

# Process Control for the Production of Compacted Graphite Iron

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## Abstract

Compacted Graphite iron provides at least 70% higher tensile strength, 35% higher elastic modulus and approximately double the fatigue strength of conventional gray cast iron. In comparison to the common aluminium alloys, CGI provides double the strength and stiffness and three times higher mechanical fatigue limits. These properties allow engine designers to improve power-to-weight ratios and to achieve the cylinder bore pressures required for optimal performance of the next generation of direct injection diesel engines. In preparation for the future use of CGI, the foundry industry is now investigating and implementing process control strategies for the reliable series production of CGI.

The decision to proceed from prototype design to series production of CGI engines is governed by risk. The production of high quality compacted graphite iron is only stable over a range of approximately 0.008% magnesium, and the loss of as little as 0.001% magnesium can cause the formation of flake-type graphite resulting in an immediate 25-40% decrease in mechanical properties and possible product liabilities. The present paper describes a thermal analysis based measurement and process control system that prevents flake graphite formation by simulating magnesium fade and thereafter conducting an on-line correction of the molten iron. This measure-and-correct control strategy minimises process variation and eliminates the risk associated with CGI production.

## Introduction

Despite the narrow control range for compacted graphite iron (CGI), many foundries have successfully produced CGI castings using standard production techniques and good foundry discipline. However, the recent interest in CGI cylinder blocks requires the production of large volumes of complex components with uniform microstructure. While standard techniques may allow for the successful production of the majority of cylinder blocks, process control systems are required to ensure that the remaining potentially out-of-spec castings are identified and corrected prior to casting.

The need for process control depends on the production volume, the complexity of the component and the narrowness of the microstructure specification. As shown in Figure 1, relatively simple low-volume components such as ingot moulds can generally be produced with standard foundry practice and controls. Additional process control is neither necessary nor cost-justifiable. With increasing production volume, for example exhaust manifolds, bedplates, bearing caps or brackets, the implementation of additional process control becomes more appropriate. However, despite the high production volume (pieces/year), the annual foundry tonnage remains relatively small and the microstructure specification can usually allow up to 50% nodularity.

Furthermore, because the machining requirements of these components are limited, their production can also tolerate the use of titanium poisoning. For these reasons, standard foundry practice and good production discipline are often sufficient, but

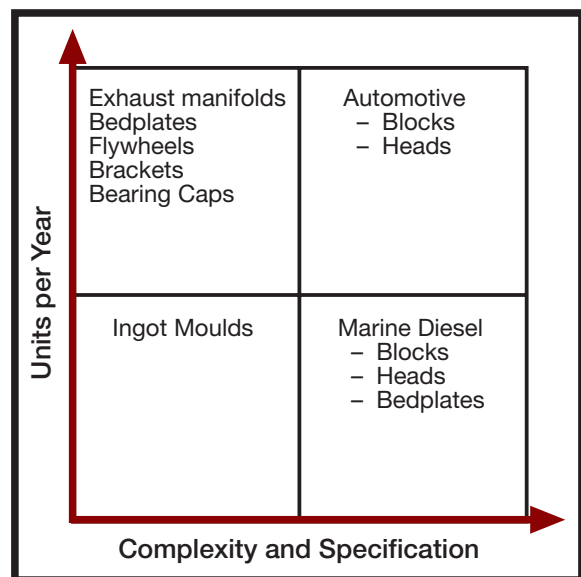


Figure 1: The need for CGI process control increases with increasing production volume, geometric complexity and narrowness of the microstructure specification

process control would be reassuring from a quality control point-of-view. Likewise, process control is reassuring during the production of large stationary and marine diesel blocks and heads. Their large size and low production volume facilitate production, but the cost risk associated with out-of-spec castings fully justifies an on-line process control strategy. The most obvious case in the volume/complexity/specification matrix is automotive blocks and heads. The production volumes and tonnages are high, the geometric complexity and shrink tendencies are high, the microstructure specification is narrow, and the risk tolerance is zero.

The production and ultimate performance requirements of automotive blocks, heads and bedplates serve as the basis for defining a product specification. For proper castability, machinability and performance, a 0-20% nodularity range is required in all performance-critical sections. More importantly, flake-type graphite must be avoided to prevent local weaknesses that could lead to component failure. For optimal machinability, carbides must be avoided and titanium additions must not be used. Finally, from the production point-of-view, the foundry needs a reliable process that minimises metallurgical scrap rates and the automotive OEM requires a quality assurance certification that 100% of the castings satisfy the microstructure specification. The reliable series production of automotive blocks, heads and bedplates requires an accurate analysis of the molten iron and an on-line control action to eliminate process variation before casting.

## CGI Stability

The reason that CGI has not yet been adopted for series production of complex components such as cylinder blocks is that the stable range is too narrow to ensure risk-free production. Although the actual size and location of the stable CGI plateau is different for each product, it generally spans a range of approximately 0.008% Mg, as shown in Figure 2. However, in practice, the usable Mg-range is even smaller. Because active magnesium fades at a rate of approximately 0.001% every five minutes, the initial starting point of the iron must be sufficiently far away from the abrupt CGI-to-gray iron transition. This 'buffer' is necessary to ensure that flake-type graphite does not form before the end-of-pouring, which may be as long as fifteen minutes after the initial magnesium addition.

