feeding distance is simply equal to the maximum riser zone length value of 3.05T. This information is given in the sketch inset in the lower right portion of Figure 19.

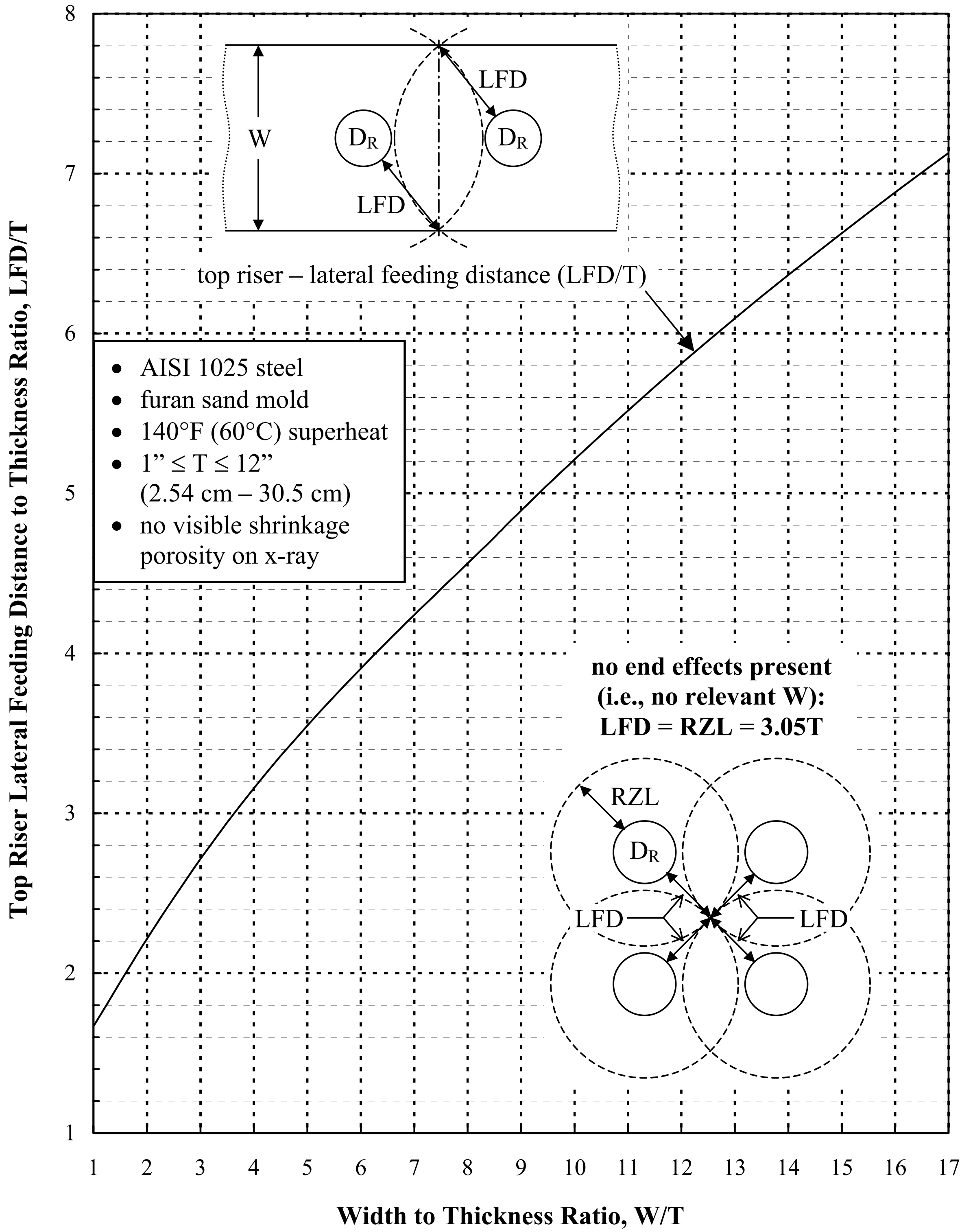


Figure 19 Lateral feeding distance (LFD) as a function of width and thickness for top-risered sections.

5.3 Side Riser With End Effect

The normalized feeding distance, FD/T, for side-risered casting sections (Figure 3) is plotted in Figure 20 as a function of the width-to-thickness ratio, W/T. Note that, unlike FD/T for top risers shown in Figure 18, the feeding distance for side risers cannot be given by a single curve. Instead, FD/T in Figure 20 is also a function of the normalized riser diameter, D_R/T. This is due in part to the more complicated nature of feeding with a side riser, because the feed metal must turn corners at the riser/casting junction instead of simply moving along straight, radial paths. Another contributing factor is simply the geometric dependence of FD on the riser size. The curve in Figure 20 labeled "Feeding Distance for $W = D_R$" is an important limiting case. When $W = D_R$, the side-risered casting reduces to a top-risered casting with the riser placed at one end, as shown in the sketch at the top of Figure 20. In this limiting case, FD/T for side risers is the same as FD/T for top-risers. In other words, the $W = D_R$ curve is simply the FD/T curve from Figure 18. The dash-dot-dotted lines shown in Figure 20 represent lines of constant normalized length, L/T. If the feeding distance, riser diameter, and casting section width are known, the casting section length can be calculated from

$$L = \sqrt{(0.5D_R + FD)^2 - 0.25W^2} - 0.5D_R \tag{2}$$

These L/T lines are included to give some feeling of how the length changes with the other parameters involved in this plot.

