Avoiding Shrinkage Defects and Maximizing Yield in Ductile Iron

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ABSTRACT

The presentation discusses factors to control to avoid shrinkage defects and maximize casting yields. These are:

- maximizing %CE just below the level where flotation will occur, while using the minimum final Si and Mg contents,
- maintaining base S as steadily as possible,
- use of nodulizer containing a low level of pure La and/or proprietary S and O coated inoculant, to generate a nodule size distribution skewed to the finer nodule sizes,
- adjusting for loss of nucleation in base iron and/or treated iron, due to excessive holds times,
- using means to accelerate freezing at appropriate places rather that riser including metal chills, chill fins, or chilling inserts that freeze within the casting, and
- maintaining mold strength.

What Carbon Equivalent to Use?

Figure 1 shows guideline trends to avoid problems by selecting a suitable CE. To avoid shrinkage defects we must also avoid flotation of graphite nodules. The chart advises that the total C plus 1/3rd Si should not exceed 4.55. This diagram was developed as a general rule for sections varying from about ½” to about 1 ½” thick. For very thin sections such as for manifolds, the CE may be higher. For thicker sections, it must be lower to avoid flotation and an increased risk of shrinkage. When carbon precipitates from liquid iron during freezing, there is an expansion effect. Shrinkage will be minimized at the highest possible C content, where the iron freezes in the eutectic mode, just below the content where primary graphite precipitates and nodule flotation occurs.

Use the Highest CE - While Avoiding Nodule Flotation.

Figure 2 is a table that was produced by BCIRA as a research project for AFS. It shows much more detail regarding the maximum C for various Si values to avoid flotation of graphite nodules for various section thicknesses of different shapes. This is also the maximum value to minimize shrinkage. A correction for variations in pouring temperature is also included.

Generally shrinkage is reduced as the % C increases, provided that freezing continues to follow a eutectic process. Eutectic freezing involves simultaneous precipitation and growth of graphite contained within austenite shells. If the %C becomes too high however and primary graphite starts the solidification process, a great deal of the expansion effect available from graphite precipitation is consumed very early during freezing. This is due to the very rapid precipitation of graphite as it floats in the liquid metal. This can result in insufficient graphite expansion effect during the latter stages of freezing, within the last isolated pools of iron to freeze.

This chart in Figure 3 is a plot of the data from the previous slide for square bar shapes. There are 3 curves shown for 3 different Si levels. These lines have been extended to the CE = 4.3 line. This shows the thickness where the CE must be at or below eutectic. All thicker sections must also be at or below 4.30% CE to avoid primary graphite precipitation, flotation, and a jump to a higher level of shrinkage.

For square bars, this transition point is with thicknesses from 95 to 108mm (3.8” to 4.3”), depending upon base Si from 1.8 to 2.6%. The same data has been converted to the equivalent diameter for round bars in Figure 4. When round sections reach 83mm (3.3 in.) with 1.8% Si, the CE needs to be 4.30 or less.

In Figure 5 the square bar data has been converted to the equivalent thickness of a plate shape. For 1.8% Si ductile iron, the CE would need to be 4.30 or less as the section thickness reaches or exceeds 42mm (1.7”)
In Figure 6, the data for the square bars has been converted to equivalent modulus of the part in millimeters. Modulus is the ratio of the cast part volume divided by the cast part area. Extending the lines to the CE = 4.3 line, shows the modulus where the CE must be 4.30 or less to avoid flotation. For 1.8% Si, the modulus is 21mm (0.84") For 2.2% Si, the modulus is 22mm (0.88")

Timing the Expansion from Carbon Precipitation

Carbon precipitation as graphite nodules is required at the start of freezing to ensure that carbon does not take the iron carbide form as edge chill. Too much early graphite precipitation must be avoided however, or the result will be too little graphite precipitation during the end of freezing, when the gating system and risers can no longer deliver more liquid to compensate for contraction. It is important to understand which foundry variables alter the amount of graphite precipitation at each stage of freezing.