Simultaneously, the starting point must not be too close to the right side of the plateau in order to minimize the formation of nodular graphite in the faster-cooling thin sections.

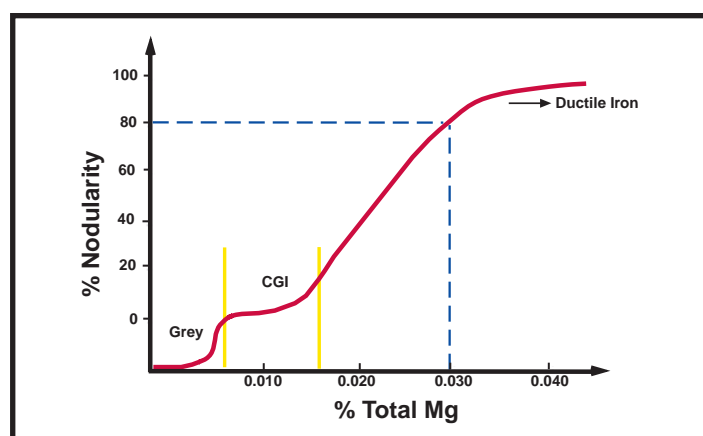
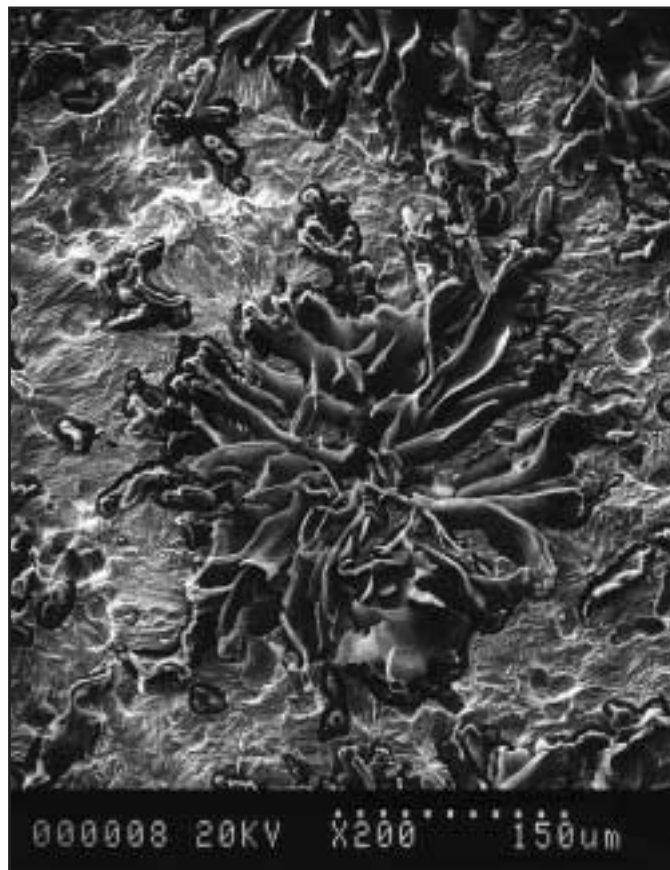


Figure 2: The stable CGI plateau exists over a range of approximately 0.008% magnesium and is separated from grey iron by an abrupt transition

A second consideration is that the stable CGI plateau is not stationary. If the active oxygen and/or sulfur contents are high, they will consume the active magnesium and shift the entire plateau toward higher total magnesium values. Conversely, if the oxygen or sulfur levels are relatively low, the CGI plateau will shift toward the left. For these reasons, variations in the composition, cleanliness, oxidation and humidity of the charge material make it impossible to define a fixed chemistry specification for CGI.

Despite that the transition from CGI-to-gray iron occurs over as little as 0.001% active magnesium, the natural Mg-fading does not always cause the CGI microstructure to revert entirely to flake graphite. In the absence of sufficient magnesium, the graphite begins to grow with a flake morphology. As the solidification proceeds radially outward, the magnesium segregates ahead of the solid liquid interface and, depending on the initial magnesium content, the compacted graphite morphology may become stable near the perimeter of the eutectic cell. As shown in Figure 3, the result is that flake-type graphite first appears in CGI microstructures as discrete flake patches. In contrast to fully flake graphite structures, these isolated flake patches are not easily detected by ultrasonic tests due to the probability of the patch occurring in the ultrasonic test path.



*Figure 3: The formation of flake type graphite in CGI microstructures first appears as isolated flake patches*

The sensitivity of CGI to magnesium is illustrated in Figure 4 which shows that a flake patch structure in a 25 mm diameter test bar can be converted to a fully compacted microstructure with the addition of only 10 grams of magnesium in a one tonne ladle. The flake patch microstructure provides an ultimate tensile strength of 300 MPa while the tensile strength of the fully compacted microstructure is 450 MPa.

