

Compacted Graphite Iron Production at Cifunsa Using a Process Control System

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ABSTRACT

Recent advances in foundry process control technology have made possible the reliable production of compacted graphite iron (CGI) in complex components such as passenger car engine blocks. During September 1996, the Cifunsa Foundry produced more than 2000 engine blocks in a make-like-production trial. The finished castings contained an average cylinder-bore-wall nodularity of 9% (specification range: 0–20%; target: 10%) and an average pearlite content of 70% (specification range: 65–85%; target: 70%). This pearlite range was chosen in order to maintain the Brinell hardness range for the existing design gray iron block. The average tensile strength from test bars obtained directly from the castings was 63,000 psi, which is approximately double that of the Grade 30 gray iron.

All castings were produced on the green sand molding line with conventional gray iron tooling and core processes. Melting operations required a similar discipline to ductile iron with regard to sulfur and carbon control. Although modifications were made to the gating design, the mold yield was slightly improved, compared to gray iron, while despruing was unchanged. Overall, the excellent castability and improved mechanical properties of CGI have prompted a redesign of the original gray iron block with a target of 16% weight reduction.

INTRODUCTION

Recent increasing demands for reduced weight and improved performance in the transportation sector have forced automotive engineers to investigate and adopt lightweight alternatives to conventional gray iron components. The excellent mechanical properties of compacted graphite iron (approximately 90% increase in tensile and fatigue strength and 35% increase in elastic modulus relative to gray iron) result in improved operating performance and weight reduction opportunities, while retaining all of the environmental and recyclability benefits of cast iron. In essence, compacted graphite iron (CGI) provides a new opportunity for the cast iron industry to withstand the pressures from alternative materials and maintain or even increase market share.

In general terms, high quality CGI is characterized by the predominance of individual vermicular or worm-shaped graphite particles on a metallographic plane of polish, with fewer than 20% of the particles in spheroidal form and no flake-type graphite. A typical example of a high-quality compacted graphite iron microstructure is provided in Fig. 1. This micrograph shows that, in comparison to conventional gray iron, compacted graphite particles are shorter, thicker and have rounded edges. Ultimately, it is this graphite morphology that gives CGI improved strength and toughness relative to gray iron while maintaining much of the thermal conductivity, castability and machinability of gray iron.

Although the advantageous graphite morphology of CGI has been known for more than four decades, its worldwide production and thus application have been limited by an inability to control the foundry process within the narrow range of CGI stability. In the absence of reliable foundry process control, design engineers have been prevented from including CGI in the most recent stages of the ongoing materials revolution. However, Cifunsa and SinterCast have recently joined forces to provide high-volume CGI production capability through the utilization of SinterCast's process control system (System 1000). The purpose of this paper is to describe the production process, which has now been implemented, and provide some practical experiences with the production of CGI cylinder block castings.

CGI PRODUCTION PROCESS

The transition behavior of graphite from flake to compacted and, ultimately, to a spheroidal morphology is well known as a function of the degree of magnesium modification and solidification rate. Practical experience shows that CGI is stable within a range of $\pm 0.003\%$ total magnesium. The amount of magnesium treatment alloy required to attain this rather narrow range, however, is difficult to determine, due to magnesium reaction with sulfur and oxygen in the base iron and normal variations in iron temperature, alloy recovery and fading time. To overcome these difficulties, a production strategy of base treatment, System 1000 measurement, magnesium and inoculant correction, and pouring has been adopted.¹

The base treatment practice employs standard Mg treatment alloys and inoculants common in the production of ductile irons.

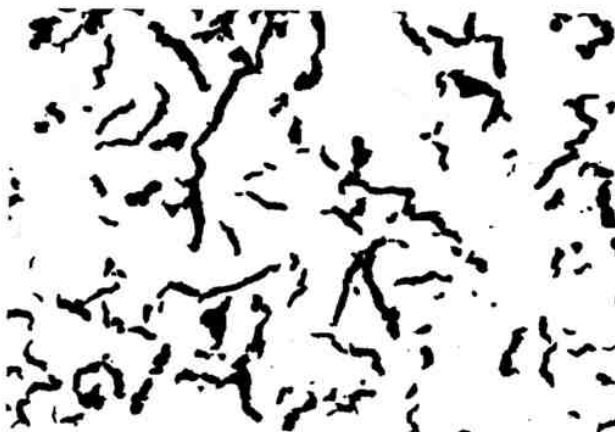


Fig. 1. High-quality compacted graphite iron contains individual worm-shaped graphite particles, less than 20% nodularity and no flake-type graphite (100X).

Titanium is not added. The amount of alloy required in subsequent ladles is determined from the modification and inoculation levels measured by System 1000 in the previous ladles. The process controller feeds this data back to the base treatment preparation area, where the alloys and sandwich cover material are added directly in the pouring ladle. The production strategy is to undertreat the base iron, in terms of magnesium modification and inoculation, by an amount that directly corresponds to the amount of variation in the base treatment recovery. This prevents over-nodularity in cases where the magnesium recovery is high, and simultaneously allows small and time-efficient corrections of magnesium and inoculant cored wire. The average corrective magnesium addition is 5 meters of wire (12 g Mg/meter), which, at a 40% recovery rate, corresponds to 0.002% Mg in the 1200-kg ladle.

