Production Experience With Compacted Graphite Iron Automotive Components

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ABSTRACT
In response to OEM demands for more durable cylinder block and head materials, Tupy has developed process capability for series production of compacted graphite iron (CGI). Prototype CGI block and head castings have provided 90% increase in tensile strength and 40% increase in elastic modulus relative to the production gray iron castings. The present paper provides an overview of the properties of CGI and the process control requirements for the production of low nodularity CGI microstructures without the use of titanium and without the risk of flake graphite formation. Product results are provided for fourteen different automotive castings.

INTRODUCTION
Emissions legislation and the demand for higher performance from smaller engines have together driven the development of diesel engine technology over the past ten years. One of the most significant of these developments has been the advent of common rail and unit injector fuel management and delivery systems, which allow for higher cylinder pressures in direct injection diesel engines. The higher peak firing pressures provide more efficient combustion, improved performance, reduced emissions and quieter engine operation. At the same time, the increased firing pressures place increased mechanical loads on the main bearing region of the cylinder block, potentially resulting in premature fatigue failures. The irreversible trend toward higher peak firing pressures have prompted engine designers to seek stronger materials in order to meet their durability targets without increasing the size or weight of their engines.

Given that new engine programs are typically intended to last for approximately three vehicle generations, the chosen engine materials not only need to satisfy current design criteria but must also provide the potential for future performance improvements without changing the overall block architecture. With at least 75% increase in ultimate tensile strength, 35-40% increase in elastic modulus and approximately double the fatigue strength of gray cast iron, compacted graphite iron is ideally suited to meet the current and future requirements of diesel engine design. In response to production enquiries from OEM's in Europe, Asia and the Americas, Tupy Fundições has developed the capability for volume production of cylinder blocks and heads in compacted graphite iron. Based on experience from the production of CGI exhaust manifolds since 1992, Tupy has implemented the SinterCast process control technology to meet the demands of increased production volume, increased part complexity and a narrower microstructure specification. This paper describes the control technology and the experiences with prototype production.

COMPACTED GRAPHITE IRON
As shown in Figure 1, the graphite particles in compacted graphite iron appear as individual 'worm-shaped' or vermicular particles. The particles are elongated and randomly oriented as in gray iron, however they are shorter and thicker, and have rounded edges. While the compacted graphite particles appear worm-shaped when viewed in two dimensions, deep-etched scanning electron micrographs (Figure 2) show that the individual 'worms' are connected to their nearest neighbors within the eutectic cell. The complex coral-like graphite morphology, together with the rounded edges and irregular bumpy surfaces of the graphite particles, results in strong adhesion between the graphite and the iron matrix. The compacted graphite morphology inhibits crack initiation and growth and is the source of the improved mechanical properties relative to gray iron.

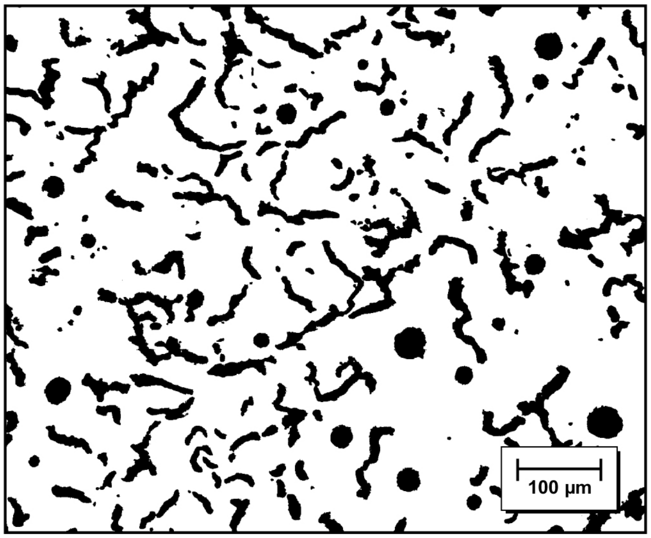

Figure 1: CGI microstructure containing 10% nodularity.