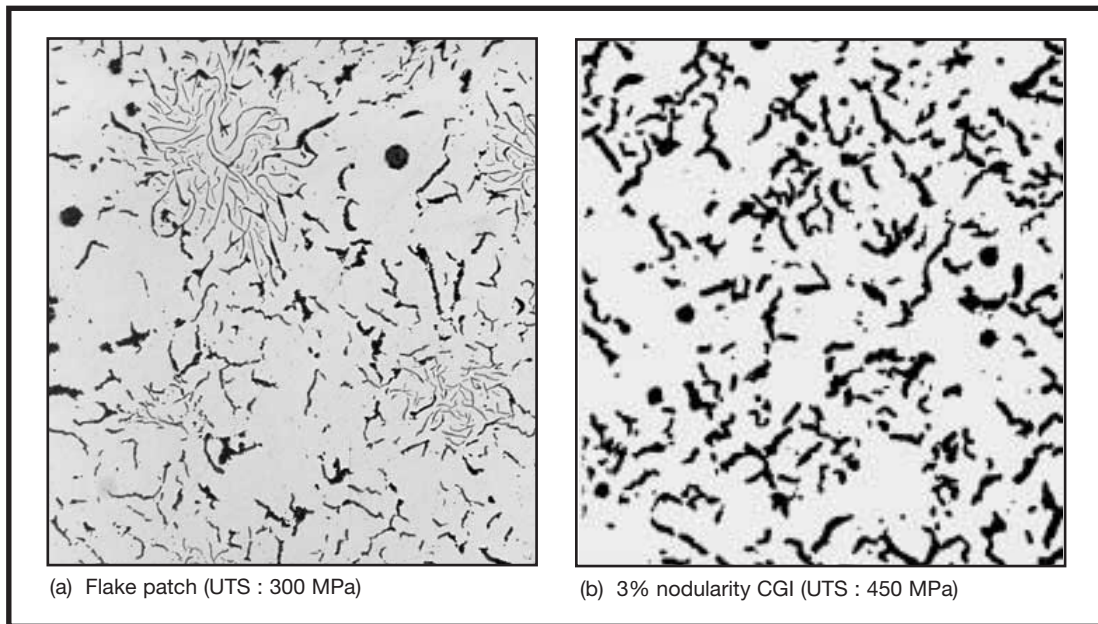


Figure 4: An addition of 0.001% active magnesium is sufficient to convert a flake-patch microstructure into a high quality CGI microstructure

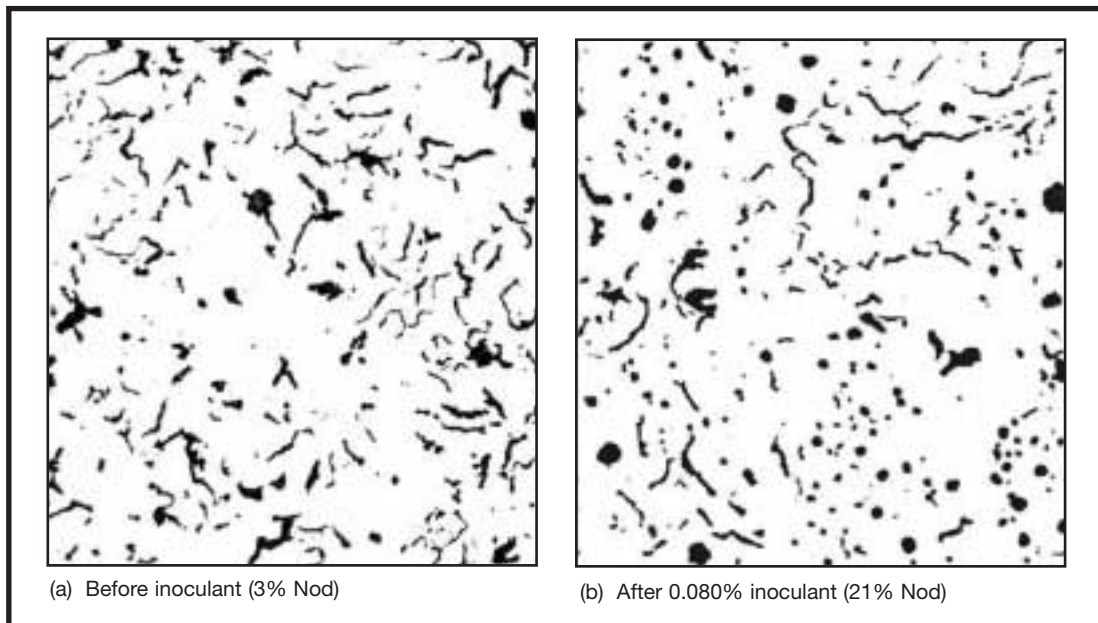


Figure 5: An addition of 0.080% post-inoculant can cause the CGI nodularity to increase from 3% to 21% in a 25 mm diameter test bar

The CGI plateau is also sensitive to the addition of inoculant. Higher inoculation levels provide more nuclei which favours the formation of nodular graphite. Therefore, higher inoculation levels shift the CGI plateau toward higher nodularity values while lower inoculation levels cause the plateau to shift downward. Factors such as furnace superheat, holding time, charge composition and type and amount of inoculant therefore influence the location of the stable CGI plateau. The sensitivity to inoculation is illustrated in Figure 5 which shows that the addition of 80 grams of inoculant to a one tonne ladle can change the nodularity from 3% to 21% in a 25 mm diameter test bar.