The amount of alloy required to correct the melt to the desired modification and inoculation level is determined by thermal analysis. A small (200 g) but representative sample of the base-treated iron is obtained by immersing a patented probe into the liquid iron. As the iron sample solidifies, two thermocouples positioned in the probe, one in the center of the crucible and the other adjacent to the wall, provide a pair of cooling curves. The wall thermocouple cools relatively quickly and thus indicates solidification behavior in thin walls, while the center thermocouple simulates solidification in thicker walls.

Ultimately, the process controller evaluates the two cooling curves and independently determines the degree of modification and inoculation in the melt. The modification and inoculation are expressed as index values, which are then compared to the index values proven to provide the desired microstructure. The necessary wire additions are calculated from the difference between the measured and desired index values. The thermal analysis takes place over a period of approximately two minutes while the sample volume of liquid iron solidifies. During this time, standard operations, such as deslagging, quality control checks and ladle transportation, are performed and the ladle positioned in the correction station.

The structure of the correction station supports the dual wire feeder heads and positions the ladle for safe and accurate additions of magnesium and inoculant cored wires. When the thermal analysis is complete, the results are fed to the wire feeder and the prescribed amounts of magnesium and inoculant wire are injected into the melt, one after the other. The ladle is then removed from the correction station and immediately transported to the molding line for pouring. The average time from start-of-sampling to end-of-correction is less than three minutes. Figure 2 illustrates the process flow from base treatment preparation to pouring.

Production Experiences

The foundry began successful series production of prototype quantities of CGI engine blocks in September, 1996. The same foundry facilities have been used for production of gray, ductile and compacted graphite irons. The configuration and layout of the individual System 1000 process control modules were adapted to fit the existing foundry layout. With the exception of base iron preparation, the foundry processes have also remained the same.

Base iron preparation for CGI requires that the sulfur level be held to 0.022%, maximum, to accommodate the magnesium fading over the maximum possible casting time. Molding and core processes were not modified relative to gray iron. Although the gating was modified, the ultimate CGI mold yield was slightly better than that obtained with gray iron. Despruing is the same as in gray iron, with the gates breaking free of the casting during shakeout. Overall, the key area of focus has proved to be the melting operation, where a discipline equal to, or perhaps even better than, ductile iron is required.

Microstructure Experiences

The percent nodularity (number of spheroidal graphite particles divided by the total number of particles, times 100), evaluated by the chart comparison method² specified in the cylinder bore wall was

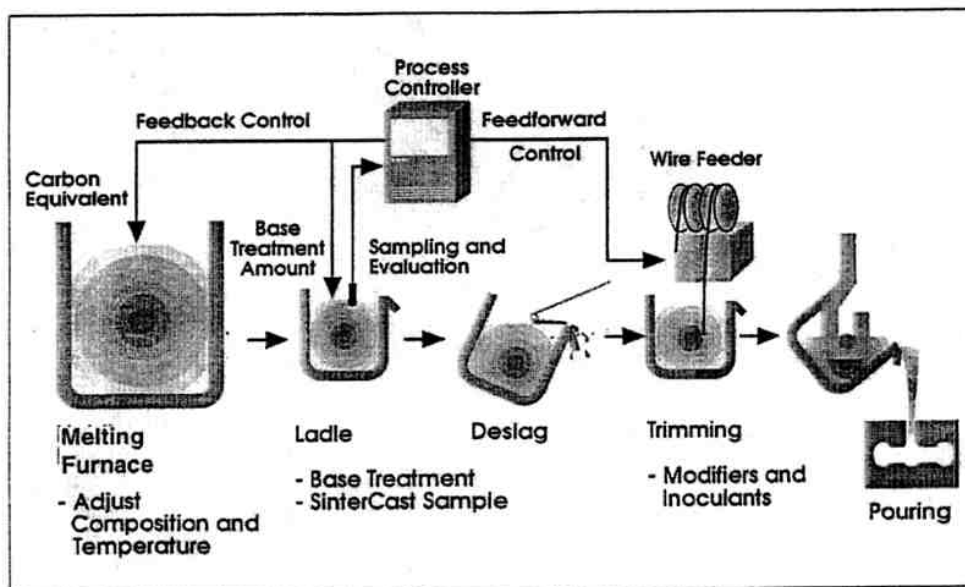


Fig. 2. Process control system is integrated directly into the foundry processing route.

0–20%, with a target nodularity of 10%. During four production runs in September 1996, in which more than 2000 engine blocks were produced, the actual percent nodularity averaged 9% and was held within a range of 3 and 16%.