The curves in Figure 20 for D_R/T = 1, 2 and 4 look complicated, but can be readily understood by tracing one of these curves, beginning from the limiting case just described. Consider, for example, the curve for $D_R/T = 2$. When $W/T = D_R/T = 2$, the value of FD/T is 5.0, just as it is for top risers when W/T = 2 (see Figure 18). As W/T increases from this point, notice that the D_R /T curve is nearly parallel to the line representing L/T = 4.9. Thus, as W/T increases along the $D_R/T = 2$ curve, L/T remains nearly constant, and the casting section is simply becoming wider. FD/T increases with W/T until W/T reaches its maximum of about 14.5, at which point the FD/T curve makes a sharp turn and W/T begins to decrease. W/T = 14.5 represents the maximum section width that can be soundly fed by a riser with diameter $D_R/T = 2$. As the FD/T curve for $D_R/T = 2$ turns at W/T = 14.5 and begins heading down and to the left, notice that both L/T and W/T begin to decrease. This can be understood by considering that, as the section length L is decreased, the width W that can be soundly fed by a given riser will decrease as well. As L decreases, the end zone extending from the edge of the casting section opposite from the side riser causes a solidification front to begin advancing from that edge toward the riser zone extending from the riser. In addition, there are end effects on the sides of the casting next to the riser/casting junction that promote solidification of the casting in those regions. As the solidification fronts caused by these end effects move toward the middle of the casting, they begin to solidify the feeding path and force the feed metal to make sharper turns to feed tangentially. In essence, as L becomes smaller, it becomes harder for the feed metal to turn corners and feed tangentially into the casting section, and the feeding path solidifies sooner. Therefore, as L decreases, W must also decrease for the casting section to remain sound.

Notice the "sound" label in Figure 20. This indicates that any casting geometry that lies inside the "U" of the FD/T curves will be sound, while any geometry that falls outside this area is likely to contain shrinkage porosity. Consider, for example, a side-risered casting section with $D_R/T = 2$ and $W/T = 12$. The lower portion of the $D_R/T = 2$ curve crosses $W/T = 12$ at a value of $FD/T = 5.8$. L/T at this location is 2.2. The upper portion of this curve crosses the $W/T = 12$ line again at about $FD/T = 7.4$, where L/T is about 4.8. This can be interpreted as follows: if $D_R/T = 2$ and $W/T = 12$, a side riser can soundly feed casting sections with L/T ranging from 2.2 to 4.8. If L/T is larger than 4.8, the section is simply too large for the riser to feed. If L/T is smaller than 2.2, end effects will cause the difficulties in tangential feeding, and the feeding path will solidify prematurely.

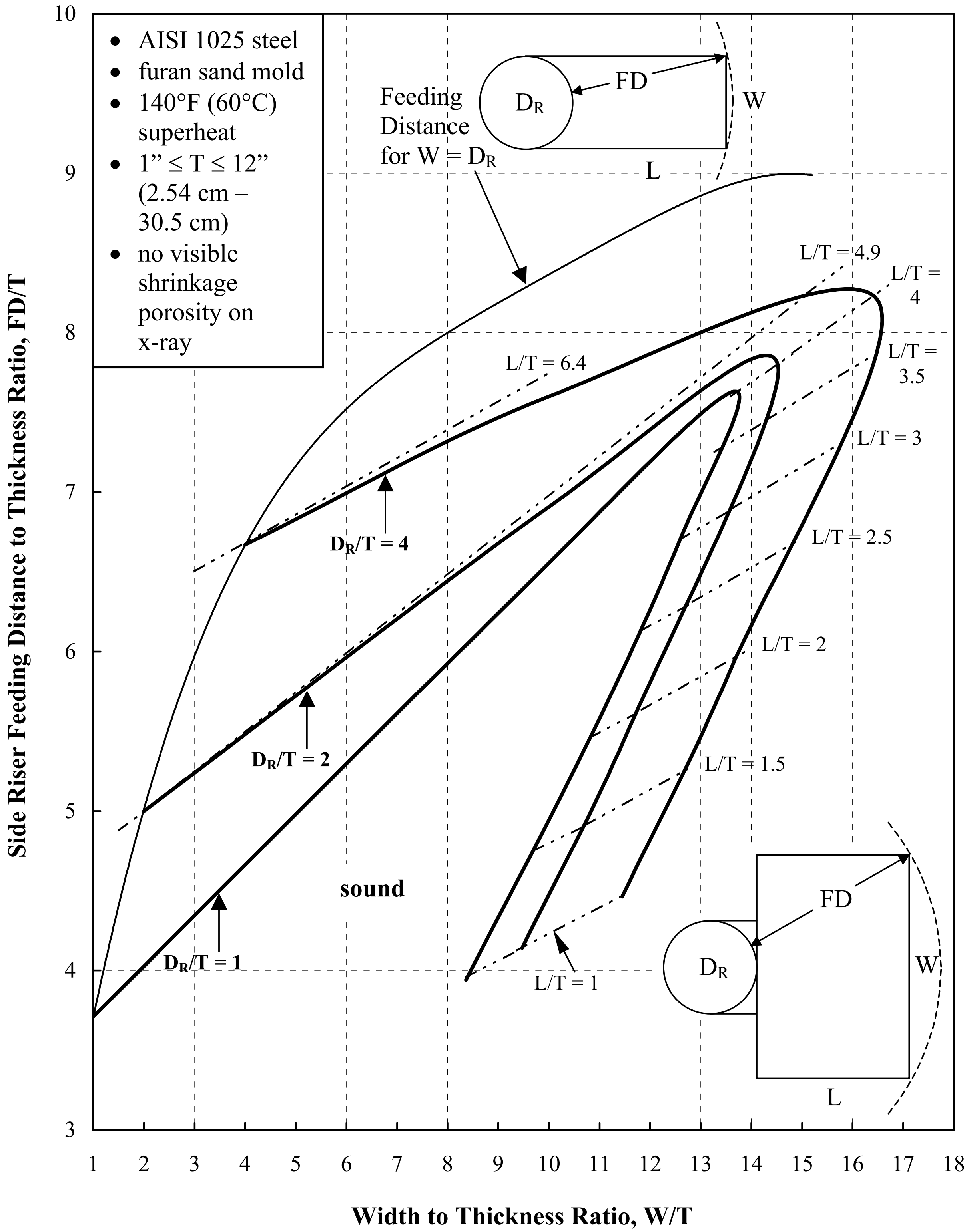


Figure 20 Side riser feeding distance, FD, as a function of D_R, L, W and T.

