Some Basic Considerations in Controlling the Mechanical Properties of Cast Iron — Part II

value which will produce uniformity of structure and mechanical properties in different gray iron castings of varying section thicknesses. This was covered quite extensively in Foundry Facts No. 23. However, when it is necessary to pour both light and heavy section castings from the same heat, or ladle of iron, the following points should be considered:

1. Often, it is necessary to pour different section size gray iron castings from the same ladle of iron. What carbon equivalent value would be best to obtain the least variation in mechanical properties among the various size castings?
2. In regard to the effects of sulfur in gray cast iron,
   a. What should the sulfur range be?
   b. Why is this range desirable?
   c. What is the best form in which to add sulfur?
   d. How should it be added?
   e. What is the usual sulfur recovery?
   f. Will sulfur attack the furnace, or ladle linings?
3. In producing gray iron castings from an iron with a carbon equivalent in the range of 4.00–4.15%, what are the optimum carbon and silicon contents and why?
In regard to question 1, it is well known that there is no carbon equivalent resulting in smaller Type A graphite flakes. In addition, by pouring at the lowest possible temperature, the molds will not be heated to the extent that they would be at higher pouring temperatures. This means that after solidification, the castings will cool more quickly, thus promoting the formation of more pearlite in the matrix.

(3) If the section thickness among different castings varies extensively, for example from ½” to 4 or 5”, then after pouring the thinner castings, the balance of the iron can be alloyed with molybdenum, nickel, copper, or tin. These alloys can be added to the ladle and stirred in to insure complete solubility and uniform dispersion. It might also be necessary and desirable to add an additional 0.025 to 0.05% of a graphitizing inoculant at this time to insure sufficient nucleation for proper solidification. In addition, it might be advantageous to allow the thin castings to cool in the molds to below 1200°F before shake out. The heavier section castings could be shaken out shortly after solidification. By using this practice, more comparable matrix structures between the thin and thick castings might result.

Carbon Equivalent a Key in Obtaining Uniform Properties
(4) As shown in Figure 1, carbon equivalent can play an important role in developing more uniform properties and structures between thick and thin
section gray iron castings. However, this chart must be used with caution. For example, if an iron with a carbon equivalent of 3.30% is picked, the probability of the thin section castings being carbidic is great. Careful tests should be conducted with adequately inoculated gray iron before a final decision is made as to the optimum carbon equivalent to use.

In spite of the fact that with the higher carbon equivalent irons there will be more variation in the properties between thin and thick section castings as compared to irons with lower carbon equivalents, many foundries use the higher carbon equivalent irons. Actually, the practice in many foundries where both light and heavy gray iron castings are poured is to base the carbon equivalent on the thinnest castings. In other words, a carbon equivalent is chosen which produces the desired "as-cast" properties in the thin castings. Fluidity of the iron must be considered in using this practice. The properties in the heavy section castings are then obtained by alloying, as mentioned above, with such elements as molybdenum, copper, nickel or tin. Often combinations of molybdenum and/or copper are used.

In order to secure the best casting characteristics of the gray iron when using the same base iron for the thin and thick section castings, a carbon equivalent of 4.3% is employed. An iron with this carbon equivalent value will have excellent fluidity and good casting characteristics for three reasons:

a. It has the lowest solidification temperature of any of the cast iron compositions.

b. It will solidify at a nearly constant temperature, thereby insuring less composition variation in the iron dendrites.

c. There is practically no mushy stage during solidification. This helps prevent shrinkage during solidification.

The mechanical properties of thin section castings (%"-⅛" thickness) will include tensile strengths greater than 30,000 psi, with hardness values in the range of 175-190 HB. By the proper utilization of the alloying elements mentioned above, similar mechanical properties in the same carbon equivalent iron can readily be achieved in casting sections up to 8" in thickness.

The second question in this issue involves the effects of sulfur in gray cast iron. The first part of this six-part question has to do with what the sulfur range should be in gray cast iron.

Effect of Sulfur Can Be Critical

In previous issues of Foundry Facts, reference has been made to the work of Alfred Boyles and his publication entitled "The Structure of Cast Iron." In this work it is recognized that sulfur, in combination with the proper amount of manganese, is important in making the gray cast iron more responsive to inoculation. Otherwise, even undercooled forms of graphite, such as Types B and D, will be present in casting sections under ½" in thickness, or a high degree of inoculation will be required to insure Type A graphite and freedom from undercooling.

Many foundrymen produce gray iron castings with satisfactory structures and properties in low sulfur irons. By the same token, other foundrymen find it is necessary to maintain sulfur contents in the range of 0.06-0.12% in order to achieve satisfactory mechanical properties and freedom from excessive chill in gray iron castings. Why should there be such differences?