Higher silicon leads directly to higher nodule count, more ferrite, and more early C precipitation. To minimize shrinkage, it is recommended that the CE be on target, with the maximum C content and the minimum Si content. C provides the expansion effects, and too much Si can lead to excessive initial expansion effect and too little in the last iron to freeze. Si should be used at a level to avoid carbides and provide strengthening of ferrite to meet mechanical properties, but not excessively more. Normally excessive nodule count that leads to shrinkage has a structure where the nodule size looks identical for most nodules. In such a case all the nodules started forming at the same time, early during freezing. The structure is pleasing to the eye, but bad for shrinkage. Figure 7 shows how nodule count can increase with higher silicon.

Other factors that can lead to high nodule counts with very uniform size are excessive inoculant addition rate or the use of Bi to increase nodule count. Later we will see that high nodule counts can be useful to turn off shrinkage, but only if a nodule size distribution can be produced that has a wide distribution of nodule sizes. This implies that graphite precipitation (C expansion) proceeds at a steadier pace from start to end of freezing, and not too fast during the first part of freezing.

Mg content is another factor that needs to be controlled to minimize shrinkage. Figure 8 is a graph that shows that shrinkage increases as the final Mg content increases. Enough Mg is required to produce good nodules but a large excess should be avoided. Excessive Mg should be avoided for a number of other reasons such as slag defects, spiky graphite formation, etc…

Keep Base S Content Consistent

The base iron S content can have a large impact on nodule count and nodule size distribution. Figure 9, shows the result of some Japanese work measuring nodule count as base S was changed. As the base S increased from the nodule count increased. For very thin castings, prone to carbides, some foundries will intentionally operate with higher base S. This can be a useful strategy when making thin sections to avoid carbides. These nodules appear to be very similar in size and may lead to shrinkage problems if nodule count becomes too high, with all similarly sized early forming nodules, especially if this occurs in heavier sections. For reproducible nodule count, it is important that base S be uniform from one treatment to the next. Large variations in base S, such as when converting between gray and ductile iron, could lead to variable nodule counts and nodule size distributions, and shrinkage propensity.

Avoid Long Hold Times for Base Iron

As base iron is held, the state of nucleation changes over time. After holding for about 30 minutes at tapping temperature, the subsequently Mg treated and inoculated iron will become both shrinkage and carbide prone. Ladle and stream inoculation may be unable to eliminate the carbides. This effect was observed in a foundry using medium frequency furnaces, where one furnace served as the melter and the other was used to deliver iron for tundish treatments. Six tundish treatments were made over the period of about 1 hour to drain the furnace, before switching treatments to the next furnace. The consequence was that the first 3 treatments were as desired and the last 3 treatments produced carbides within the structure, despite the use of powerful continuous stream inoculation with high potency specialty inoculants.

The foundry learned that some of the lost nucleation effect could be restored by adding crystalline graphite to the iron while replacing the carbon losses during holding. 100% graphite electrode turnings were reported to be the best type of carbon replacement material to eliminate the carbide tendency.

It is believed that the rate of loss in nucleation effect from holding base iron will be different for different types of holding furnaces and for different holding temperatures.
Avoid Long Holds for Mg Treated Iron

A similar phenomenon occurs for Mg treated iron as for base iron. After 25 to 30 minutes of holding iron in an autopour, without any freshly treated iron additions, the state of nucleation of the iron changes and becomes shrinkage prone. Chad Moder from Neenah Foundry presented a paper on this subject, and showed that thermal analysis could be used as a tool to study this problem, and means to rapidly return the iron to a suitable low shrinkage state. They learned to recover “dead iron” by adding 0.1% by weight of a proprietary S and O coated inoculant to the iron while 1 new treatment ladle of freshly melted iron was added to the autopour. They learned to rejuvenate iron after holding it over a weekend with this technique. Prior to this, several freshly treated ladles of iron were normally required and sometimes a considerable amount of treated iron in the autopour had to be pigged.