## The SinterCast Probe

The basis of any process control technology must be an accurate analysis of the behavior of the molten iron. In the case of compacted graphite iron, the previous section has shown that the reliable control of CGI requires simultaneous measurement of the magnesium proximity to the abrupt CGI-to-gray iron transition, the subsequent magnesium fading, and the inoculation level.

The 200 gram SinterCast thermal analysis sample is obtained by immersing the sampling probe into the molten iron after the magnesium and inoculant base treatment has been made. During the three second immersion time, the walls of the sampling cup are heated to thermal equilibrium with the molten iron. In comparison to conventional thermal analysis sand cups, the thin-wall immersion sampler ensures a constant sample volume, prevents oxidation of the iron during pour-in filling and provides a more accurate measurement of undercooling because of the elimination of chill-solidification.

As shown in Figure 6 (a), the immersion probe is fabricated entirely from a stamped and drawn steel sheet and has a predominantly spheroidal sample containment area. The steel walls containing the molten iron provide a double-wall Dewar type insulation of the sample. The void space between the two walls varies symmetrically along the height of the probe to regulate heat loss and impose a uniform (spheroidal) solidification behavior. The probe contains two Type N thermocouples (in a closed-end protective steel tube) which are extracted after each analysis and re-used at least 100 times. One of the thermocouples is located at the bottom of the sample containment area while the other is located in the thermal centre of the sample. The spheroidal shape of the probe, combined with the fact that it hangs freely during solidification rather than being supported by a base that behaves as a heat-sink, results in the generation of thermal convection currents in the sampled iron. As shown in Figure 6 (b), these convection currents rinse the iron around the probe and cause the formation of a flow-separated region in the bottom of the vessel.

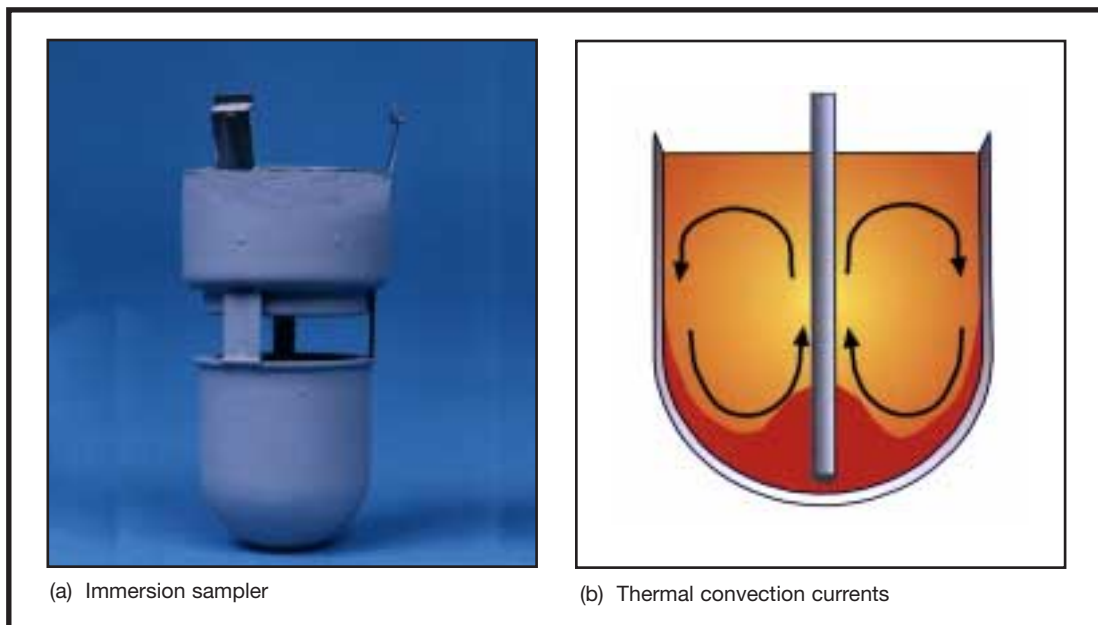


Figure 6: The immersion-type sampling probe prevents oxidation of the sampled iron and provides thermal equilibrium between the vessel and the molten iron

In order to simulate the natural fading of magnesium that occurs in both the ladle and in the castings, the walls of the sample vessel are coated with a reactive material that consumes active magnesium.

The convection currents rinse the sampled iron along the reactive walls and cause a low-magnesium iron to accumulate in the stagnant flow-separated region at the base of the probe. In the simplest sense, the centre thermocouple monitors the non-reacted iron and thus determines the start-of-casting behavior while the bottom thermocouple predicts the end-of-casting solidification behavior. The reactive coating is designed such that the iron that accumulates in the flow-separated region contains 0.003% less active magnesium than in the bulk iron. Therefore, if the initial magnesium content of the iron is too close to the CGI-to-gray iron transition, the flow-separated area will solidify as gray iron yielding a gray-like cooling curve from the bottom thermocouple. This result alerts the foundry to add more magnesium before the start of casting to compensate for the inevitable magnesium fade. In contrast, if the bottom thermocouple yields a CGI cooling curve even after the loss of 0.003% Mg, then the magnesium start point is sufficiently high to avoid flake graphite formation during the pouring time.

