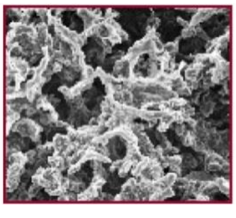
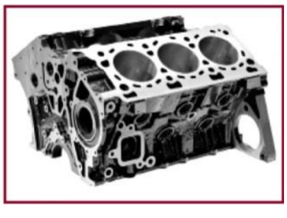
SinterCast

— Supermetal CGI —

Process Control for the Reliable High Volume Production of Compacted Graphite Iron



Abstract

The demands for improved engine performance, fuel economy and durability continue to pose challenges for engine designers and the materials they choose. As Compacted Graphite Iron (CGI) has established successful high volume series production references in the passenger vehicle, commercial vehicle and industrial power sectors over the last decade, engine designers have become more aware of the benefits of CGI cylinder blocks and heads and the competitive benchmarks set by CGI engines. The increasing requirements for CGI engine components places new demands on the cast iron foundry industry to establish efficient and robust CGI series production processes.

The production of high quality Compacted Graphite Iron is only stable over a range of approximately 0.006% magnesium. The loss of as little as 0.001% magnesium at the lower end of the stable range can cause the formation of flake-type graphite, resulting in an immediate 25-40% decrease in mechanical properties and causing field failures. At the upper end of the stable range, particularly in complex components such as cylinder blocks and heads, increases in magnesium or inoculation can quickly lead to porosity defects, resulting in leakage failures after machining. The present paper describes a thermal analysis process control system that enables the consistent production of CGI with low nodularity, without risking the formation of flake graphite. The technology is currently used for the cost-effective production of more than 500,000 CGI cylinder blocks per year, in Europe, North and South America, and Asia.

Introduction

The production and operating demands of modern automotive cylinder blocks and heads provide the basis for defining the requirements of Compacted Graphite Iron (CGI) production techniques. Specifically, these demands include:

- ***Foundry:*** stable high volume production with no risk of flake graphite formation. Minimal scrap due to porosity, without resorting to expensive feeders
- ***Machining:*** consistent incoming quality, microstructure and properties to allow optimisation of the machining parameters. Minimal after-machining scrap due to porosity
- ***Engine:*** consistent high strength to provide mechanical durability. Consistent high thermal conductivity to prevent thermal fatigue failures in heads and piston seizing in blocks

These requirements can only be simultaneously satisfied by producing CGI in the 0-20% nodularity range. Within this consistent, low nodularity range, the castability, machinability, heat transfer and wear resistance are optimised, providing cost-effective production in the foundry and machining operations, and delivering confidence to the end-users.

The need for a 0-20% nodularity specification for modern automotive cylinder blocks and heads has been widely agreed by international OEMs and by standards organisations. For example, the CGI specifications of Audi, Caterpillar, Cummins, DAF Trucks, Ford, General Electric, General Motors, Hyundai, Navistar, Rolls Royce Power Engineering, Scania, Toyota and Volvo all require 0-20% nodularity. Likewise, the international ISO 16112 and the SAE J1887 standards, and the American ASTM 842 and the German W50 standards also specify the 0-20% nodularity range for high quality CGI. This unanimous recognition of the need for a narrow CGI microstructure specification to optimise castability, machinability, heat transfer and wear resistance has recently been reflected in the Chinese standards, where the former 4403-87 standard for CGI that allowed 0-50% nodularity has been replaced by the new GB/T 26655-2011 standard that specifies 0-20% nodularity.

For the foundry, the challenge is to reliably remain within the narrow 0-20% nodularity range without risking the formation of flake-type graphite that will cause local weakness and lead to durability failures in the engine and without incurring high porosity scrap rates or high feeding costs to compensate for excessive Mg-treatment. The reliable, cost-effective series production of modern CGI cylinder blocks and heads requires a process control technology that provides an accurate analysis of the molten iron and an on-line control action to ensure that the risk for out-of-spec castings is identified and prevented prior to casting.

The Stable CGI Range

The reason that CGI had not been adopted for series production of complex components prior to the late-1990's was that the stable range of CGI was 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 0.006% Mg. A schematic illustration of the stable range for CGI, for a base iron that contains 0.010-0.015% sulphur, is shown in Figure 1.