Special MgFeSi Alloy that Reduces Shrinkage

Historically MgFeSi alloys have been alloyed with RE metals. The RE elements are intended to neutralize tramp element effects such as from lead, to avoid edge carbides at low pouring temperature, and to optimize nodule count. For many years mischmetal was the most common type of RE added into these alloys.

Special alloys have been developed that use pure La metal rather than the mixture of RE elements. When the amount of La in the MgFeSi alloy is optimized, a high nodule count with a very different nodule size distribution is observed. The number of large early forming nodules is reduced slightly and there is a large increase in the number of medium and smaller nodule sizes. This is an indication that graphite precipitation has been steadier through freezing, with more expansion effect during the latter stages of freezing.

Figure 10 shows the 2 different chemistries of MgFeSi alloys compared with an ON THE MOLD treatment process. One alloy employed a high level of a traditional mischmetal type RE. The other used about 1/3 the amount as pure La metal with no other RE elements present. It is important to note that the La input from these 2 alloys is about the same. The mischmetal based RE type adds a significant amount more of other RE elements. We will see the negative effect of this upon shrinkage. In these experiments, iron was delivered from an autopour, so the molds containing the 2 different alloys were poured just a few seconds apart. This means that the base iron was at a constant chemistry and temperature for both molds, providing ideal test conditions for a comparison. Figure 11 shows the microstructures obtained from the iron treated with the mischmetal containing MgFeSi and the pure La containing MgFeSi alloy. The ductile iron produced using MgFeSi containing pure La metal provided a structure with fewer large nodules and a high population of medium and small nodules. This can be seen visually in the microstructure as well as in the nodule size distribution graphs. Please note that the nodule size distribution is skewed to the finer nodule size, and is not a bimodal distribution as sometimes described.

Since nodule size can be related to the time they precipitated and started to grow, we can see that the mischmetal based alloy precipitated more graphite during the early stage of freezing and less graphite during the later stages of freezing. The MgFeSi alloy with pure La type RE is therefore predicted to reduce shrinkage, since there is more C precipitation just before the end of freezing, when risers can no longer deliver more liquid feed metal to accommodate for shrinkage.

In Figure 12 we see gross shrinkage in the iron treated with MgFeSi containing a high level of mischmetal, and no shrinkage when using MgFeSi containing pure La with no other RE elements included. Conserving expansion effect by saving some C precipitation to the latter stages of freezing has a profound effect on shrinkage. We can correlate the shrinkage tendency of iron somewhat by looking for a wide nodule size distribution, highly skewed to the finer sizes.

Special Inoculant that Reduces Shrinkage

It is also possible to gain a nodule size distribution which is skewed to the finer sizes by using a proprietary inoculant coated with S and O compounds. In Figure 13, we see the microstructure of ductile irons inoculated with a conventional inoculant and that proprietary inoculant. In the thin sections (5mm = ¼”) the structures are similar.

In the thicker sections the structures are not similar. The iron treated with a conventional inoculant shows a drop in nodule in the thicker section, and the large nodules are quite a bit bigger due to the longer freezing time which provided more time for the nodules to grow. The iron treated with the proprietary S and O coated inoculant did not show a drop in nodule count in the thicker section as is normally expected. It surprisingly showed an even higher nodule count with only a few large nodules, and a very high number of medium and small nodules.

In Figure 14 we see the profound difference in shrinkage for this iron treated with different inoculants, with shrinkage minimization correlating
with a structure that has a wide nodule size distribution which is highly skewed toward the medium and finer nodule sizes.