5.4 Chills

Chill blocks are inserted into the mold to enhance the feeding distance by creating a steeper temperature gradient. The chill surface in contact with the casting must be clean and dry. Surface roughness has little effect on heat transfer characteristics. Chills can be used with a thin refractory coating or carbon black. Cast iron or steel chills, for all practical purposes, are equally effective. Water-cooled copper chills are more effective than uncooled cast iron or graphite. However, the effectiveness of these external chills is greatly reduced by the formation of a gap at the casting/chill interface as the casting shrinks away from the chill. Graphite chills may deteriorate with use. Chills are used at the end of casting sections ("end chills") and as "drag chills" between two risers. Their use and effectiveness are described separately in the following.

End chill: End chills increase the feeding distance by increasing the end zone length. As shown in Figure 21, end chills have a chill thickness, CT, defined perpendicular to the casting/chill contact surface. The chill thickness should be chosen to be between 1/2 T and 2/3 T; larger chill thicknesses do not further increase the feeding distance. The end chill multipliers given in Equations (3) and (4) below were developed using a chill thickness of CT = 2/3 T. The chill width, CW, and the chill length, CL, should be chosen to match the section geometry, i.e., CW = T and CL = W. The feeding distance FD in this case is defined the same as in the end effect case, as the distance from the edge of the riser to the furthest point in the casting section (not including the chill). Although Figure 21 shows an example of an end chill used with a top riser, end chills can also be used in the same manner with side risers. In each case, end chills increase the end effect feeding distance by about 19%, i.e.

$$\left(\frac{FD}{T}\right)_{\text{end chill}} = 1.19\left(\frac{FD}{T}\right)_{\text{end effect}} \tag{3}$$

Since end chills only affect the end zone length contribution to the feeding distance, the effect of an end chill can also be expressed in terms of how much it alters the end zone length. Simulation results indicate that adding a chill increases the end zone length by about 38%, i.e.

$$\left(\frac{EZL}{T}\right)_{\text{end chill}} = 1.38\left(\frac{EZL}{T}\right)_{\text{end effect}} \tag{4}$$

where the subscript 'end effect' refers to the curve for EZL/T in Figure 11.

Drag chill: Figure 22 illustrates the placement of a chill in the drag between two top risers. This procedure increases the lateral feeding distance by essentially creating an end effect between the risers. As with end chills, the chill thickness, CT, is defined perpendicular to the chill contact surface and should be chosen to be between 1/2 T and 2/3 T. The chill width, CW, is defined parallel to the contact surface in the length direction and should also be chosen to be between 1/2 T and 2/3 T. Larger CT and CW do not increase the feeding distance further. In fact, for CW greater than about 2T, porosity can form above the chill [1]. The drag chill multiplier given in Equation (5) below was developed using CT = CW = 1/2 T, but there is little difference in this multiplier whether 1/2 T or 2/3 T is used for CT and CW. The chill length, CL, is chosen to match the section geometry, i.e., CL = W. As shown in Figure 22, the feeding distance with a drag chill is measured from the riser edge to the furthest point in the casting section that is not above the drag chill. Note that this feeding distance does not extend all the way to the symmetry line between risers (i.e., the centerline of the drag chill), but rather only to the edge of the chill. Drag chills create a pseudo-end effect between risers equal to about 95% of the end effect created when a casting section ends in the mold, i.e.

$$\left(\frac{\mathrm{FD}}{\mathrm{T}}\right)_{\text{drag chill}} = 0.95\left(\frac{\mathrm{FD}}{\mathrm{T}}\right)_{\text{end effect}} \tag{5}$$

In terms of lateral feeding, if one compares Equations (1) and (5), it is seen that a drag chill nearly doubles the lateral feeding distance.

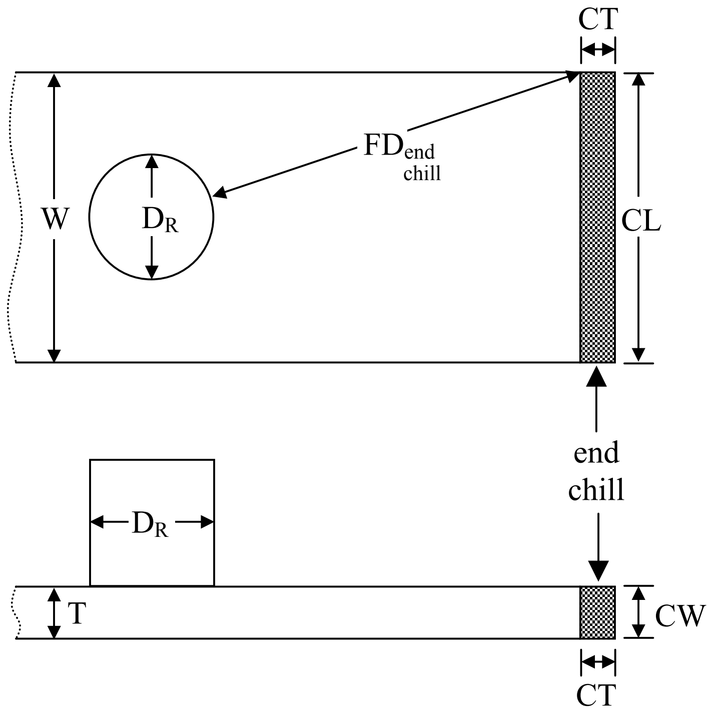


Figure 21 End chill dimensions for a top-risered casting section.