An etched cross section of a solidified SinterCast probe (Figure 7) shows the separated-flow region, the bulk iron and the protective thermocouple tube. The loss of 0.003% active magnesium in the flow separated region has resulted in the formation of undercooled D-type flake graphite and, due to reduced diffusion distances, a ferritic matrix. The size of the flake-type graphite zone in the bottom of the probe is directly proportional to the initial magnesium content of the bulk iron and can be calculated from the bottom thermocouple cooling curve as the time-integrated heat release prior to the eutectic undercooling minima. The r-squared correlation coefficient for the relationship between the calculated heat release and the size of the flake zone is in excess of 0.9. This insight into the current and simulated after-fading end-of-pour behavior of the iron allows corrective magnesium additions to be made before casting begins.

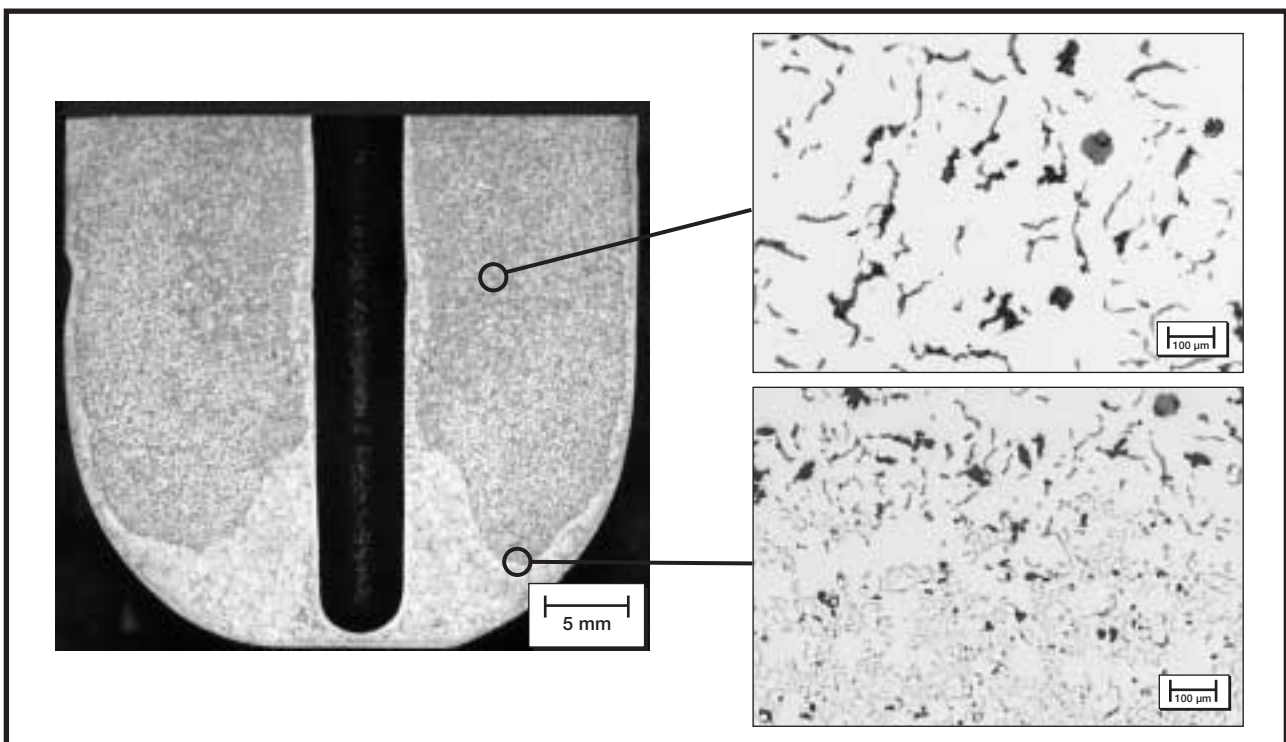


Figure 7: The reactive wall coating and thermal convection currents combine to simulate magnesium fading in the bottom of the SinterCast probe (etched)

## Production Considerations

Unlike gray and ductile irons, the sensitivity of CGI to magnesium and inoculant additions prevents foundries from adopting the traditionally conservative philosophy of overtreatment. As illustrated in Figure 8, the sensitivity of CGI to both magnesium and inoculant means that CGI is actually stable within a four-sided window and not on a simple magnesium plateau. Reliable CGI production therefore requires simultaneous control of the magnesium and inoculant from the start until the end of casting in order to stay within the microstructure specification.