Percent nodularity in other areas of the cylinder block were similar with the exception of very thin walls (3.75 mm) where higher nodularity (approximately 35%) results from the faster cooling rates. The pearlite content in the production blocks averaged 70%, which was the target value in the range of 65–80% pearlite. Carbides have not been a problem at any time. Prior to September 1996, several hundred prototype CGI castings were produced on two other green sand production lines that use desulfurized cupola iron for base metal preparation. Chromium content was as high as 0.018% without presence of cementite in the castings.

Dimensional Results

The compacted graphite iron cylinder blocks have been produced with the existing gray iron tooling and core packages. All specified dimensions, as shown in Table 1, are within tolerance.

Mechanical Properties Experiences

The mechanical properties of CGI are clearly superior to conventional gray iron. The tensile strength measured in the casting is approximately double that of gray iron, averaging 63,000 psi. Tensile strength measured in separately cast tensile bars poured from each ladle cast has averaged 75,000 psi. The higher strength on the test bars has been attributed to the increased cooling rate and, therefore, slightly higher nodularity. Both ASTM A-5346-80 "Y" blocks and ASTM A-4876 bars have been produced with no statistical difference in the measured strengths. Presently, the ASTM A-48-76 bars are poured for their ease of handling. Based on the improved mechanical properties, an initial redesign of the four-cylinder engine block has identified the potential for a 16% weight reduction.

The Brinell hardness of the CGI castings was targeted to the range previously specified for gray iron castings. This was accomplished by lowering the pearlite content in the cylinder walls from 100% in gray iron to 70% in CGI. The pearlite content is controlled through the addition of pearlite stabilizers to the base iron. Prototype castings have shown that it is equally possible to achieve a 100% pearlitic matrix, as may be specified, for example, for some diesel applications.

The consistency of the hardness over the length of the cylinder bore wall is summarized in Table 2, together with hardness data from the head face. These data were obtained from test bars sectioned from

the Siamese junction between the two central cylinder bores. Hardness evaluations were made directly on the bore wall at the top, middle and bottom locations and also on the main bearing saddle, directly below the bore wall. The total length from the head face to the bearing saddle was approximately 200 mm. Separate studies have shown that the bore wall pearlite content and Brinell hardness are not sensitive to variations in shakeout time. Uniform hardness has been obtained with shakeout times varying from 45 minutes to 43 hours (over weekend).

More than 2000 CGI engine blocks have been successfully machined on the standard gray iron transfer line using existing cutting materials and parameters. Results have been positive, although different (yet conventional) tool materials were required for the final boring operation.

SUMMARY

After installation of the SinterCast System 1000 and an initial testing and calibration period, short-run production series of CGI engine blocks have been successfully conducted to demonstrate production readiness. More than 2000 engine blocks were produced in four separate production runs during September 1996.

Microstructure specifications were met with an average cylinder bore wall nodularity of 9% and an average pearlite content of 70%. Brinell hardness values were consistent throughout the length of the bore wall and did not vary notably for shakeout times varying from 45 minutes to 43 hours. Although increased discipline was required in the melting operation, tooling, molding, core processes, despruing and finishing were unchanged relative to gray iron.

Test bars obtained from the cylinder block castings provided an average tensile strength of 63,000 psi. Separately cast test bars provided an average tensile strength of 75,000 and 35% increase in elastic modulus relative to gray iron. Based on this increase in strength, an initial redesign of a four-cylinder engine block has identified the potential for a 16% weight reduction. Similar efforts will be applied to other automotive components in the near future.

REFERENCES

1. S. Dawson: "The SinterCast Process and Compacted Graphite Iron," *BCIRA International Conference on Latest and Best in Melting and Metal Treatment in Ferrous and Non-Ferrous Foundries*, 19-21 Apr, 1994, Coventry England, pp 28.1-28.6.
2. SinterCast CGI Microstructure Evaluation Charts. Nodularity Range: 0–50%. SinterCast Inc., 1996.

Table 1.
Dimensional Results of a Four-Cylinder Engine Block
Produced With Common Tooling

Dimension	Specification		Gray Iron (mm)	CGI (mm)
	Nominal (mm)	Tolerance (mm)		
Deck Width	140.00	+2.0, -2.0	140.18	139.92
Base Width	234.60	+2.0, -2.0	234.06	234.24
Base Length	395.00	+6.0, -2.0	402.66	402.50
Total Height	215.30	+6.0, -2.0	222.10	222.40
Dia Bore 1	84.80	+1.0, -6.0	79.62	79.60
Dia Bore 2	84.80	+1.0, -6.0	79.64	79.64
Dia Bore 3	84.80	+1.0, -6.0	79.50	79.57
Dia Bore 4	84.80	+1.0, -6.0	79.52	79.52

Table 2.
Brinell Hardness Data From Top Deck and Length of
Cylinder Wall Between Two Central Bores

Sample Number	Head Face BHN	Cylinder Bore Wall (BHN)			Bearing Saddle	Mid-Wall %
		Top	Middle	Bottom		
1	187	174	174	174	161	65
2	223	207	207	207	202	70
3	223	211	211	207	207	75
4	229	215	215	215	207	80