From an investigation and study of the practices at the various foundries where these differences exist, a number of observations and possible conclusions have been made.

First, it has been observed that the carbon equivalent of gray cast iron is related to the effect of sulfur. In most instances, the lower the carbon equivalent of the gray iron, the more important it is to maintain the sulfur of the iron in the range of 0.06-0.12%. This appears to be logical, because in the lower carbon equivalent gray cast iron it is necessary to inoculate to a greater degree to prevent undercooling than in higher carbon equivalent gray irons. In other words, for a given section gray cast iron, the lower the carbon equivalent, the greater is the tendency for undercooling and consequent chill and undesirable type graphite. Such conditions mean poor machinability and inferior mechanical properties. In order to prevent these conditions, the sulfur in the above range makes the gray cast iron more responsive to inoculation.

Consider Section Size and Pouring Temperature

Second, casting section size is a factor. The thinner the casting section, the more important are the proper sulfur and manganese contents. It has always been recognized that with the optimum sulfur content, properly tied up with manganese, thin gray iron castings require more inoculation than heavier section castings. This is tied in with solidification rate. The thinner castings solidify more quickly than heavy section castings and therefore require more nucleation centers furnished by inoculants, and the proper amount of manganese sulfide, in order to prevent undercooling. Heavy section castings which solidify more in accordance with equilibrium conditions, do not require the degree of inoculation, and therefore, the higher sulfur content necessary in the thinner section castings.

Third, pouring temperature of the castings has an effect on the need for the proper amount of sulfur and subsequent inoculation. The higher the pouring temperature of the gray cast iron, the slower will be the solidification rate. If the solidification rate is slow, the need for inoculation and the response to inoculation is not as critical as it is in iron which has a fast rate of solidification. Therefore, in gray iron that is poured at high temperatures (2750°F or higher), the sulfur content is not as critical as in irons poured at lower temperatures, even in the case of thin section castings.

Mold Material also a Factor

Fourth, the mold material has an effect on the need for sulfur in gray cast iron. If the molds are made from dry type materials and no moisture is present, the rate of solidification will be slower at a given pouring temperature compared to the solidification rate in a green sand mold. Therefore, the need for maximum response to inoculation, which is assisted by having the optimum sulfur and manganese contents, is minimized. In addition, mold temperature is a factor which affects solidification rate. When metal is poured in molds below about 70°F, the solidification rate will be faster than for the same metal poured at the same temperature in hotter molds. Therefore, the proper sulfur range would be more important for increased response to inoculation in order to minimize undercooling in the gray iron poured in the colder molds.

Fifth, the degree of oxidation in the metal appears to affect the response to inoculation. The greater the degree of oxidation, the more necessary it is for the base iron to have the sulfur in the range of 0.06-0.12% with sufficient manganese to tie up this sulfur. Having the right amount of sulfur and manganese in this instance, as in the other cases cited, makes the iron responsive to a minimum amount of inoculant. The degree of oxide in the metal is increased with increased rust in the charge material. Atmospheric conditions such as high humidity, which also oxidizes the iron, adversely affects its response to inoculation.

Since sulfur in the range of 0.06-0.12% with sufficient manganese to form
manganese sulfide is not harmful to gray cast iron, it is advisable to hold it in this range to insure maximum response to inoculation under all conditions. To prevent iron sulfide—which can embrittle the iron—from forming, the amount of manganese should be at least six times greater than the sulfur.

When a sulfur addition is needed to achieve the optimum range in the iron discussed previously, it can be added as iron pyrite, or flowers of sulfur either with the furnace charge, after melt down, or in the ladle during tapping. Actually iron pyrite seems to be better than flowers of sulfur so far as the rate of solution in the iron is concerned. In both instances, however, the sulfur recovery is close to 100%.

Whether added in the furnace with the charge, after melt down, or in the ladle during tapping, there have been no reports of any detrimental effect of sulfur on either the furnace or ladle linings. However, in induction melting, if a sulfur addition is made to a gray iron charge, the furnace lining may absorb a small amount of sulfur. This might result in a slight pick up of sulfur in subsequent ductile iron heats being melted in the same furnace. Any sulfur increase, however, would be minor.

Some of the aspects involved in question 3 have been discussed in Foundry Facts No. 21 (pages 2 and 3). However, further discussion is necessary in order to clear up some of the confusion which exists concerning this subject.

Achieving the Optimum Carbon and Silicon Contents

In order to recommend the optimum carbon and silicon content for a gray cast iron with a desired carbon equivalent in the range of 4.00 to 4.15%, it is necessary to consider a number of things, including:

1. Casting section thickness.
2. The mechanical properties and matrix structures desired.
3. The mold materials being used; e.g., green sand, dry sand, metal (permanent molds), masonry, etc.
4. Pouring temperature.
5. Shake out temperature.
6. Residual or purposely added alloying elements.