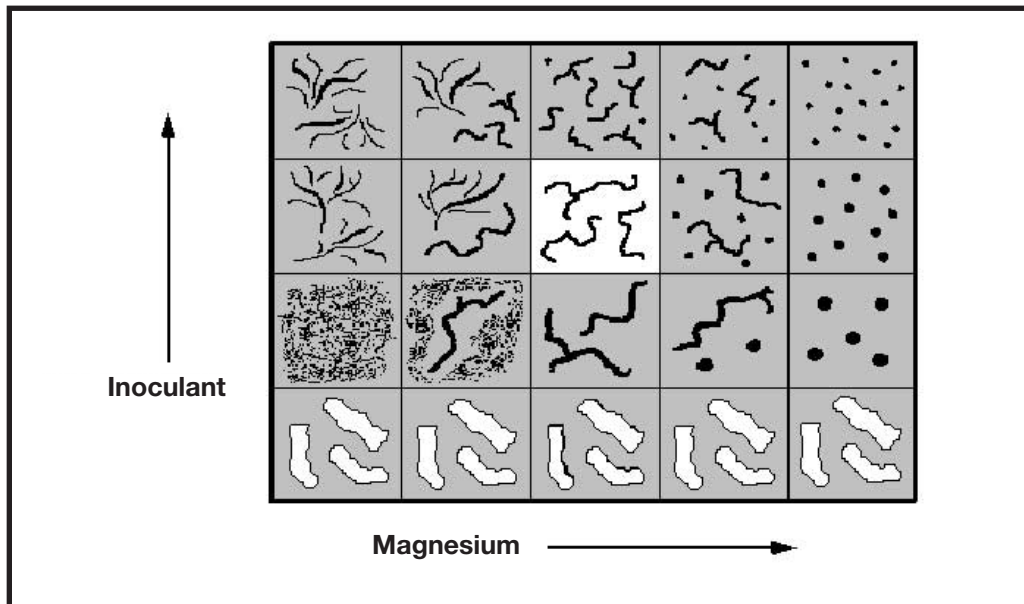


Figure 8: The sensitivity of Compacted Graphite Iron to both magnesium and inoculant means that CGI is only stable within a four-sided window

Despite all good efforts and discipline, variation in the base treatment result is inevitable. Regardless of the state of knowledge of the base iron, one-step treatment methods such as the sandwich method cannot be relied upon to always fall within the narrow CGI window. Variations in parameters such as charge mix, furnace temperature, furnace holding time, ladle pre-heating, tapping rate, tap stream impact location (inside or outside of alloy pocket), tap weight, condition of the alloy pocket, actual Mg content in the FeSiMg alloy, layering of the alloy sandwich and amount of steel cover all affect the magnesium recovery. In addition to these variables, the active oxygen and sulfur content of the base iron actually change the size and location of the CGI window while variations in ladle holding, transport and pouring times change the time available for fading. However, the most unpredictable source of variation can be operator error, or the difference in work habits between different operators.

During large volume series production, the only certain way to eliminate process variation is to evaluate the solidification behavior of the iron after the base treatment has been made. In this way, all of the variables influencing alloy recovery and the size and location of the CGI window have been exhausted and thus accounted for. Corrective additions of magnesium and/or inoculant can thereafter be made, if necessary, to bring each melt to the desired solidification behavior before the start of casting. A two-step measure-and-correct control strategy minimizes variation and eliminates the risk associated with flake type graphite appearing in the final product.

## Process Control for Ladle Production

As shown in Figure 9, the control process begins by obtaining a thermal analysis sample of the magnesium and inoculant base treated iron in the SinterCast probe. Depending on the result of the thermal analysis, the wirefeeder is automatically instructed to add the necessary amount of magnesium and inoculant cored wires and the operator is prompted to start the feeding. At the conclusion of wirefeeding the ladle is transported to the moulding line to begin casting. The entire on-line measure-and-correct process requires approximately three minutes and is conducted in parallel with standard foundry activities such as deslagging and ladle transport thus allowing for continuous operation of the molding line.

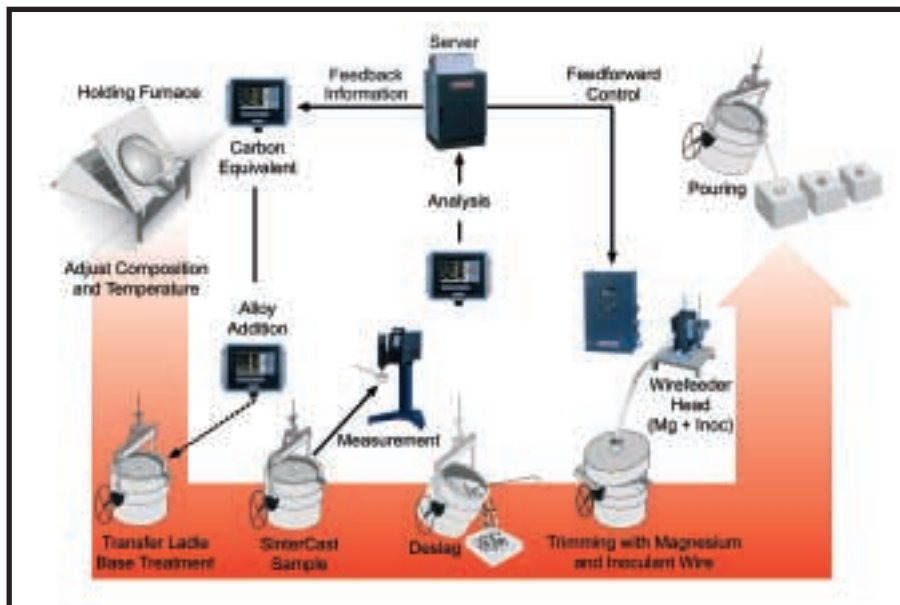


Figure 9: A thermal analysis conducted after base treatment eliminates process variation and allows for corrective action prior to casting

When the sample volume in the probe has solidified, the cooling curves are analysed and the results are presented as dimensionless Inoculant and Magnesium Indices. With reference to the microstructure 'chessboard' previously presented in Figure 8, these two indices are sufficient to fully define the solidification behavior and potential microstructure of the base treated iron. As shown in Figure 10, the 'chessboard' can be simplified by removing the different microstructures and only showing the base treatment result and the CGI specification window for the product to be cast. Although the exact size and location of the window is different for each product, the production strategy is to always start casting in the top corner of the specification window. If every ladle is brought to these precise coordinates before the start of casting, the fading of magnesium and inoculant will neither result in flake patches nor carbides.