**Thermal Analysis, Nodule Size Distributions, and Shrinkage**

Studies of iron produced with these 2 alloys that produce nodule size distributions skewed to the fine sizes have included thermal analysis. Traditional alloys tend to result in curves which are rounded off during the last half of solidification. Curves with a nodule size distribution skewed to the fine sizes tend to produce flatter curves. This is due to steadier precipitation of C (and austenite) throughout freezing. Figure 15 show cooling curves generated from iron inoculated with a conventional material and with the proprietary O and S coated inoculant. You can see that the iron treated with conventional inoculant showed a cooling curve with a quite rounded finish compared to the flatter curve for the proprietary S and O coated inoculant. The cooling curve treated with the O and S coated inoculant was different in other ways as well. Freezing occurred with less undercooling and less recalescence. High recalescence is a sign of rapid initial freezing, i.e. rapid austenite and C precipitation. Flatter curves are preferred, since these correlate with reduced shrinkage or elimination of shrinkage.

Figure 16 shows the differences in the first derivatives of the 2 cooling curves. The smaller angle around the freezing point is an indication of lower shrinkage tendency.

There used to be an old foundry axiom saying that you needed to be careful that you did not over inoculate, as you might turn on shrinkage defects. Studies have shown this to be true, if you are increasing the nodule count simply by adding more nodules of the same size. In the graph shown in Figure 17, increasing from 175 to 225 nodules per square millimeter increased shrinkage.

If however the nodule count is increased to much higher numbers, and the size distribution becomes skewed to the finest sizes, shrinkage can be greatly reduced. Simply having a higher nodule count will not help reduce shrinkage; in fact it may increase it. It is necessary to have the skewed nodule size distribution to the finer sizes.

**Increasing Freeze Rate Rather than Risering**

Many foundries have flow and solidification modeling software. This software can be very useful to predict where shrinkage is likely to occur in castings. At that point there is a decision to make to avoid that problem. Should we add risering to feed more liquid iron longer to the spot where shrinkage is predicted or should we somehow make that part of the casting freeze more quickly by some chilling technique? In large castings it is sometimes a struggle to produce structures with high nodule counts and high nodularity. It may be useful in such situations to use chilling to avoid the shrinkage effect since there can also be an improvement with the structure. Risers may make the structure worse by extending the freezing time in addition to reducing the iron yield.

There are a number of ways to chill the heavy shrink prone areas of castings.

The 2 photos in Figure 18 show holes drilled into cores and the subsequent cooling pins cast during mold filling. These pins of iron serve as “radiators” to transfer heat from the casting into the sand more rapidly, to avoid shrinkage in those areas. In some cases pins or fins can simply be added to a pattern. Drilling is only done if they cannot be included automatically with patterns or core boxes. The fins or pins will be removed from the castings after cleaning. Sometimes this can be done automatically if a de-fining operation is already being done.

In the 2 photos of Figure 19, we see a coiled spring shape used to very rapidly freeze a section of a casting prone to shrinkage. The greater surface area of a spring can chill the iron more rapidly than a straight wire or bolt. The photo on the right shows the spring fused into the casting with a shrink free result. In some cases a hole is drilled through the center of the area where the spring is located, and in other castings the spring is entirely machined out. In both cases the drilled surface must not reveal shrinkage voids of any size.

Figure 20 includes 2 photos that show an application where chills are embedded into a core as the core is produced, in order to provide chilling of the iron at places subject to shrinkage defects. The metal chills do not melt into the casting but simply extract heat more quickly from those shrinkage prone sections of the casting. Metal chills must have clean dry surfaces and are often coated with a ceramic wash.

Figure 21 shows an application where 2 bolts have been formed into a mold as “ram-up” type inserts. These were set into the pattern before forming the mold section. The objective was to accelerate freezing at an area prone to shrinkage in this greensand mold.