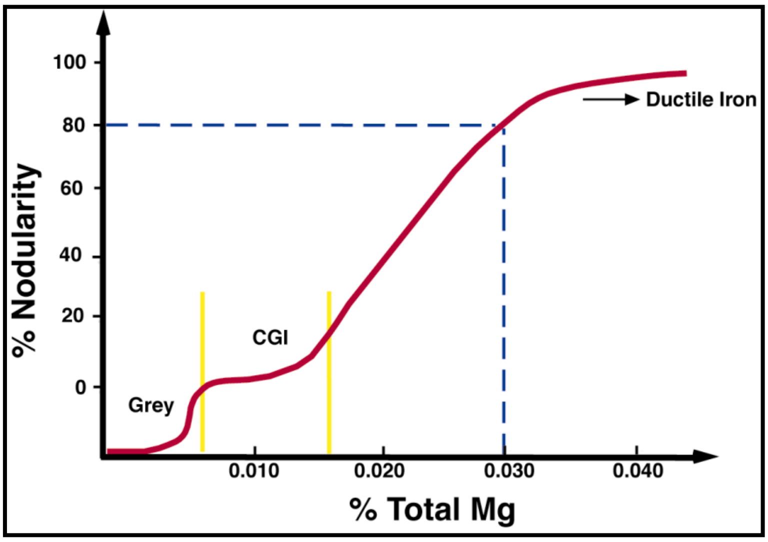


Figure 1: The stable CGI plateau exists over a range of approximately 0.006% magnesium and is separated from grey iron by an abrupt transition.

In practice, the usable Mg-range is much smaller than 0.006%. The first reason for this is that the active magnesium fades at a rate of approximately 0.001% Mg every five minutes. Therefore, the initial starting point of the iron must be sufficiently far away from the abrupt CGI-to-grey iron transition to ensure that the iron does not deteriorate to form flake-type graphite before the end-of-pouring. This inability to start casting at the 'left end' of the CGI plateau effectively narrows the useable Mg-range by approximately 0.002%. As the sulphur content increases, the Mg-fade rate becomes faster. Therefore, the production of high quality CGI requires that the base iron contain less than 0.020% sulphur. If the base iron sulphur content is higher than 0.020%, the Mg-fade rate can be too fast to enable the entire ladle to be cast before the iron fades below the flake graphite transition, causing grey iron formation in the castings. The presence of higher sulphur also increases the number of sulphide inclusions, increasing the risk of filling defects caused by clogged filters and casting defects caused by dross and inclusions. The demand for low sulphur is more important in CGI production than in the production of high quality ductile iron because ductile iron allows for the over-treatment of magnesium to compensate for the Mg-fade. However, Mg over-treatment cannot be relied upon in the production of CGI because the additional Mg will increase the nodularity beyond the 0-20% specification range and cause the formation of porosity defects.

For cost-effective CGI production, the most important consideration is that the starting point for casting must not be too close to the right end of the stable CGI plateau. As the magnesium content increases, the risk of porosity formation quickly increases. This is particularly true in modern castings such as cylinder blocks and four-valve cylinder heads, where complex geometries often require a maximum nodularity of less than 10% in order to produce porosity-free castings without resorting to expensive exothermic feeders. Foundries must always design gating and feeding systems to protect for the worst-case situation. For shrinkage defects in CGI, the worst-case is defined by the maximum nodularity and therefore, controlling the nodularity in a consistently low range allows gating systems to be optimised and feeding to be minimised, resulting in improved mould yield and reduced feeding cost. Series production experience with more than 40 different CGI cylinder blocks and heads has shown that porosity can be reliably avoided without the use of expensive feeders by simultaneously optimising the magnesium content, the Carbon Equivalent, the inoculation level and the pouring temperature. The on-line control of these parameters provides more cost-effective solution to porosity prevention than feeding.

While high nodularity is the main cause of casting defects in CGI production, it is also the main source of cost inefficiency throughout the entire CGI chain. First, high nodularity leads to porosity, increasing foundry scrap rates. These porosity defects are usually found during leakage testing after machining, resulting in the highest value of scrap, and impacting the productivity and capacity of both the foundry and machining facilities. In cylinder heads, high nodularity reduces heat transfer, leading to thermal fatigue failures during operation. In cylinder blocks, the reduction in thermal conductivity caused by high nodularity, together with increased elongation, increases the risk of galling and piston seizing and is the main source of failure in poorly controlled CGI cylinder blocks. Finally, high nodularity also results in increased tool wear during machining, requiring more frequent tool changes. It is clear that the best contribution that the foundry can make to the cost efficiency of the entire CGI production process is to deliver castings with consistently low nodularity.

