1) Basic elemental information

<table>
<thead>
<tr>
<th>Element &amp; Symbol</th>
<th>Atomic Number</th>
<th>Atomic Weight</th>
<th>Melting Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium (Mg)</td>
<td>12</td>
<td>24.3</td>
<td>1200 F</td>
</tr>
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</table>

2) How magnesium is introduced in the iron

Sources of magnesium include metallic magnesium, magnesium-ferro-silicon alloys (MgFeSi), nickel-magnesium alloys (Nimag), and Mg-filled wire.

Magnesium has a very low boiling point (1994 F), which is lower than the melting point of cast iron. At common Mg treatment temperatures (2750F) the vapor pressure is 4 atmospheres. Therefore, the addition of Mg to molten iron causes boiling and produces large volumes of Mg vapor at very high evolution rates. Because Mg is also a highly reactive element, it combines with O in the air and produces bright light. Consequently, there is a violent reaction accompanying the addition of Mg to the melt, which is dangerous and requires great care and safe foundry practices.

3) Effects on the Microstructure

Magnesium is the principal element used to produce spheroidal, or nodular graphite in cast iron. There is an optimum amount that must be added to achieve a nodular or spheroidal graphite (SG) structure. Too little Mg recovered will result in some vermicular graphite and possibly even flake graphite in the cast microstructure. Compacted graphite iron is produced by intentionally adding too little Mg to result in a fully nodular structure. Excessive Mg additions will result in intercellular carbides or even white iron (a carbide-free iron). The effects of Mg on graphite shape are shown in Figures 1a and 1b.

Excess final Mg concentrations will also lead to other problems, including intercellular carbides, dross defects, exploded graphite (see Figure 2), and shrinkage porosity.

When Mg is added to the melt, it first reacts with available sulfur and oxygen in the molten iron and forms very fine, solid inclusions that become suspended in the molten iron. The remaining Mg is dissolved in the molten iron and is termed “residual” magnesium. Depending on the method of chemical analysis, the amount of Mg measured may include the residual Mg and the Mg in sulfide and oxide inclusions, which is what is measured when using an optical emission spectrometer.
4) Magnesium Requirements
Magnesium will react with oxygen and sulfur before it becomes available to spheroidize the graphite phase. The Mg consumed to make oxides and sulfides will not contribute to the spheroidization of graphite. Therefore, the amount of Mg consumed to make oxide and sulfide inclusions will affect the calculation of the total amount of Mg that must be added.

Variations in charge materials and melting practices, determine the amount of oxygen and sulfur in the melt. In addition, Mg vaporizes to a greater or lesser extent, depending on the treatment practice. Thus the amount of Mg that must be added to achieve a fully nodular structure will vary with each foundry’s practice.

Various methods have been used to specify the amount of Mg (final Mg) needed to assure 100% nodularity. Some have used Mg:S ratio, specifying 3:1 or 4:1. Another common method is to specify a minimum “excess Mg” (such as 0.020%) according to the following formula.

\[
\%Mg = 0.020 + \frac{1}{3} (\%S)
\]

The minimum excess Mg is determined empirically based on the foundries experiences.

The amount of Mg required to obtain a fully nodular structure varies with solidification rate. Light sections require less residual Mg. For example, thin-walled castings may be made 100% nodular at 0.022% Mg. Mg concentration in heavy section ductile iron (sections above 2 inches) generally exceeds 0.040%. A schematic diagram illustrating the effects of section size is shown in Fig. 3.

Fig. 3 Influence of section size on Mg requirement.

Fade
From the moment the Mg treatment is accomplished there is a tendency for the Mg effect to fade, that is, for the graphite nodule shape to degrade. Loss of magnesium will occur as Mg continues to react with oxygen at the surface of the melt and to leave the melt by vaporization. As fade occurs, the nodule count decreases along with nodularity. The degradation increases with time as shown in Fig. 4, and most foundries will avoid holding the treated iron beyond 15 minutes. Some loss of nodularity can often be restored by post inoculation. Leaner treatment alloys with 3% Mg or less are also available to restore the proper Mg level in the iron.