All of these factors, as well as others, affect the final properties of gray cast iron.

In regard to casting section thickness, the final silicon and carbon contents are important in controlling the solidification shrinkage of cast iron. In a given carbon equivalent gray iron, running the silicon on the high side and the carbon on the low side may result in excessive shrinkage in heavy section castings. The reason for this involves the fact that a given weight of graphite occupies seven times the same weight of iron. Therefore, in order to minimize solidification shrinkage in heavy section gray cast iron with a carbon equivalent in the range of 4.00-4.15%, the silicon should be on the low side and the carbon on the high side in order to produce more graphite. To be more specific, Table 1 gives some suggested carbon and silicon values to minimize solidification shrinkage for various section size castings made from gray iron having a carbon equivalent in the range of 4.00 to 4.15%.

<table>
<thead>
<tr>
<th>Casting Thickness (Inches)</th>
<th>Carbon</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>3.00-3.10</td>
<td>3.00-3.10</td>
</tr>
<tr>
<td>1</td>
<td>3.10-3.20</td>
<td>2.75-2.95</td>
</tr>
<tr>
<td>1 1/2</td>
<td>3.20-3.30</td>
<td>2.45-2.60</td>
</tr>
<tr>
<td>2</td>
<td>3.30-3.40</td>
<td>2.15-2.35</td>
</tr>
<tr>
<td>2 1/2</td>
<td>3.40-3.50</td>
<td>1.80-1.95</td>
</tr>
<tr>
<td>3</td>
<td>3.50-3.60</td>
<td>1.50-1.65</td>
</tr>
<tr>
<td>4</td>
<td>3.60-3.70</td>
<td>1.20-1.35</td>
</tr>
<tr>
<td>8</td>
<td>3.70-3.80</td>
<td>0.90-1.05</td>
</tr>
</tbody>
</table>

If the silicon content is on the high side in a heavy section gray iron casting with a carbon equivalent of 4.00-4.15%, the matrix structure will be less pearlitic than the same section casting made from the same carbon equivalent iron with the silicon on the low side. For example, referring to Table 1, if an 8" section casting with a 4.00% C.E. is made from the iron suggested for a 1/4" section casting, the matrix of the heavy section casting would most likely be all ferritic. The matrix of the 1/4" section casting should be mostly pearlitic. Even though the carbon equivalent is the same for each casting, the shrinkage of the 8" section casting would be much less than that of the thinner casting. However, by using the carbon-silicon values suggested for the 8" section casting rather than those suggested for the thinner castings, the matrix structure of the heavy casting should contain more pearlite and therefore be stronger than if it were made from the higher silicon iron.

Effect of Carbon and Silicon on Mechanical Properties and Matrix Structure

The effect of the carbon and silicon values of a given carbon equivalent gray cast iron on the mechanical properties and matrix structures will now be considered. It is well known that the mechanical properties of gray iron castings are dependent on a marked degree on the matrix structure of the iron. A gray iron casting with a pearlitic matrix is stronger than the same casting with a ferritic matrix. Also, in the case of a gray iron casting with a pearlitic matrix, its strength is affected by the fineness of the pearlite.

Unalloyed gray iron castings with the same carbon equivalent having fine pearlite structures are stronger than the same castings with coarse pearlite structures. The silicon content of the iron not only affects the amount of pearlite in a given section casting, but it also affects the fineness of the pearlite. For example, two identical gray iron castings—A and B—have the same carbon equivalent of 4.00%. In casting A, the carbon is 3.20% and the silicon is 2.40%. In casting B, the carbon is 3.50% and the silicon is 1.50%. The section thickness of the castings is about 1/4". Both castings are poured at the same temperature into identical molds. Prior to pouring, the iron with the silicon for each casting is inoculated in an identical manner with the same inoculant. Both castings are cooled to room temperature in the molds.

In checking the tensile strengths of these castings from test bars taken from the same location in each casting, the following results can be expected:

1. In casting A, with the higher silicon content, the tensile strength will be about 32,000 psi.
2. In casting B, with the lower silicon content, the tensile strength will be about 34,000 psi.

In examining the microstructure of each test bar, it will be found that the matrix of the bar from casting A has a coarser pearlitic structure than that of the bar from casting B. This accounts for the difference in the tensile properties of the two castings and illustrates the effect of silicon on the pearlite spacing. This effect is further illustrated by referring to the microstructures shown in Figures 2A and 2B. Both of the iron has a carbon equivalent value of 4.00%. The analysis of the iron in Figure 2A is 3.20% C and 2.40% Si, while that of the iron in Figure 2B is 3.40% C and 1.80% Si. The microstructures were made from tensile test specimens machined from 1.2" diameter bars. It will be noted from these photomicrographs that the pearlite shown in Figure 2A is slightly coarser than that shown in Figure 2B.