Perhaps the most difficult consideration in CGI production is that the stable plateau is not stationary. If the active oxygen and/or sulphur contents are high, these elements consume the magnesium and shift the entire plateau to the right, requiring higher total magnesium values. Conversely, if the oxygen or sulphur levels are low, the CGI plateau shifts toward the left, resulting in the formation of higher nodularity at the same magnesium levels. At the same time, the active oxygen also influences the efficiency of the inoculation. Higher active oxygen contents create more nuclei, resulting in more graphite precipitation and favouring the formation of spheroidal graphite particles. This effectively shifts the stable CGI plateau upward. In contrast, lower active oxygen reduces the number of nuclei, shifting the stable CGI plateau downward, leading to inhomogeneous graphite distribution, and potentially, toward carbide formation. As a result of this sensitivity to the composition of the base iron, variations in the composition and cleanliness of the furnace charge materials, and variations in the holding time and temperature in the furnace, make it impossible to define a fixed chemistry specification for CGI. Due to the movement in the size and location of the stable CGI plateau, Compacted Graphite Iron cannot be reliably produced by controlling the chemistry of the liquid iron. For the reliable high volume production of CGI, foundries must adopt the philosophy that the chemistry is subordinate to the microstructure and therefore, the focus must be on controlling the microstructure.

Microstructure Sensitivity

Even though the transition from CGI-to-grey iron occurs over as little as 0.001% active magnesium at the low end of the stable CGI plateau, the natural Mg-fading does not immediately 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, 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 2, the result is that flake-type graphite first appears in CGI microstructures as isolated flake patches.

Figure 2: The formation of flake type graphite in CGI microstructures first appears as isolated flake patches. The flake patches can transition to a compacted morphology as the magnesium concentration increases due to segregation.

The sensitivity of CGI to magnesium is illustrated in Figure 3, which shows microstructures from a 25 mm diameter test bar produced from a one tonne ladle in a production foundry. The flake patch structure shown in Figure 3(a) was obtained as a result of insufficient Mg-addition in the base treatment. The good (<5% nodularity) CGI structure shown in Figure 3(b) was obtained after adding only additional 10 grams of magnesium (0.001% Mg) to the one tonne ladle by cored wire. No other changes were made to the ladle. The flake patch microstructure provides an ultimate tensile strength of approximately 300 MPa while the tensile strength of the fully compacted pearlitic CGI microstructure in Figure 3(b) would be more than 450 MPa in the test bar. This rapid transition from CGI to flake patches can occur either due to insufficient base treatment or due to Mg-fading during casting.

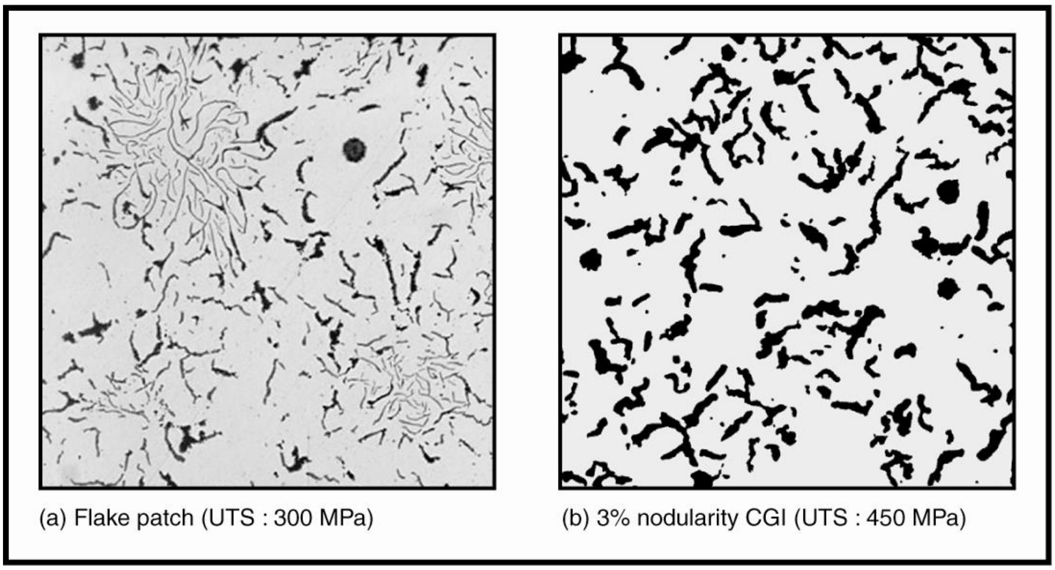


Figure 3: An addition of 0.001% magnesium is sufficient to convert a flake-patch microstructure into a high quality CGI microstructure.