In many foundries the treated metal is immediately inoculated as the metal is transferred to the pouring ladle. To sustain high nodularity and high nodule count, it is commonly recommended that the ductile iron be inoculated at every transfer operation.

Fig. 4 Mg spheroidization effect fades with time.
5) Magnesium Treatment Methods
Various methods have been devised for introducing magnesium to the molten iron. The oldest is the “pour-over” method, which consists of placing MgFeSi in the bottom of a ladle and pouring the molten metal on top of the alloy. The “sandwich” method, an improvement over the pour-over method, consists of covering the alloy with ferro-silicon and/or steel punchings. For both methods, the ladle has a pocket in the bottom, for accommodating the alloy, and a high aspect ratio (typically 3:1) to improve the Mg recovery.

The “pour-over” and “sandwich” methods give poor Mg recoveries, generally 30 – 50%. This condition causes two major problems; the Mg recovery is not consistent and predictable and the amount of Si added can be excessive.

The “tundish cover ladle (covered ladle)” is a significant improvement over the pour over method. The tundish cover ladle employs a similar ladle design but it is enclosed with a lid that contains a pouring basin. Using the tundish cover ladle, Mg recoveries are much higher (50-70%) and more consistent because the vessel is closed, minimizing exposure to oxygen in the air.

The Mg recoveries in the above three methods are dependent on the treatment temperature, alloy sizing, Mg content of the alloy, and the concentrations of other elements in the alloy, particularly Ca.

The Fischer converter process uses metallic magnesium to introduce Mg to the melt. This process is extremely violent and utilizes a low-cost Mg source. Similarly, Mg-filled wire can use metallic Mg as the source.

In-mold treatment offers another way to introduce Mg to the molten iron. In this method, a reaction chamber is molded into the mold runner system. MgFeSi is placed in the chamber before closing the mold and each casting is treated individually. The size of the alloy is carefully controlled to attain uniform dissolution and treatment of the metal in the mold. Mg recoveries are also high with in-mold treatment and Mg fade is not an issue.

The Flotret process is similar to in-mold treatment in that the metal is poured through a box containing a reaction chamber. The box is placed over a ladle and the metal flowing into the ladle is uniformly treated and boasts high Mg recoveries.

6) Effects on the Mechanical Properties
The highest strength and elongation are achieved with a fully nodular structure. When nodularity falls off, due to insufficient Mg, the tensile strength and tensile elongation also decreases. Yield strength does not immediately fall off.

Excess Mg levels can lead to intercellular carbides, which also cause a reduction in tensile elongation. Excess Mg can also promote remote area shrinkage, and such shrinkage porosity may affect the performance of the casting.

7) Effects on Castability
A fully nodular structure generally requires more feeding and risering than an under-treated melt. As stated above, over treating with Mg can lead to remote area shrinkage porosity.

8) Environmental considerations
There are no known environmental or health concerns associated with magnesium as metallic Mg or as a dissolved component in cast iron. Mg is prone to ignite when present as finely divided particles, and care should be taken in handling and storage. MgFeSi is a stable substance and does not create the same problems as metallic magnesium.

9) Effects on melting and chill
Melting losses are high because of the high volatility of magnesium. Special processes are employed to limit volatility during Mg treatment. Higher Mg contents favor intercellular carbides and, at high concentrations, a propensity for chill.

10) Considerations in various ductile iron grades
The optimum magnesium concentration does not vary with ductile iron grades. For ferritic grades, a lower Mg residual is advantageous.

11) Effect of section thickness
The optimum magnesium level varies with section size and solidification rate. The minimum Mg requirements increase with section size.

12) Counteracting detrimental effects
Over-treated iron is not generally a problem with the manufacture of ductile iron. However, excess Mg levels can be reduced by dilution with untreated iron or by the addition of sulfur to the melt.

13) References