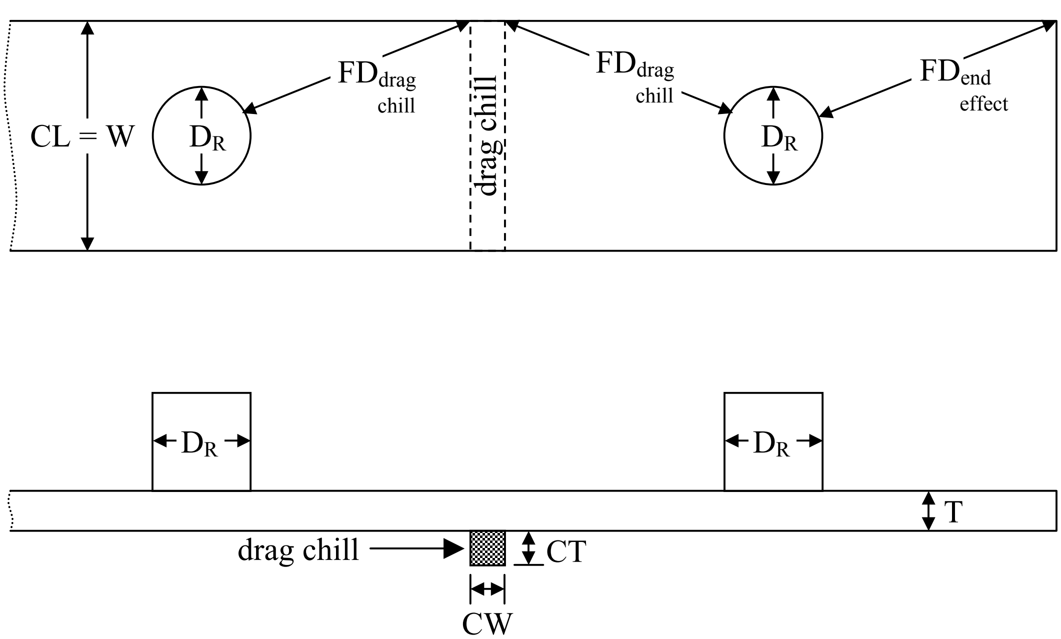


Figure 22 Use of a drag chill for top-risered lateral feeding.

5.5 Taper

A taper (or "metal padding") on a surface normal to the thickness direction of a casting section may be employed to produce the longitudinal thermal gradients required to feed any length to soundness. There exists a certain critical taper above which the section can be made infinitely long. Employing a taper below this critical value has no beneficial effect, i.e., the length of the casting section cannot be increased.

An example of a tapered section with a top riser is shown in Figure 23. It can be seen from this figure that a taper increases the wall thickness. The increase in thickness can be minimized by taking advantage of the fact that the casting end does not require taper over the end zone length EZL, and the region adjacent to the riser does not require taper over the riser zone length RZL. EZL and RZL are given in Figure 11.

The critical taper at which a section can be made infinitely long is given as a function of the width-to-thickness ratio W/T in Figure 24. In this chart, the taper is expressed as H_{taper}/L_{taper}, where H_{taper} and L_{taper} are the height and length of the tapered section, respectively. Note that the taper is relatively large for small W/T. The taper drops sharply as W/T increases, until it reaches a nearly constant value of about 0.011 around W/T = 6.

The taper curve shown in Figure 24 was developed based on numerical simulations, in the same manner as the feeding distance curves already presented in this handbook. However, it should be stated that, unlike the feeding distance curves, there is currently no direct experimental data available to support this curve. The taper values presented here should therefore be used with some caution.

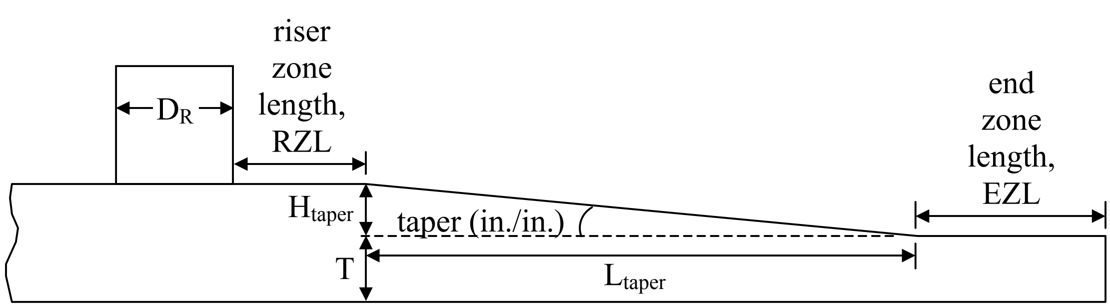


Figure 23 Taper in a plate with a top riser.

