INOCULATION OF DUCTILE IRON: WHY AND WHEN?

By Pierre-Marie Cabanne and Martin Gagné, Sorelmetal Technical Services

WHAT IS INOCULATION? WHY SHOULD YOU INOCULATE DUCTILE IRON MELTS?

In its liquid state, graphitic iron (lamellar, vermicular or nodular) is a liquid solution in which carbon atoms are dissolved in iron. Without any other alloy additions, an extremely slow cooling rate would result in the precipitation of carbon as graphite, following the Iron-Carbon (graphite) dual phase diagram. However, the solidification of castings deviates from this rule. Under industrial conditions, the combination of the quality of the metallic charge, the melting and treatment of the liquid iron, and the addition of ferroalloys, results in a complex solidification route resulting in an “Iron-Cementite-Graphite” composite.

A high cooling rate, which results typically from a thin section size casting, favours the reaction of carbon and iron to form eutectic cementite (iron carbides). This reaction is promoted by the presence of elements, such as Cr and Mn, that are brought into the melt by charge materials (e.g. steel scrap, certain pig irons,...). These elements, and others (V, Mo, Nb,...), segregate to cell boundaries to form intercellular carbides. Moreover for Ductile Irons, the Mg spheroidization treatment increases the risk of carbide formation by favouring the metastable “Iron-Cementite” solidification route. (It is worth noting that Keith Millis, one of the inventors of Ductile Iron, was adding magnesium to cast iron to manufacture “Ni-Hard” type cast iron with a carbidic structure!).

The solidification of Ductile Iron is an exogenous process, i.e. it is initiated at nucleation sites called “nuclei”. On these nuclei, carbon atoms precipitate as hexagonal graphite crystals, initially growing in direct contact with the liquid iron. Further, during the solidification process, an austenitic shell crystallizes on the growing graphite spheroids. A solidified cell is then formed. This cell grows and often associates with others to form solid islands floating in the liquid. During this process, the intercellular liquid metal is enriched with certain elements (e.g. Cr, P, Mn, V, Mo,...) while the concentrations of others, mainly C and Si, are reduced. Depending on the initial number of nuclei (and then, the number of cells), the concentrations of the deleterious elements increase in the remaining liquid and often results in the formation of complex carbides and of other detrimental phases such as steadite. In order to minimize the enrichment of the cell boundaries in residual elements, one solution is to significantly increase the number of solidifying cells which results in the diminution of the volume of liquid metal between the cells. However, in most cases, this action has to be combined with the careful selection of charge materials containing very low concentrations of residual elements. Sorelmetal, with its exceptional chemical purity level, fulfills this requirement.

It is a well-known fact that a low nodule count (number of nodules) in Ductile Iron is associated with large, poorly shaped spheroids. This detrimentally affects the mechanical properties of the material. Also, the lower the nodule count, the higher the tendency to form pearlite, carbides and micro-porosities. Therefore, inoculation, which has a multiplying effect on the formation of nuclei and solidifying cells in Ductile Iron, is an essential process step for the production of quality castings. The resulting increased nodule count favours the formation of ferrite and minimizes the occurrence of intercellular carbides and micro-porosities. Moreover, since the inoculating alloy is rich in
silicon, it further contributes to the solidification of the iron according to the stable “Iron-Graphite” phase diagram.

HOW AND WHEN TO INOCULATE?
The efficiency of the inoculation event(s) is very dependent upon a good quality metallic charge and a robust, well controlled melting process. A metallic charge with low nucleation potential, such as those mainly based on steel scrap, requires more inoculants. Similarly, a non optimized melting process (e.g. long melting and/or holding time, high superheat, holding temperature higher than 1450°C (2650°F)) “kills” the iron and requires stronger inoculation! To make the inoculation of Ductile Iron more efficient, it is recommended to optimize the charge composition with a significant ratio of Sorelmetal, to rapidly melt the metallic charge and, when liquid, to hold it at as low a temperature as is practical.

The evaluation of the nucleation potential of the iron is the next step before starting the inoculation process itself. One of the proven techniques to evaluate the nucleation potential is thermal analysis, using the undercooling and recalescence parameters as indicators (see Suggestions for Ductile Iron Production #103). Chill wedge and plate wedge tests are also utilized to evaluate base iron nucleation potential. Variations should be correlated to variations in castings. A stable nucleation potential in Ductile base iron generally leads to a more uniform nodule count in castings. A Ductile base iron with a high degree of nucleation potential offers a better opportunity to achieve as cast structures free from carbides and can negate the need for expensive salvage heat treatment.