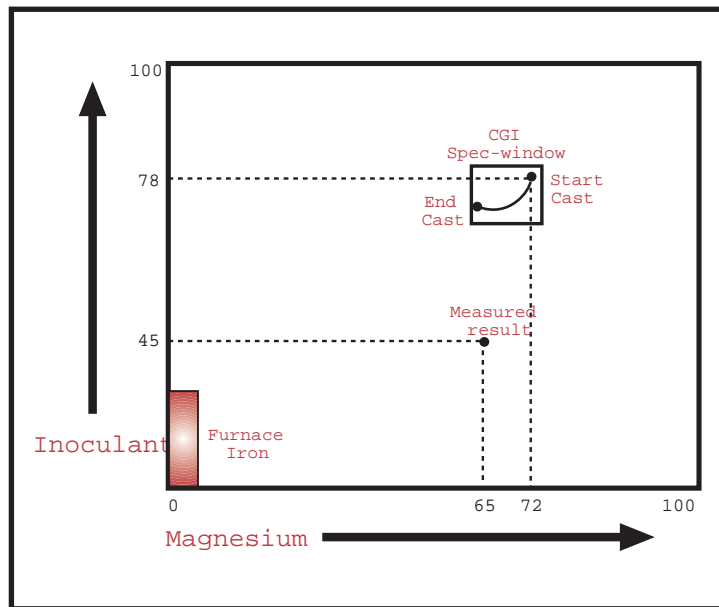


Figure 10: Corrective additions of magnesium and inoculant cored wire shift the base iron the desired start-cast co-ordinates

From an operational point-of-view, the base iron being held in the furnace has no magnesium and relatively little inoculating potency. During base treatment, the magnesium and inoculant additions first consume the active oxygen and sulfur and thereafter the iron ‘jumps’ upward on the chessboard. In the present example, the after base treatment Magnesium and Inoculant Indices are 65 and 45 respectively. Because the most significant process variables manifest themselves as variation in the base treatment result, and are thereafter exhausted, the thermal analysis result obtained after base treatment indicates the state of a static and stable melt. It remains, then, to add extra magnesium and/or inoculant to move from the base treatment coordinates to the desired start cast coordinates. In the example of Figure 10, an amount of magnesium cored wire equivalent to 7 Magnesium Index units is added to the melt followed by an equivalent inoculant wire addition of 23 Inoculant Index units. The correlation between Index units and metres of cored wire are calibrated for each foundry (ladle size, temperature, etc) and product (solidification rate, time to empty ladle, etc) and programmed in the correction algorithm. According to experience with more than 100,000 CGI castings, the average corrective addition of magnesium wire is only five metres per one tonne ladle which, at 12 grams of magnesium per metre of wire and a recovery of 50% corresponds to just 30 grams of magnesium per tonne of iron. Because the corrective additions are very small, and because the process variables are eliminated during the base treatment operation, the recovery during correction is very reliable. It is not necessary to obtain a second thermal analysis sample.

The objective of the base treatment operation is to intentionally undertreat the iron relative to the start-cast coordinates such that even if all factors combined to achieve the highest possible magnesium and inoculant recovery, the iron would only arrive at the start-cast coordinates. Beyond overtreatment, the only operational requirement of the base treatment process is that the sampled iron is neither fully gray nor fully white. To optimize the efficiency of the foundry process, the SinterCast Magnesium and Inoculant Indices for each ladle are displayed as histogram run charts. Depending on the trend in the run chart, the amounts of magnesium and inoculant added to subsequent base treatments can be changed by the operator according to the foundry SOP. The measured carbon equivalent value is also displayed. These data are ultimately compiled in daily production summaries to satisfy traceability and quality assurance requirements.

Although the thermal analysis and subsequent control strategy ensures the reliable production of CGI, an optional end-of-pour quality assurance sample may also be obtained by immersing the probe directly in the pouring basin of the last mould poured. In comparison to conventional quality assurance tests, the thermal analysis result provides a real-time evaluation of the iron which, if necessary, would allow for early segregation of castings. The magnesium fade simulation in the sampling device makes this NDT quality assurance technique more effective than metallographic or ultrasonic inspection as it inspects a larger sample volume and also shows how the iron would solidify if pouring were to continue for an additional 10-15 minutes.

## Process Control for Pouring Furnaces

Similar to ladle production, the process control of CGI production from pressurized pouring furnaces requires that the thermal analysis result be applied in a way that minimizes process variation and precludes operator error. As shown in Figure 11, the process flow for CGI production from pressurized pouring furnaces requires that desulfurized base iron be treated with magnesium and held in the pouring furnace. It is preferable to use relatively 'pure' magnesium sources such as wire or converter to minimize slag accumulation and furnace cleaning requirements. The magnesium treated iron is held in the furnace and is inoculated by feeding cored wire into the pouring spout during the time that the stopper remains open. Thus, a fully treated compacted graphite iron is poured into the molds.