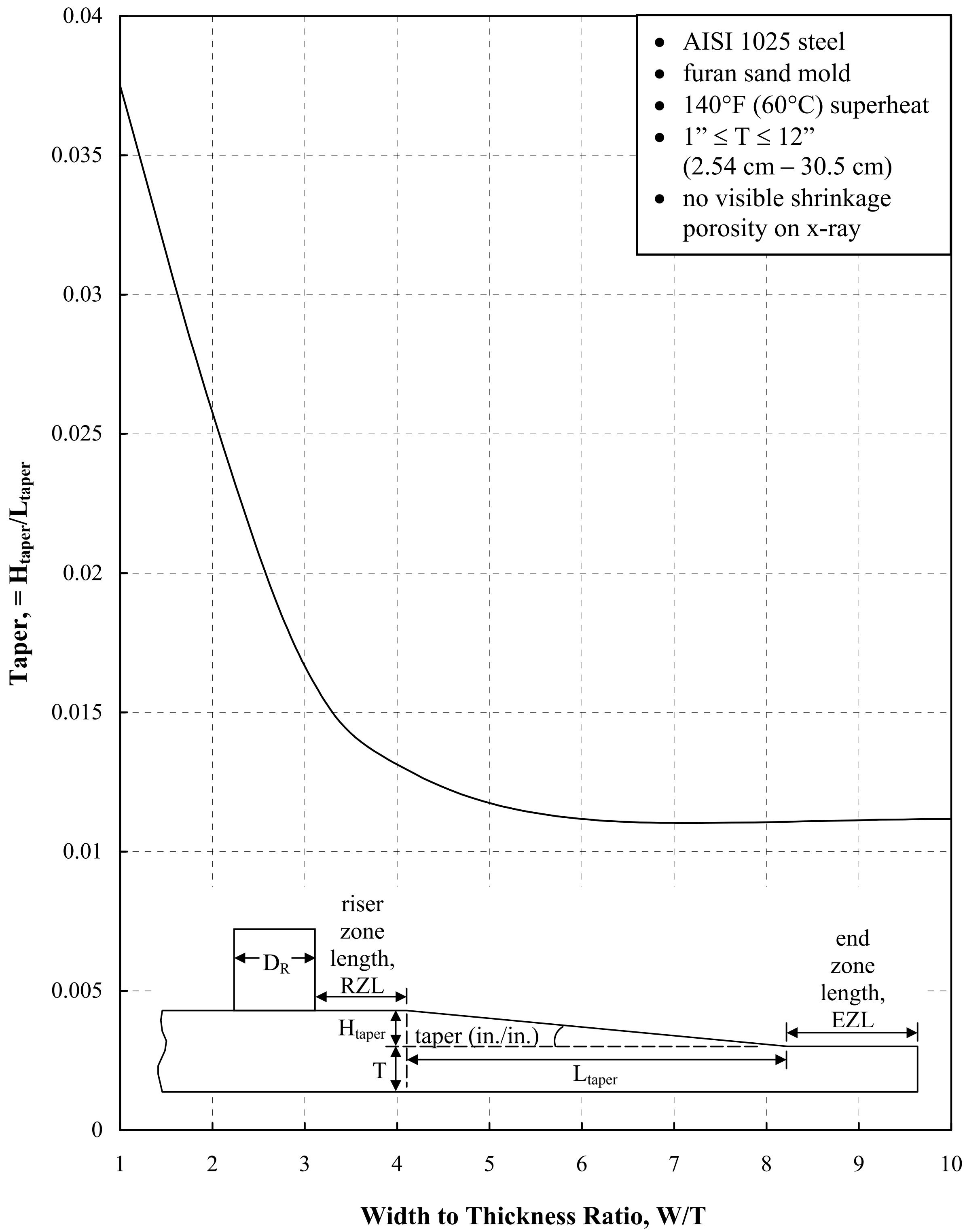


Figure 24 Taper, expressed as H_{taper}/L_{taper}, given as a function of W/T.

5.6 Other Casting Conditions

The feeding distances presented in the previous subsections can be applied to casting conditions other than the stated base conditions through the use of multipliers. Table 1 contains a list of multipliers for alternate sand mold materials, cast alloy compositions, pouring superheats and desired casting soundness. The feeding distance for casting conditions other than the base conditions is then computed with the equation:

$$\left(\frac{FD}{T}\right)_{\substack{\text{different}\\\text{conditions}}} = \left(\frac{FD}{T}\right)_{\substack{\text{base}\\\text{case}}} \times C_{\text{superheat}} \times C_{\substack{\text{cast}\\\text{alloy}}} \times C_{\substack{\text{sand}\\\text{mold}}} \times C_{\text{soundness}} \quad (6)$$

where $(FD/T)_{\text{base case}}$ is the normalized feeding distance for the appropriate casting situation from the previous subsections. Again, the division by the thickness T in the above equation is not necessary, since T cancels out. Note that the multipliers for lateral feeding and chills introduced in the previous subsections could be multiplied into Equation (6) if the base case corresponds to end effect. For any conditions that are the same as the base casting conditions, a value of C = 1 is used. The multipliers supplied in Table 1 were originally developed for the end effect feeding distance given in Figure 18, and they are valid for the entire range of this curve (i.e., up to about W/T = 15). Through the use of Equation (1), these multipliers can also be used for lateral feeding. However, they are only accurate up to about W/T = 7. Beyond this point, they are only approximate. In a similar manner, the multipliers can also be used for the riser and end zone lengths, which reach constant values at about W/T = 7. Finally, the multipliers are also approximately valid for side riser feeding distances.

The soundness multiplier, $C_{\text{soundness}}$, for ASTM shrinkage x-ray levels 1 – 5 can be obtained from Figure 25. The hollow symbols on this plot represent plates from the casting trials that served as the basis for development of the present feeding rules [2, 3]. The numbers below these symbols indicate multiple plates. The solid squares represent the mean value of $C_{\text{soundness}}$ for x-ray levels 1 – 4, and are shown with bars indicating plus/minus one standard deviation from the mean. The mean values are shown over the solid squares, in bold numbers. Recall that the base case was defined to produce castings that are radiographically completely sound. These radiographically sound plates are a subset of ASTM shrinkage x-ray level 1 (which implies "level 1 or better"), and they are grouped separately in Figure 25, below level 1. This is done to emphasize that, if a level 1 rating is desired, an x-ray level multiplier greater than unity may be used (note that the mean value of $C_{\text{soundness}}$ for level 1 is 1.14). No mean value is indicated for level 5, since this level includes all castings that are worse than level 4. In other words, any sufficiently large value of $C_{\text{soundness}}$ will result in a level 5 casting.

It is clear from Figure 25 that $C_{\text{soundness}}$ increases with x-ray level. However, there is a large amount of scatter in $C_{\text{soundness}}$ for each level, which is primarily due to the uncertainty in assigning x-ray levels according to ASTM standards [6, 7]. Still, if used with care, Figure 25 can be utilized to choose a soundness multiplier when the required ASTM shrinkage x-ray level for a casting is any value from 1 to 5 (i.e., not radiographically completely sound). For example, if x-ray level 1 is acceptable, the mean value of $C_{\text{soundness}}$ for level 1 (1.14) could be used; i.e., the feeding distance would be 14% longer than those plotted in Figures 18 – 20. Such increases are significant, considering that an end chill only increases the feeding distance by 19%. For higher x-ray levels, the allowable increase in the feeding distances is even more significant (up to 61% in the mean for level 4), and should not be overlooked when risering steel castings.

A more conservative approach to the example just given would be to choose a soundness multiplier somewhere to the left of the mean value for the desired x-ray level; the further left one goes, the more conservative the choice. In the end, the choice of soundness multiplier is left to the foundry engineer. Figure 25 provides a general idea of how this multiplier relates to x-ray level, but effective use of this multiplier will require experience with it in a foundry setting.