INOCULATION PROCESS

Step 1: Preconditionning
Preconditionning describes the addition of a particular inoculant to the clean, deslagged surface of a furnace melt prior to the nodulizing treatment process. This event serves to normalize the nucleation potential of the melt. The inoculant may be high purity graphite, inoculating grade ferrosilicon, or silicon carbide grain. In each case, the addition must be of a size that will dissolve quickly. This is particularly true for silicon carbide as this addition dissolves rather than melts. Typically, an addition of 0.1% or 1 kg per metric ton (2 lb per US ton) is sufficient to enhance the formation of nuclei.

Step 2: Pre-inoculation
At this stage, an addition of inoculating grade ferrosilicon is made either to the stream of iron filling the treatment ladle, or as part of the alloy “package” in the treatment ladle. The inoculant may be part of the cover material in a sandwich or tundish treatment. Combining the Mg alloy and the ferrosilicon inoculant can contribute to weaken the carbide promoting effect of Mg and to adjust the silicon content in the iron according to the grade targeted and the casting section size. As in the other inoculation steps, the primary function of the inoculant is to add nucleation sites to facilitate the growth of graphite particles versus the growth of carbides.

Step 3: Ladle Inoculation
Ladle inoculation, often referred to as “post inoculation” is possibly the most important step of the inoculation procedure. Because of the violence of the Mg reaction during the spheroidization treatment, a significant fraction of the nuclei generated by steps 1 and 2 can become entrained in the surface slag covering the iron melt. Magnesium treated melts also tend toward more undercooling. It is therefore necessary to rehabilitate the nucleation potential of the iron. The addition of between 0.1 to 0.3% (acceptable 0.4%) of a powerful inoculant during the transfer from the treatment ladle to the pouring ladle should be enough to restore the nucleation potential of the iron and to offset the carbide promoting effect of Mg. If the metal is transferred to the mould via a pouring furnace, the selection of the inoculant(s) and the quantity added should be determined experimentally to avoid build up in the furnace area.

Step 4: Late Inoculation
This step is the most expensive of the inoculation procedures for the following reasons:
- The inoculants, typically added at a rate of 0.08 to 0.15%, can have a specially designed composition;
- If added in the metal stream during filling the mould, it requires a fine particle size distribution which is more costly; moreover, yield can be relatively low due to spilling of the fine particles around the pouring basin. This practice may contaminate the moulding sand and result in defects in future production;
- If added as pressed and sintered or cast inserts in the gating system, the cost of agglomeration is added to the alloy.
Late inoculation is however the most effective step in the inoculation series. It is well known that the effects of both the magnesium treatment process as well as the addition of inoculants fade with time. By moving the inoculation event to as late in the pouring process as possible, the effects of fading are minimized. Often, a small addition of a late inoculant can replace a much larger addition at earlier steps. In some cases, late inoculation may be avoidable. This last step can serve as safety procedure rather than an absolutely required one. In some instances, late inoculation compensates for less than optimal charge composition and/or melting procedure and/or spheroidization processes. For example, although late inoculation does not completely offset the effect of deleterious elements such as Cr, V, Mo, Sb, V, Ti..., it can minimize the detrimental effect by increasing nodule count and decreasing the degree of segregation. The use of high quality charge materials, namely Sorelmetal, has been shown to improve inoculant effectiveness. Additionally, the use of Sorelmetal in the charge can reduce the quantity of inoculant required while allowing a faster melting rate and the reduction of the occurrence of intercellular defects.

Although not always considered essential for the production of high quality Ductile Iron castings, late inoculation remains of prime importance for thin wall casting production (equal to or less than 3 mm) or for the fabrication of heavy section castings (100-200 mm) in order to ensure a high nodule count and to minimize intercellular defects detrimental to mechanical properties. In both situations, foundrymen include a high ratio of Sorelmetal in the charge to complement the effect of late inoculation.

In summary, foundrymen need to understand why they have to inoculate Ductile Iron and when and how they should do it, but they also have to optimize their procedures to obtain the high quality structure targeted at the lowest cost.

Do not hesitate to contact the Sorelmetal Technical Services metallurgists directly, via your Sorelmetal agent or Rio Tinto Iron & Titanium regional offices to further discuss your inoculation process and how it could be optimized.