The CGI microstructure is also sensitive to the addition of inoculant. Higher inoculation levels provide more nuclei, favouring the formation of nodular graphite. Therefore, factors such as furnace superheat, holding time, charge composition and type and amount of inoculant also influence the nodularity. The sensitivity to inoculation is illustrated in Figure 4, which shows microstructures from a 25 mm diameter test bar produced from a one tonne ladle in a production foundry. Figure 4(a) shows a high quality CGI microstructure (<5% nodularity) after base treatment, while Figure 4(b) shows a significant increase in the nodularity (>35% nodularity) after the addition of 0.8 kg of inoculant (0.08% inoculant) to the one tonne ladle by cored wire. No other changes were made to the ladle. In a complex casting such as a cylinder block or head, the good structure shown in Figure 4(a) will provide good castability while the higher nodularity structure shown in Figure 4(b) will almost certainly lead to porosity defects.

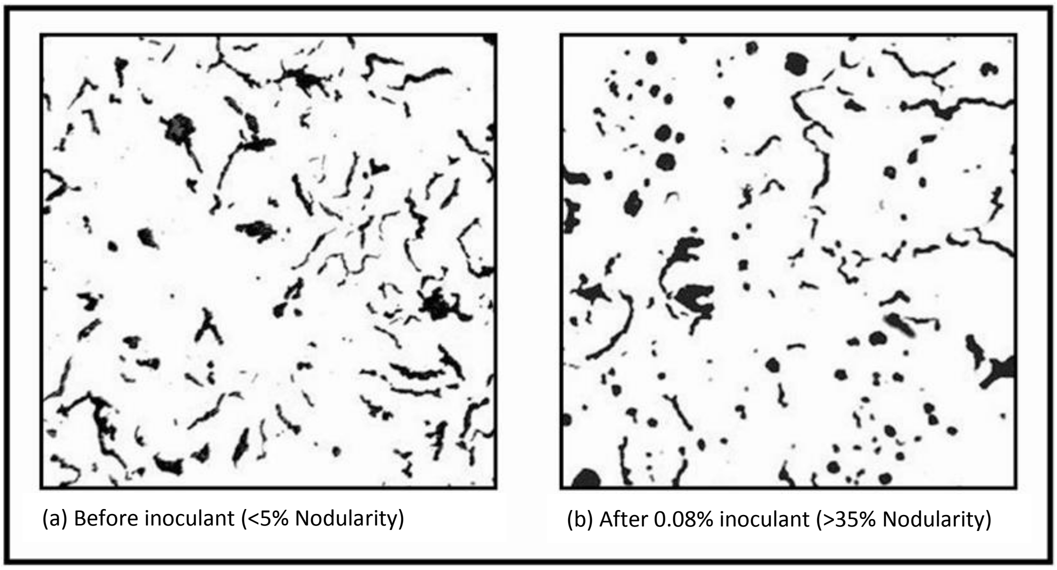


Figure 4: Inoculation causes the nodularity to increase, leading toward increased porosity risk.

Series Production Requirements

Unlike grey 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 5, the sensitivity of CGI to both magnesium (or 'Modification', indicating the combined effect of all graphite shape modifying elements, such as magnesium, rare earth metals, calcium, oxygen and sulphur) and inoculant means that CGI is stable within a four-sided window and not on a simple magnesium plateau, as suggested in Figure 1. The reliable high volume production of CGI therefore requires simultaneous control of the Modification and Inoculation, together with control of the Carbon Equivalent. As a result of the natural fading of both magnesium and inoculant, the process control technique must also ensure that the Modification and Inoculation levels remain within the stable CGI window from the start of casting until the end of casting in order to ensure that all castings are produced according to the microstructure specification.