Included in Table 1 is a multiplier labeled "no leaks due to microporosity." The use of this multiplier gives about 25% shorter feeding distances than those given earlier in this section for radiographically sound castings. These shorter feeding distances are intended to prevent microporosity sufficient to potentially cause leaks in fluid-containing castings. This multiplier was derived from simulations based on the results of a recent SFSA Research Report on predicting and preventing leaks in steel castings [8]. The stated value of 0.75 is approximate; the true value is likely in the range 0.7 – 0.8. Experience with this multiplier in the foundry will be necessary to provide a more accurate multiplier.

Table 1 Multipliers used to apply base case feeding rules to other conditions. Base case conditions are listed with the multiplier C = 1.

	Condition Description	Multiplication Factor C
Sand Mold Material ($C_{sand\ mold}$)	furan	1
	green sand	1.09
	zircon	0.96
	chromite	0.88
Steel Alloy Composition ($C_{cast\ alloy}$)	AISI 1025	1
	AISI 1522	0.97
	AISI 4125	0.98
	AISI 4135	0.97
	AISI 8620	0.96
	AISI 8630	0.95
	AISI 4330	0.97
	AISI 4340	0.86
Superheat ($C_{superheat}$)	140°F (60°C)	1
	86°F (30°C)	0.94
	194°F (90°C)	1.06
	248°F (120°C)	1.12
Casting Soundness ($C_{soundness}$)	no shrinkage visible on x-ray	1
	no leaks due to microporosity	~0.75
	ASTM shrinkage x-ray levels 1-5	see Figure 25

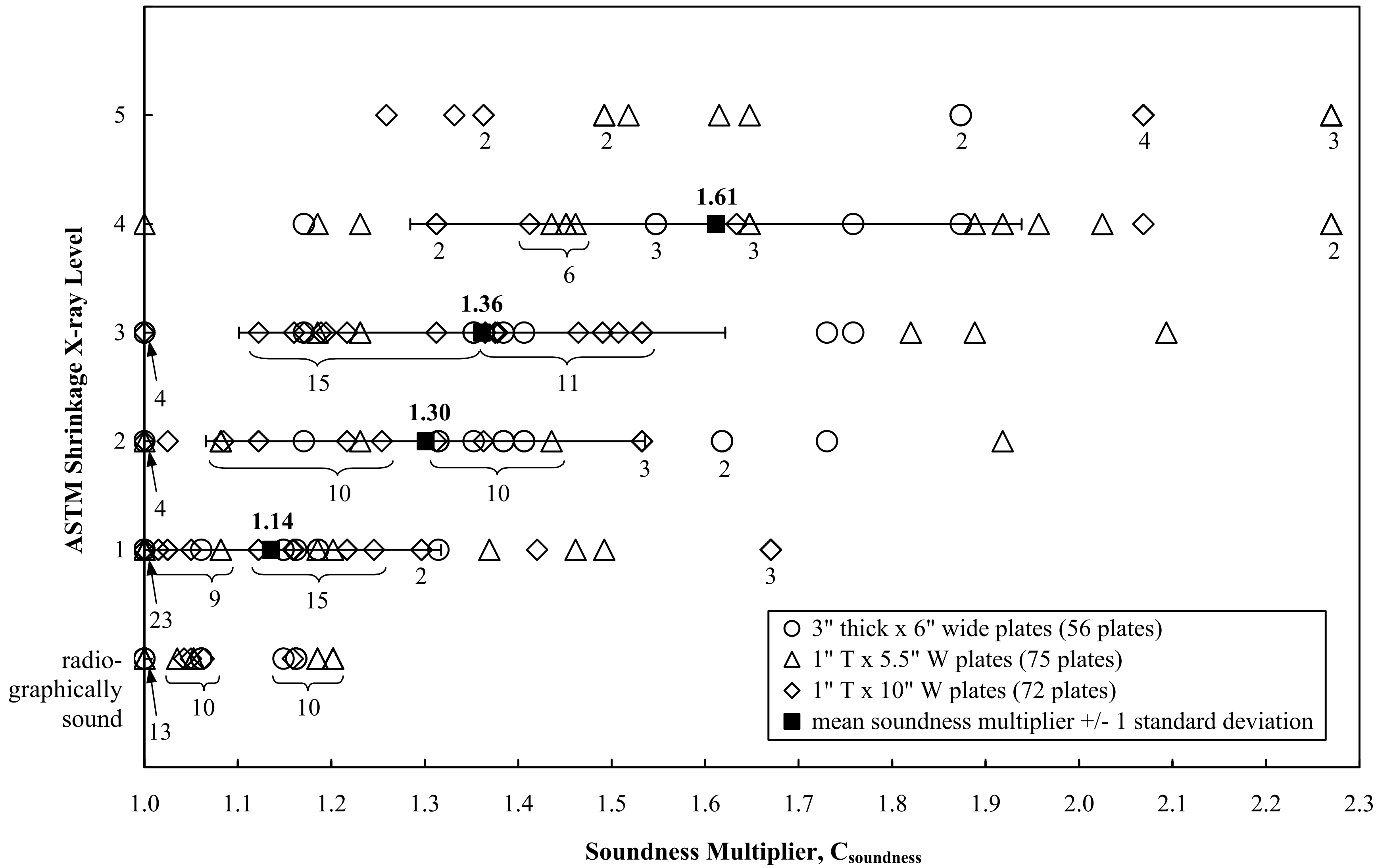


Figure 25 Multipliers for desired ASTM shrinkage x-ray level of casting section, with plus/minus one standard deviation intervals.

6 CALCULATION OF RISER SIZE

The procedures for placing risers on steel castings are discussed in Section 3. They involve the identification of feeding zones and feeding paths. The rules presented here for calculating the size of a riser are applicable for the plate-like sections that make up distinct feeding zones in a complex casting. Each section may require more than one riser. The guidelines presented here were originally developed for full contact, centrally-located top risers [1]. However, they apply equally well to side risers if a hemispherical bottom on the side riser is used to prevent premature freezing of the riser/casting junction.