Figure 22 shows the cast part from the prior photo. Ultimately it was decided to use 3 bolts to quench the iron to avoid shrinkage in that area of the casting. The 3 bolt heads will later be cut off.
Producing Uniformly Strong Rigid Molds

It is well known that ductile iron can be produced without risers if molds are suitably strong. This normally means a chemically bonded sand rather than greensand. For greensand molds, it is important that molds be as strong as possible to avoid shrinkage induced by mold wall movement. This means attention must be paid to maintain sand properties and molding machine maintenance. For example, wear on valves on impact machines can result in weaker molds. Means to maintain mold strength when the pattern has very deep pockets should be considered, including adequate venting of air expelled during impact compaction.

Summary of Techniques to Minimize Shrinkage

1) Using the graphs generated in the paper, select a C content that is coordinated with a minimum Si level, your maximum pouring temperature, for the maximum casting modulus or section size. That C will be as high as possible for your situation, while just avoiding nodule flotation.

2) Avoid producing high nodule counts with an apparently uniform nodule size. This is sometimes seen if the iron is over-inoculated or treated with Bi.

3) Keep base S and final S at uniform levels, as these can make considerable changes to nodule count.

4) Avoid hold periods of base iron over about 30 minutes without adding new freshly melted base iron. If this occurs, and freshly melted iron is not available, replaced carbon lost during the hold period with 100% crystalline graphite, preferably crushed graphite electrodes or electrode turnings.

5) Avoid long hold periods of Mg treated ductile iron in autopours. The use of proprietary O and S coated inoculant added with 1 treatment of freshly treated iron can restore the nucleation effect to treated iron in the autopour.

6) Consider use of MgFeSi alloyed with pure La metal rather than other rare earth metals or rare earth mixtures and/or proprietary inoculant coated with S and O compounds. These materials can generate nodule size distributions that are skewed to the finer sizes which can reduce or eliminate shrinkage defects.

7) Maintain mold strength to uniformly high levels through sand controls and

8) Use flow and solidification simulation software to predict and minimize shrinkage. Compare various chilling techniques versus risering to increase yield and structure quality for heavy slow freezing sections that are shrinkage prone.
Max % C to Avoid Nodule Flotation
AFS Transactions, 1986 – paper 86-150
(Fuller and Blackman – BCIRA)

<table>
<thead>
<tr>
<th>Section Size of sample (mm)</th>
<th>20</th>
<th>30</th>
<th>50</th>
<th>80</th>
<th>Square Bars (mm)</th>
<th>4.79</th>
<th>7.06</th>
<th>11.34</th>
<th>17.23</th>
<th>Volume-to-surface area ratios (mm) (Modulii)</th>
<th>10</th>
<th>15</th>
<th>23</th>
<th>35</th>
<th>Cooling rate thickness in large plates (mm)</th>
<th>19</th>
<th>28</th>
<th>45</th>
<th>70</th>
<th>Cylindrical sections diameters (mm)**</th>
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<table>
<thead>
<tr>
<th>% Silicon*</th>
<th>MAX. % Carbon to Avoid Nodule Flotation</th>
<th>For pouring Temperature</th>
<th>=1400°C (2550°F)</th>
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<tr>
<td>1.8</td>
<td>4.00  3.96  3.88  3.76</td>
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<tr>
<td>2.2</td>
<td>3.90  3.86  3.78  3.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>3.80  3.76  3.67  3.55</td>
<td></td>
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</tr>
<tr>
<td>3.0</td>
<td>3.69  3.65  3.57  3.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4</td>
<td>3.59  3.55  3.47  3.34</td>
<td></td>
<td></td>
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<tr>
<td>3.8</td>
<td>3.49  3.45  3.36  3.24</td>
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<td>4.2</td>
<td>3.38  3.34  3.26  3.13</td>
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<td>4.6</td>
<td>3.28  3.23  3.16  3.03</td>
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<td>5.0</td>
<td>3.18  3.13  3.05  2.93</td>
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Carbon contents should be decreased by 0.05% for each 50°C (90°F) increase in pouring temperature.
*Silicon contents must include additions made in magnesium treatment and inoculation.
**Plus lengths greater than 5x the diameter.
Max. CE for Square Bars