Silicon is also important in controlling the chill of gray iron castings. Again, referring to Table 1, it might be unwise to use the suggested analysis shown for
an 8" section casting in a casting with only a 1/4" thick section. Because of the low silicon content, excessive chill would most likely result. Such a condition would be undesirable from both the machinability and maximum mechanical properties standpoint.  
The solidification rate of castings, as well as their solid state cooling rates, are affected by the mold materials. Metal poured in green sand molds generally solidifies more quickly and cools more rapidly after solidification than the same metal poured in either dry or no-bake sand molds. Therefore, for a given carbon equivalent, gray cast irons with the same carbon and silicon contents and the same section thicknesses will vary in microstructures depending on the mold materials into which they are poured. For example, in a thin section casting poured in a green sand mold, the silicon content for the same carbon equivalent value should be higher than for the same casting poured in dry sand or no-bake molds if the same matrix structures are desired. In the case of an iron with a carbon equivalent of 4.00% for a casting with a section thickness of 1/8", in order to obtain a pearlitic matrix in either green or dry sand molds, the carbon and silicon contents will have to be adjusted for each type of mold. In the case of making the casting in green sand, the silicon should be higher than when making the same casting in dry sand. In the green sand molds, the 4.00% C.E. iron should have about

3.20% C and 2.40% Si. In the dry or no-bake sand molds, a better analysis would be 3.40% C and 1.80% Si.

Pouring Temperature Affects Final Properties
Pouring temperature is a factor which affects both the solidification rate and the solid state cooling rate of castings cooled in the molds to under 1200 °F. The higher the pouring temperature, the slower will the castings solidify and cool in the mold after solidification. Again, the silicon content of the gray cast iron plays an important part in what the final microstructure and mechanical properties of the castings will be. If identically designed gray iron castings having the same carbon equivalent and the same carbon and silicon contents are poured into molds of the same material but at different pouring temperatures, different microstructures and mechanical properties will result. Castings poured at higher pouring temperatures will have less pearlite and, therefore, lower mechanical properties than those poured at the lower temperatures. If these castings are poured at the same temperature from irons with the same carbon equivalent value but different carbon and silicon contents, different microstructures and mechanical properties will also result. The castings with the lower silicon contents will have more pearlite and higher strengths than those with the higher silicon. This is assuming that all other casting conditions are similar. The reason for the differences in structure and mechanical properties stems from the fact that as silicon increases, it limits the solubility of carbon in austenite. This, in turn, tends to either reduce the amount of pearlite, or increase the pearlite spacing in the final castings. Both of these factors decrease the as-cast strength of the castings. If the pouring temperature of the gray iron is usually on the high side and nothing can be done about it, it would be advisable to consider changing to a lower silicon content in the iron and raising the carbon content correspondingly. For example, if the normal 4.00% C.E. iron has 3.30% C and 2.10% Si for a given section casting poured at a high temperature, and the casting strength is low, changing to 3.40% C and 1.80% Si should improve the strength of the casting. This is assuming everything else remains constant.

Shake-out temperature, which affects the solid state cooling rate, can affect the mechanical properties of gray iron castings. For example, gray iron castings shaken out of molds at temperatures in excess of 1400 °F will normally contain more pearlite in the matrix structures than the same castings held in the molds until their temperatures are below 1200 °F. At the higher shake-out temperatures (above 1400 °F) gray iron castings of the same design, and the same carbon equivalent, but with different final silicon and carbon contents, will have different matrix structures. Those castings with the same carbon equivalent value, but with lower silicon, higher silicon combination, will contain less pearlite than the castings with the higher carbon, lower silicon analyses. As stated previously, the higher the silicon content of a gray iron casting of a given carbon equivalent and section size cooled at a given rate, the lower will be the pearlite content in the matrix structure of that casting.

Alloying Elements Can Influence Carbon-Silicon Ratio
Finally, the residual, or purposely added alloying elements can have an influence on the carbon-silicon ratio picked for a given section casting in the 4.00 to 4.15% C.E. range. If, because of the type of scrap available for the furnace charge, the residual elements such as chromium, molybdenum, copper, tin and nickel are present, it might be advisable to increase the silicon and lower the carbon content of the iron, still holding the same C.E. value. By running the silicon higher, there will be less tendency for chromium and molybdenum to form carbides, especially in the thin section castings. In cooling after solidification the higher silicon can lower the pearlite forming tendencies of all the above residual elements.

If the above elements are added purposely for increasing strength, reducing section sensitivity, improving wear resistance, etc., slightly increasing the silicon and lowering the carbon can help to prevent carbides from forming during solidification.

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