Since risers are typically of a cylindrical shape, their important dimensions are the riser diameter, D_R, and the riser height, H. For top risers, the riser height should be at least equal to the riser diameter, $H = D_R$. For side risers, $H = 1.5D_R$ is often used. A riser height exceeding 1.5 times the riser diameter is uneconomical and does not improve the feeding ability of the riser; in fact, it can lead to secondary shrinkage cavities inside the riser.

A plate-like casting section requires one or more risers, depending on the feeding distances and the riser diameters. To calculate the riser size, one must know the shape factor, $SF = (L + W)/T$, and the volume, $V_C = L \times W \times T$, of that part of the section that is fed by the riser. Figure 1 defines the dimensions L, W and T for both a top riser and a side riser. If a single riser can feed the entire plate-like section, the actual dimensions of the section can simply be used. If the length of the section is too long, such that multiple risers are necessary, *the dimension L is not the length of the entire section, but only of that part that is fed by the riser under consideration*. In order to determine the number of risers required and the dimension L for each riser, the feeding distances and riser diameters must be known. Since the riser diameter is not yet known, an iterative procedure is required where a preliminary estimate of the riser diameter is made first. Using this estimate, the feeding distance and the length L can be obtained. Then the actual riser diameter can be calculated. If the calculated diameter differs significantly from the estimate, the calculated diameter should be taken as a new estimate, and the process should be repeated. When using drag chills with multiple risers, note that the length L extends to the *middle* of the chill, even though the feeding distance is defined to the edge of a drag chill.

The correct procedure for calculating the size of a riser can be summarized in the following steps:

(1) With the knowledge of W and T, calculate the feeding distance for the configuration under consideration (note that for side risers, an estimate of the riser diameter may be needed as well; see the next step). Decide whether or not chills will be used.

(2) Using the feeding distance as a basis, estimate the number of risers required, as well as the length L of the casting section to be fed by each riser. If more than one riser is needed to feed the section, estimate the riser diameter, D_R. A starting guess of $D_R = 3T$ (or 2T for $W/T \sim 1.0$) should be relatively close.

(3) Compute the shape factor, $SF = (L + W)/T$, of the section fed by the riser.

(4) Compute the casting volume, $V_C = L \times W \times T$, fed by the riser.

(5) Calculate the riser volume, V_R, using Figure 26 or the following expression [9]:

$$V_R = 2.51 V_C (SF)^{-0.74} \tag{7}$$

Calculate the riser diameter D_R from the knowledge of the volume V_R and the riser shape. If the riser is a cylinder with height $H = D_R$, the diameter can be calculated directly from:

$$D_R = \sqrt[3]{3.20 V_C (SF)^{-0.74}} \tag{8}$$

(6) Check if the calculated riser diameter is reasonably close to the initial estimate. If not, go back to step 2, using the riser diameter just calculated as the next guess for D_R.

(7) Compute the distance from the edge of the riser to the furthest point in the casting section to be fed by that riser.

(8) Check that the feeding distance is greater than or equal to the distance found in step 7 for that casting section. If so, the riser sizing procedure is complete. If not, the risers need to be redistributed, and steps 1 – 7 should be repeated.