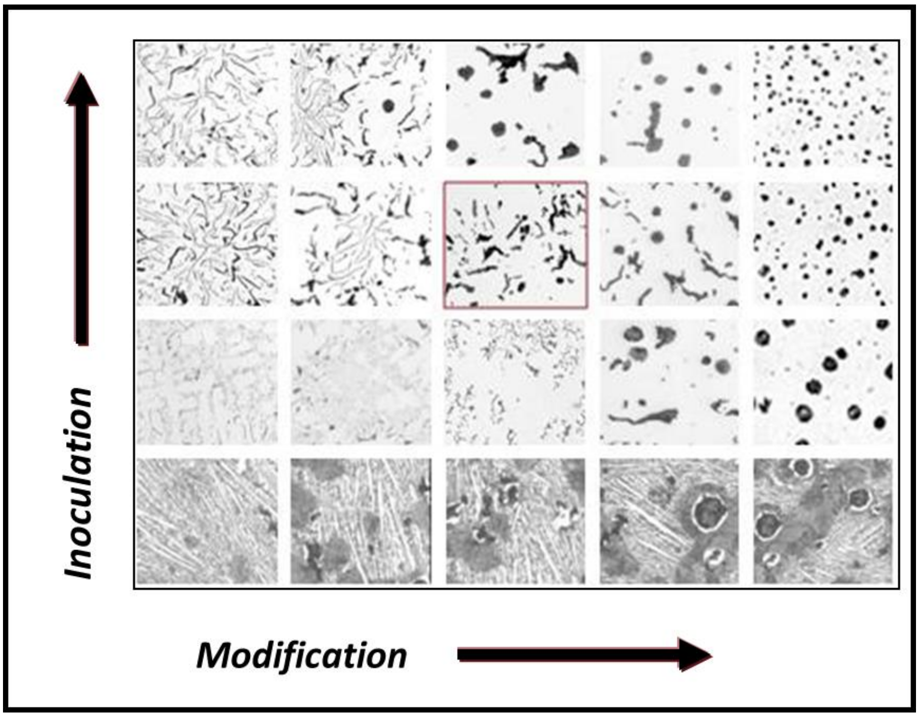


Figure 5: The sensitivity of Compacted Graphite Iron to both magnesium and inoculant means that CGI is stable within a four-sided window.

During high volume series production, the only certain way to eliminate process variation is to evaluate the solidification behaviour of the iron after the base treatment has been made. In this way, the variables that influence the recovery of the magnesium and inoculant, as illustrated in Figure 6, have exerted their influence and have been exhausted. After the base treatment, the iron is in its most stable state and corrective additions of magnesium and/or inoculant can be made to change the solidification behaviour of each ladle to the desired coordinates before the start of casting. A two-step measure-and-correct control strategy provides the opportunity to compensate for the variation that naturally occurs in the foundry process and to eliminate the risks associated with flake type graphite or porosity defects appearing in the final product.

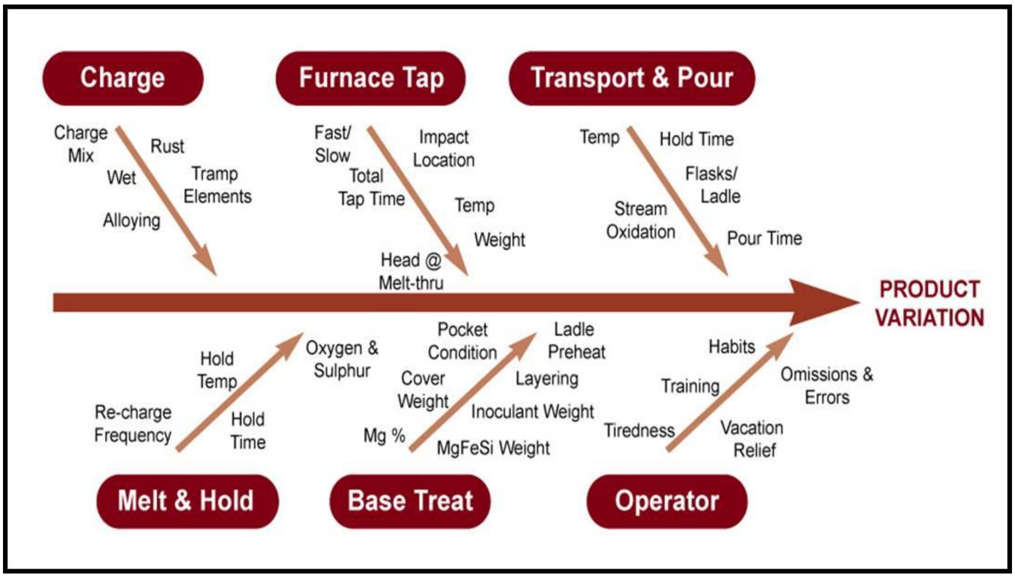


Figure 6: Most foundry variables are exhausted during the base treatment process. Measuring the iron after the base treatment allows corrective additions of magnesium and inoculant to be made before the start of casting to minimise process variation.

The SinterCast Process

The starting point of any process control technology must be an accurate measurement of the behaviour of the molten iron. In the case of Compacted Graphite Iron, the control measurement must simultaneously determine the Modification, the Inoculation and the Carbon Equivalent. In particular, the measurement must quantify the proximity of the Modification to the abrupt CGI-to-grey iron transition, and to predict the subsequent magnesium fading. With this accuracy and resolution, it is possible to prevent the formation of flake graphite and minimise the risk of porosity defects.