The process control begins by immersing the SinterCast probe directly in the pouring basin of a newly filled mold and thereafter regulating the entire process with a feedback control logic. For example, if the thermal analysis indicates the onset of flake graphite formation, the amount of magnesium added to the next base treatment can be increased to concentrate the magnesium content of the bulk iron in the furnace. Conversely, if the Magnesium Index is becoming too high, subsequent base treatment amounts can be reduced to dilute the magnesium content in the furnace. In a similar manner, the speed of inoculant wire injection into the pouring spout can be increased or decreased to regulate the amount of inoculant added during the constant pouring time.

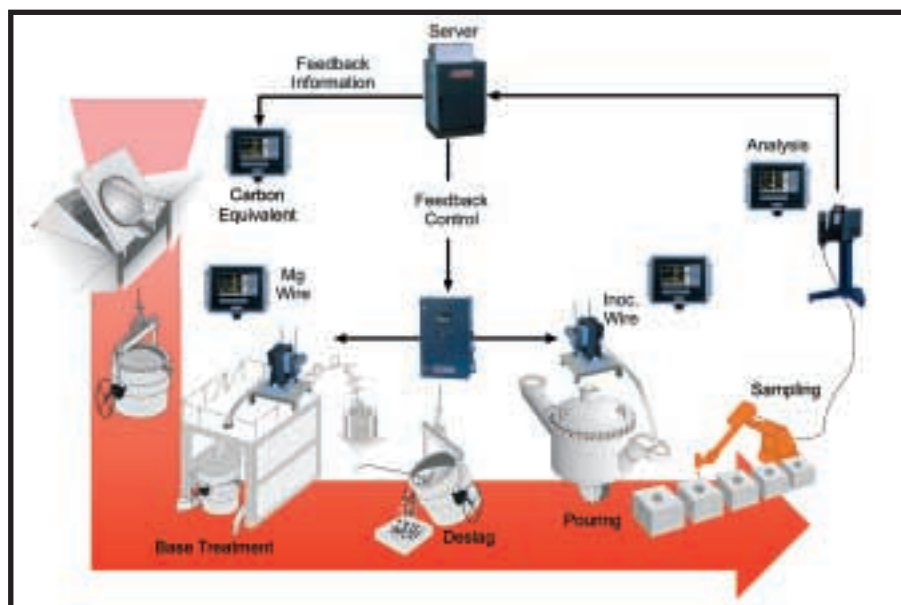


Figure 11: CGI production from pressurized pouring furnaces is controlled by a feedback control logic based on thermal analysis results obtained directly from newly-poured molds

Finally, as shown in Figure 11, a provision can also be made to inject high-purity magnesium wire directly into the furnace body. Under normal production circumstances the magnesium content in the furnace is regulated by the incoming base treated iron; however in situations such as lengthy line stoppages when the furnace body is full, the ability to add magnesium directly to the furnace prevents the need for pigging before production is resumed.

The frequency of thermal analysis sampling is determined in each foundry as a function of the furnace volume, size of the base treatment ladle and furnace throughput rate. However, in each case, the sample is obtained immediately before the next base treatment ladle is emptied into the furnace. This strategy ensures that the sampled iron represents the lowest modification level in the entire process and can therefore also serve as an end-of-pour quality assurance result. Despite that the sample evaluates the worst-case scenario in the furnace body, the 0.003% magnesium fade simulation at the bottom of the SinterCast probe eliminates the risk that the castings will contain flake graphite. The fade simulation in the probe is larger than the magnesium drop that can occur by the dilution caused by an unintentionally undertreated incoming ladle. Additionally, the thermal analysis result is available before the next base treatment is conducted, which allows for increased magnesium additions. The control strategy is not affected by magnesium fading in the bulk iron because the nitrogen atmosphere in the furnace effectively prevents magnesium oxidation.

Similar to the process control provided for ladle production, the SinterCast Magnesium Index, Inoculant Index and Carbon Equivalent values are displayed as histogram run charts to assist the overall process efficiency. The results are directly fed to network-linked wirefeeders at the pouring spout, furnace body and in the base treatment area and, where appropriate, operators are prompted to activate the feeding. The thermal analysis results are also provided in hard copy or electronic format to satisfy process documentation, traceability and quality assurance requirements.

## Summary

The requirements of a process control system are defined by the needs of both the product and the foundry production process. In the case of Compacted Graphite Iron engine blocks, the control system must be able to simultaneously control the magnesium and inoculant within a narrow specification window from the start until the end of casting. The nodularity must be kept within the 0-20% range to optimize castability, machinability and operational performance, and patches of flake graphite must be avoided to prevent local weak spots.

The starting point of any process control system is an accurate and comprehensive measurement of the molten iron. However, the metallurgical information only indicates the behavior of atoms during solidification. The reliable high volume production of Compacted Graphite Iron requires control strategies that are designed to react to the thermal analysis results to eliminate process variation and preclude operator error. The most effective way to eliminate process variation is to evaluate the molten iron after base treatment and thereafter make corrective additions of magnesium and inoculant to the iron prior to casting. This on-line measure-and-correct control strategy ensures consistency at the molding line and eliminates the risk associated with high volume CGI production.

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