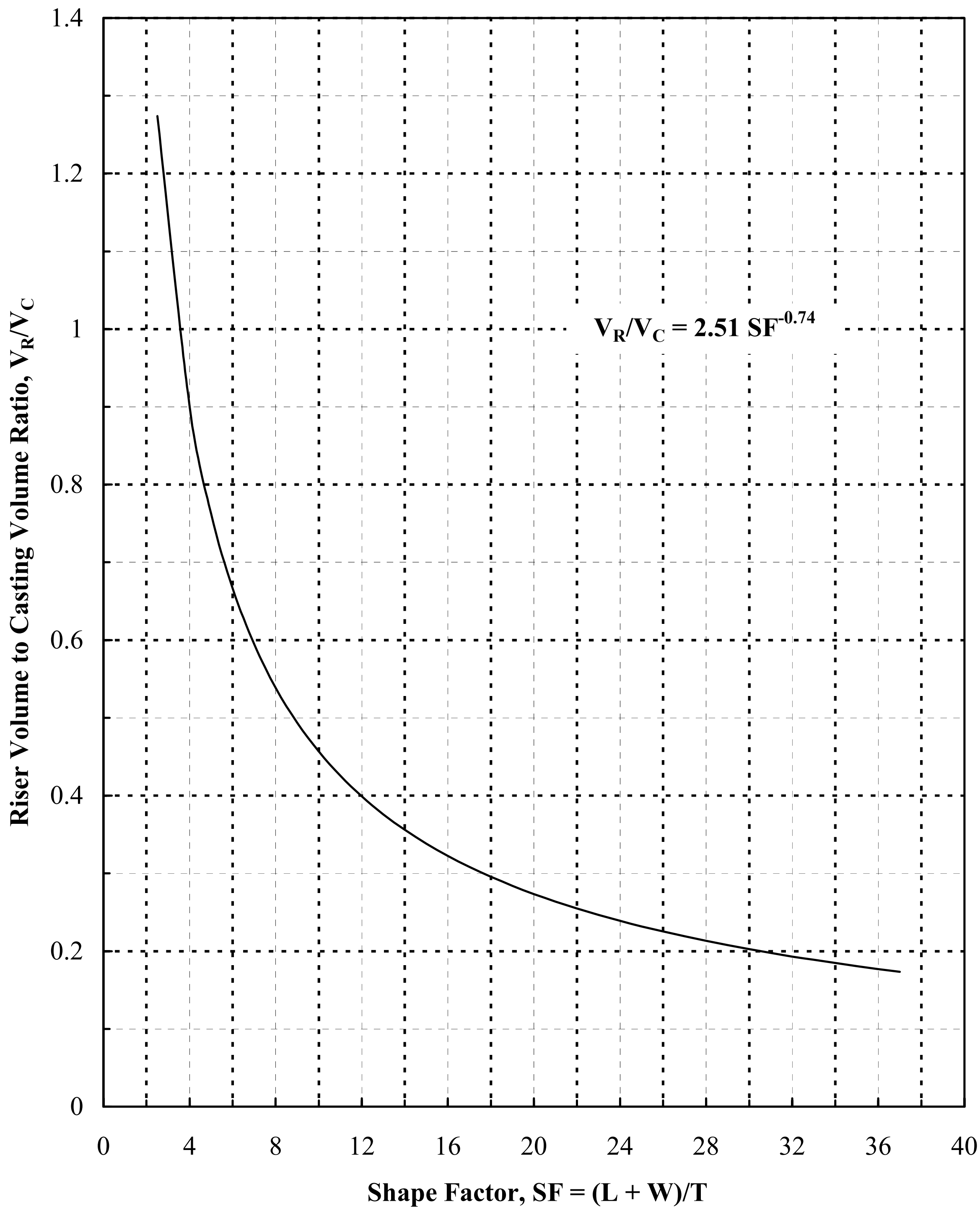


Figure 26 Riser volume to casting volume ratio as a function of shape factor. Plotted equation originally from [9], based on data from [10].

7 REFERENCES

[1] Steel Founders' Society of America, *Risering Steel Castings*, Steel Founders' Society of America, 1973.

[2] R.A. Hardin, S. Ou, K. Carlson, and C. Beckermann, “Relationship between Casting Simulation and Radiographic Testing: Results from the SFSA Plate Casting Trials,” *1999 SFSA Technical and Operating Conference*, 1999.

[3] R.A. Hardin, S. Ou, K. Carlson, and C. Beckermann, “Relationship between the Niyama Criterion and Radiographic Testing in Steel Casting,” *AFS Transactions*, Vol. 108, pp. 53-62, 2000.

[4] G.K. Sigworth and C. Wang, “Mechanisms of Porosity Formation during Solidification: A Theoretical Analysis,” *Metallurgical and Materials Transactions B*, Vol. 24B, pp. 349-364, 1993.

[5] E. Niyama, T. Uchida, M. Morikawa and S. Saito, "A Method of Shrinkage Prediction and Its Application to Steel Casting Practice," *AFS International Cast Metals Journal*, Vol. 7, No. 3, pp. 52-63, September 1982.

[6] K. Carlson, S. Ou, R. Hardin and C. Beckermann, "Analysis of ASTM X-Ray Shrinkage Rating for Steel Castings," *2000 SFSA Technical and Operating Conference*, 2000.

[7] K. Carlson, S. Ou, R. Hardin and C. Beckermann, "Analysis of ASTM X-Ray Shrinkage Rating for Steel Castings," *International Journal of Cast Metals Research*, Vol. 14, No. 3, 2001.

[8] K. Carlson, S. Ou, R. Hardin and C. Beckermann, "Development of a Methodology to Predict and Prevent Leaks Caused by Microporosity in Steel Castings," Steel Founders' Society of America Research Report No. 110, September 2001.

[9] W.D. Spiegelberg, “Computation of Solidification Gradients in Cast Steel Sections”, Ph.D. Thesis, Department of Metallurgy and Materials Science, Case Western Reserve University, 1970.

[10] H.F. Bishop, E.T. Myskowski and W.S. Pellini, "A Simplified Method for Determining Riser Dimensions," *AFS Transactions*, Vol. 63, pp. 271-281, 1955.

APPENDIX

This appendix contains fourth-order polynomial curve fits for various curves supplied in these guidelines. These curves are valid for casting sections with thickness, T, ranging from 1" to 12" (2.54 cm to 30.5 cm).

- The riser zone length and end zone length curves shown in Figure 11:

$$\frac{RZL}{T} = 2.803\times10^{-4}\left(\frac{W}{T}\right)^4 - 2.874\times10^{-3}\left(\frac{W}{T}\right)^3 - 0.0355\left(\frac{W}{T}\right)^2 + 0.5726\left(\frac{W}{T}\right) + 1.094 \quad \text{(A1)}$$

$$\frac{EZL}{T} = -1.269\times10^{-3}\left(\frac{W}{T}\right)^4 + 0.02856\left(\frac{W}{T}\right)^3 - 0.276\left(\frac{W}{T}\right)^2 + 1.446\left(\frac{W}{T}\right) + 0.852 \quad \text{(A2)}$$

Equations (A1) and (A2) are accurate up to W/T = 7, beyond which EZL/T and RZL/T take on constant values of 4.2 and 3.05, respectively.

- The end effect feeding distance curve shown in Figure 18:

$$\left(\frac{FD}{T}\right)_{\text{end effect}} = -4.29\times10^{-4}\left(\frac{W}{T}\right)^4 + 0.0174\left(\frac{W}{T}\right)^3 - 0.266\left(\frac{W}{T}\right)^2 + 1.99\left(\frac{W}{T}\right) + 1.97 \quad \text{(A3)}$$

Equation (A3) is accurate up to W/T = 15, beyond which FD/T has a constant value of 9.0.

- The lateral feeding distance curve shown in Figure 19:

$$\frac{LFD}{T} = -8.587\times10^{-5}\left(\frac{W}{T}\right)^4 + 3.408\times10^{-3}\left(\frac{W}{T}\right)^3 - 0.0533\left(\frac{W}{T}\right)^2 + 0.6967\left(\frac{W}{T}\right) + 1.019 \quad \text{(A4)}$$

Equation (A4) is accurate up to W/T = 15.

- The taper curve shown in Figure 24:

$$\text{Taper} = 9.111\times10^{-6}\left(\frac{W}{T}\right)^4 - 3.261\times10^{-4}\left(\frac{W}{T}\right)^3 + $$

$$+ 4.207\times10^{-3}\left(\frac{W}{T}\right)^2 - 0.02316\left(\frac{W}{T}\right) + 0.057 \quad \text{(A5)}$$

Equation (A5) is accurate up to W/T = 10, but the taper reaches a nearly constant value of about 0.011 around W/T = 6.