The SinterCast measurement of Modification, Inoculation and Carbon Equivalent is obtained by thermal analysis of the iron after the magnesium and inoculant base treatment reaction has been completed. The 200 gram thermal analysis sample is obtained in the patented SinterCast Sampling Cup by immersing the cup into the iron for less than three seconds. As shown in Figure 7, the SinterCast Sampling Cup is fabricated entirely from stamped and drawn steel sheet and has a predominantly spheroidal containment area. In comparison to conventional thermal analysis sand cups, the design of the thin-wall immersion sampler ensures a constant sample volume, prevents oxidation of the iron during pour-in filling, provides a more uniform solidification profile and yields a more accurate measurement of undercooling because of the elimination of chill-solidification. These design advantages are a key element of the accuracy of the thermal analysis: the CGI stable window is so small that it is essential that all measured differences in the thermal analysis can be attributed to differences in the solidification behaviour of the iron rather than to variation in the sampling conditions.

Figure 7: The SinterCast Sampling Cup provides more consistent sampling conditions and better resolution than conventional sand cups.

The thermal analysis is obtained from two high accuracy thermocouples that are contained within a protective tube in the Sampling Cup and are reused up to 250 times. One of the thermocouples is located in the centre of the Sampling Cup while the second is located at the bottom, to provide two different measurement conditions. The walls of the Sampling Cup are coated with a reactive coating that consumes active magnesium in order to simulate the fading of magnesium in the ladle. This patented Mg-fade simulation allows SinterCast to simultaneously measure the solidification behaviour at the start of casting and also to simulate the solidification behaviour at the end of casting. This measurement capability ensures that the Modification is high enough to prevent flake graphite formation, but also low enough to minimise the risk of porosity defects.

As shown in Figure 8, the process flow begins by obtaining the thermal analysis sample after the magnesium and inoculant base treatment reaction has been completed. Depending on the result of the thermal analysis, the wirefeeder is automatically instructed to add the necessary amount of additional magnesium and inoculant, in cored wire form. At the conclusion of wirefeeding, the ladle is available to begin casting. In most series production installations, the wirefeeder is located above the pouring car so that pouring can begin as soon as the wirefeeding is finished. The entire on-line measure-and-correct process requires approximately four minutes and is conducted in parallel with standard foundry activities such as deslagging and ladle transport without causing any delay in the moulding line. The final wirefeeding also extends the time available for pouring. In comparison to a process without a correction step, the fading clock must be started at the conclusion of base treatment. However, with the measure-and-correct process control strategy, the highest treatment point in the entire process is at the conclusion of the wirefeeding. Therefore, the fade clock is activated at the conclusion of the wire correction, effectively extending the time available for casting by approximately four minutes.

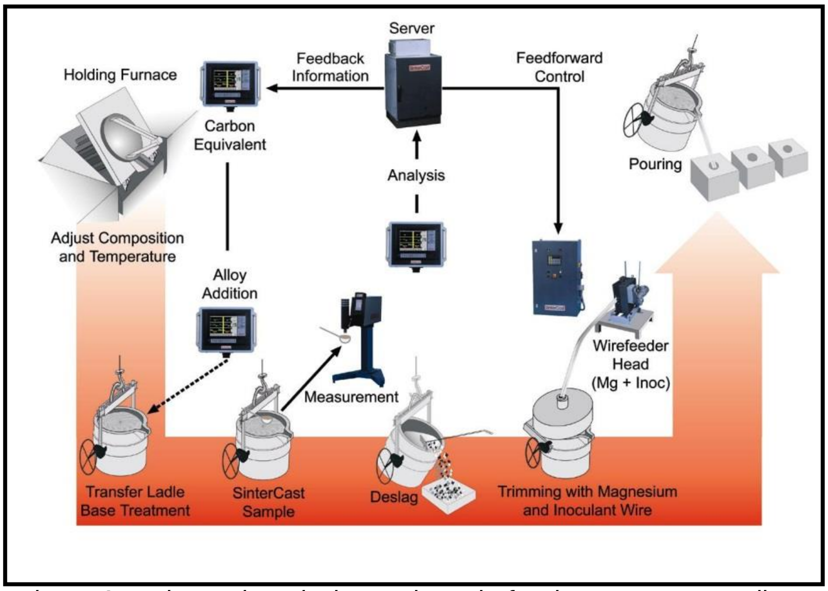


Figure 8: A thermal analysis conducted after base treatment allows for a precise feedforward correction of magnesium and inoculant to every ladle in order to minimise process variation. The SinterCast results are also used as feedback information to optimise the alloy additions in the base treatment of subsequent ladles.