Max CE for Square bars poured at 2550F with various final Si levels

Max. CE for Round Bars

Max. CE for Round Bars, poured at 2550F for various % Si contents
Max. CE for Flat Plate Sections

![Graph showing Max. CE for Thick Plates to Avoid Nodule Flotation poured at 2550F with various % Si levels](image1)

**FIGURE 5**

Max. CE versus Modulii (mm)

![Graph showing Max. CE to Avoid Nodule Flotation pouring at 2550F for various Si levels](image2)

**FIGURE 6**
Silicon in Ductile Iron

Higher silicon leads directly to higher nodule count, more ferrite, and more early C precipitation. Keep % Si steady at the minimum level – enough to avoid carbides. Avoid very high nodule counts of uniformly sized nodules from over-inoculation, Bi additions, ...

Magnesium vs. Shrinkage

![Graph showing magnesium content vs. shrinkage tendency](image)
Nakae and Igarashi Nuclei Studies
Nodule Count Increases as Base S Increases

On-the-mold Nodularizing

Objective: Compare samples of ductile iron made by the on-mould process using:

- Misch-based nodulariser
- % Si 47.0
- % Mg 4.5
- % Ca 0.3
- % RE 1.25
- % Al 0.8

- La type nodulariser
- % Si 46.0
- % Mg 5.5
- % Ca 0.5
- % La 0.35
- % Al 1.0
Graphite Nodule Size Distribution Skewed to the Fine Sizes that Reduce Shrinkage

Reduced Shrinkage - La Alloyed MgFeSi Alloy
Nodule Count/ Size Distribution vs. Section Size

<table>
<thead>
<tr>
<th>S and O coated inoculant</th>
<th>Conventional inoculant</th>
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</thead>
<tbody>
<tr>
<td>312</td>
<td>297</td>
</tr>
<tr>
<td>340</td>
<td>155</td>
</tr>
</tbody>
</table>

5 mm section

40 mm section

Shrinkage in Crossbar Samples

- Sr-FeSi: 219 Nodules/mm²
- Ba-FeSi: 221 Nodules/mm²
- S and O coated inoculant: 353 Nodules/mm²

FIGURE 13

FIGURE 14
Thermal Analysis of Inoculated Iron

O & S coated

**Conventional**

- $T_{E_{low}} = 1139^\circ C$
- Undercooling = 25$^\circ C$
- Recalescence = 6.2

**O & S coated**

- $T_{E_{low}} = 1145^\circ C$
- Undercooling = 19$^\circ C$
- Recalescence = 2.3

FIGURE 15

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Thermal Analysis of Inoculated Iron

**Conventional**

- GRF2 = 115

**O and S coated inoculant**

- GRF2 = 70

FIGURE 16
The photograph on the left shows holes drilled into cores which will become chill pins when the mold is filled with iron. The photograph on the right shows clusters of chill pins cast inside the part, to force those areas to freeze sooner so they are shrink free.
The photo on the left above shows a metal spring inserted into the core for the manufacture of a cylinder head casting. The spring is cast inside the cylinder head and serves to provide a high surface device that chills the iron during casting and solidification. The objective is to ensure that there is no shrinkage in this area, where a hole will later be drilled through the middle of the spring. The photo on the right shows a cylinder head that has been sectioned to reveal the remnants of the spring that did not totally melt, but fused to the surrounding iron.

The photo on the left shows metal chills on a pattern. The photo on the right shows the chills formed into the sand – as "ram-up" inserts. This technique provides precise positioning of the chills in the assembly while maintaining their position during assembly, transfers, and casting.
The photo above shows 2 bolts that have been formed into a large green sand mold as ram up inserts inserted into slots in the pattern prior to forming the sand. These were used to force faster solidification into the area in an attempt to avoid shrinkage defects.

The photo above shows 3 bolts cast into the part. These will be cut off and ground flat. The objective is to ensure a shrinkage free structure in that area of the casting, without the use of a riser.