As the thermal analysis sample solidifies, the cooling curves are analysed and the Modification, Inoculation and Carbon Equivalent results are presented as dimensionless indices. With reference to the microstructure 'chessboard' previously presented in Figure 5, the Modification and Inoculation indices are sufficient to fully define the solidification behaviour and potential microstructure of the base treated iron. As shown in Figure 9, 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 in order to ensure that the natural fading of magnesium and inoculant will not result in flake patches or carbides.

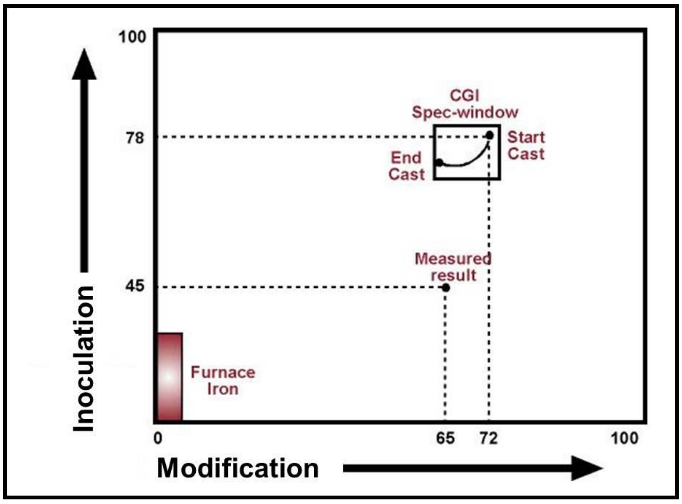


Figure 9: The thermal analysis result defines the precise coordinates of the base treated iron and provides a quantitative starting point for the feedforward correction of every ladle prior to casting.

The base iron being held in the melting or holding furnace has no magnesium and relatively little inoculating potency. During base treatment, the magnesium and inoculant additions first consume the active oxygen and sulphur and thereafter the iron ‘jumps’ upward on the chessboard. From this point, it only remains to add extra magnesium and inoculant by cored wire to move from the base treatment coordinates to the desired start-cast coordinates. In the example of Figure 9, an amount of magnesium cored wire equivalent to 7 Modification units is added to the melt followed by an inoculant wire addition corresponding to 33 Inoculant units. The correlation between index units and metres of cored wire is calibrated for each foundry depending on foundry-specific parameters such as the ladle size, geometry and temperature, and on product-specific parameters such as the solidification rate, shrinkage tendencies, and the time required to empty ladle. Series production experience shows that the average corrective addition of magnesium wire is approximately 30 grams of magnesium per tonne of iron, which influences control over the third and fourth decimal points in Mg%. Because the corrective additions of magnesium and inoculant are very small, and because the iron is stable after the base treatment, it is not necessary to deslag the ladle or to obtain a confirmation thermal analysis sample after the wirefeeding step.

The SinterCast process control system also calculates the optimum magnesium and inoculant additions for the base treatment of subsequent ladles. This calculation is based on the historical recovery results from previous ladles and automatic input of the sulphur content of the base iron and the actual ladle weight and temperature. In the case of base treatment by the sandwich method, the FeSiMg and inoculant addition amounts are displayed on a result screen to guide the operators in the ladle preparation. In the case of base treatment by cored wire, the SinterCast process control system automatically calculates and conducts the base treatment using a network-linked wirefeeder.

Despite the advance knowledge of the main parameters that determine the result of the base treatment, such as historical recovery, sulphur, weight and temperature, variation in the base treatment result is inevitable. Figure 10 shows actual series production data for the variation of base treatment Modification (‘MGM’) results during the production of heavy-duty CGI cylinder blocks from 281 ladles. The base treatment was conducted by the addition of cored wire into a 2,300 kg ladle based on statistically optimised algorithms including input from (i) SinterCast results from previous ladles; (ii) sulphur content of the base iron; (iii) ladle weight; and, (iv) ladle temperature. The Modification limits required to achieve the specified microstructure and soundness in the heavy-duty blocks range from 38 to 46, but the results shown in Figure 10(a) show that the actual base treatment result varies from 26 to 44 – more than two times wider than the permissible casting range. The actual Modification range after the correction step is shown in Figure 10(b), with all of the 281 production ladles falling within the specification range.

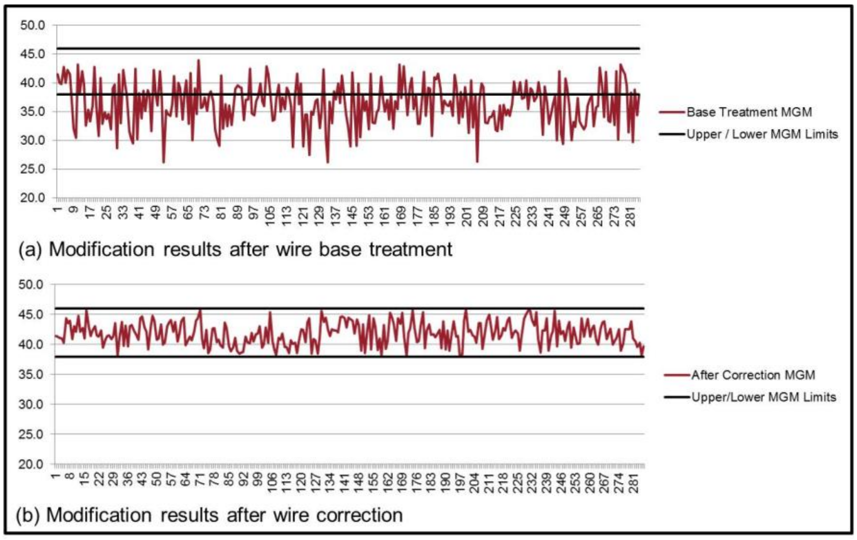


Figure 10: Series production results for Modification after base treatment and correction of 281 ladles show the need for a two-step casting process to minimise process variation.

In the SinterCast process, the strategy of the base treatment operation is to intentionally undertreat the iron in order to leave room for the wire correction step. The SinterCast control process can receive and correct a wide range of base treatment results, with the only requirement being that the iron is neither fully grey nor fully white, nor overtreated. If the target for the base treatment result shown in Figure 10(a) was shifted upward, in an attempt to directly reach the MGM casting range of 38 to 46, some of the ladles would be overtreated. These overtreated ladles would result in the formation of shrinkage defects, ultimately causing leakage scrap after machining. The requirement of the base treatment process must be that, even if all variables combine to produce the maximum base treatment recovery, the iron will still not be overtreated. The results presented in Figure 10 show that a two-step measure-and-correct process control strategy is required to achieve cost-effective high volume series production of complex CGI castings such as cylinder blocks and heads.

Summary

The requirements of a process control system are defined by the needs of the product. In the case of modern, complex Compacted Graphite Iron cylinder blocks and heads, the control system has multiple requirements. First, it must be able to maintain the nodularity as low as possible within the 0-20% nodularity range in order to minimise porosity defects. Second, it must ensure that flake graphite does not form before the end of casting, causing local weak spots and risking durability failures in the engines. Finally, the process control system must be able to accept wide variations in the base iron and the base treatment results, and to correct this prior to casting so the foundry can achieve cost-effective production with minimal internal and external scrap.

The satisfaction of these objectives requires an accurate measurement of the parameters that influence the microstructure and the casting soundness, specifically, the magnesium, inoculant and Carbon Equivalent. Thereafter, the reliable high volume production of Compacted Graphite Iron requires a control strategy that reacts to the thermal analysis result in order to eliminate process variation and to preclude operator error. The most effective way to satisfy these requirements is to evaluate the molten iron after the base treatment and thereafter to make corrective additions of magnesium and inoculant prior to casting. This on-line measure-and-correct control strategy ensures consistency at the moulding line, provides durable components for the end-users, and provides a foundation for cost-effective production in the foundry.

Head Office
SinterCast Ltd
Kingswick House
Kingswick Drive
Sunninghill Berkshire
SL5 7BH
United Kingdom
Tel: +46 150 794 40

Technical Centre
SinterCast AB (publ)
Kungsgatan 2
641 30 Katrineholm
Sweden
Tel: +46 150 794 40

USA
SinterCast Inc
1755 Park Street
Suite 200
Naperville
IL 60563
USA
Tel: +1 630 778 3466

China
SinterCast Trading (Beijing) Co., Ltd
Room 1131, 11/F, Block A, Gateway
No. 18 Xiaguangli
North Road East Third Ring
Chaoyang District, Beijing
China, 100027
Tel: +86 10 5923 1163

Korea
SinterCast Korea Co., Ltd
Rosavallcity No. 310
HyoJa-Ro 194, WanSan-Gu
Jeon Ju City, 560-900
South Korea
Tel: +82 10 9228 1764

SinterCast
— Supermetal CGI —

www.sintercast.com
info@sintercast.com