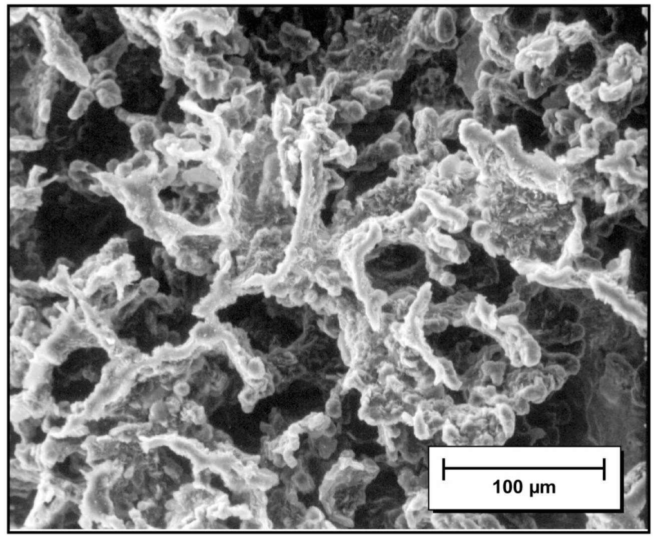

Figure 2: Deep-etched SEM micrographs show the complex coral-like graphite in three-dimensions.

Compacted graphite iron invariably includes some nodular (spheroidal) graphite particles. As the nodularity increases, the strength and stiffness also increase, but only at the expense of castability, machinability and thermal conductivity. The microstructure specification must therefore be chosen depending on both the production and performance requirements of the product. For example, the production of exhaust manifolds at Tupy since 1992 was specified with up to 50% nodularity. For manifolds, the higher nodularity provides increased strength for supporting the exhaust system and also facilitates the flow of exhaust heat into the catalyst to achieve early light-off. The higher nodularity benefits the product without increasing the incidence of casting defects. In another example, Daimler/Chrysler [1] have shown that the ductility provided by up to 50% nodularity microstructures reduces cracking defects in bedplates. In this case the higher nodularity is permissible because machining is limited to milling and short-hole drilling and the product is not thermally loaded.

In contrast to exhaust manifolds and bedplates, the geometric complexity and shrinkage tendencies of cylinder blocks and heads, combined with severe thermal and mechanical loading and extensive machining require microstructure control within the range of 0-20% nodularity. Combined with a 20% maximum nodularity for all performance-critical sections of the block and head castings, it is also imperative that the microstructure not contain any flake graphite. The presence of even a small amount of flake graphite results in an immediate 20-30% decrease in strength and stiffness promoting premature field failures. For the reliable series production of CGI cylinder blocks and heads, the foundry process must therefore sustain the balance between the onset of flake graphite formation on the one hand, and the optimization of castability, machinability and thermal conductivity on the other hand. This challenge defined the requirements of the process control system.

Historically, the production of CGI exhaust manifolds at Tupy was facilitated by the addition of 0.10-0.15% titanium. The addition of titanium 'poisons' the graphite growth thus allowing safe compacted graphite iron production at higher magnesium contents. The higher magnesium ensures that graphite flakes will not grow while the titanium suppresses the growth of nodular graphite. While the titanium process can be used for the production of exhaust manifolds, the resulting formation of hard titanium carbonitride inclusions increases abrasive wear and cannot be tolerated in machining-intensive components such as cylinder blocks and heads. The influence of the titanium on the machinability of CGI becomes evident when it is realized that, for each 0.10% titanium addition, more than 1000 titanium carbonitride inclusions will be present in each square millimeter of machined surface area. As shown in Figure 3 [2], even a small increase in the tramp titanium content dramatically reduces tool life during continuous cutting operations such as cylinder boring. It was therefore decided that the existing titanium-based CGI production process could not be used for cylinder blocks and heads.

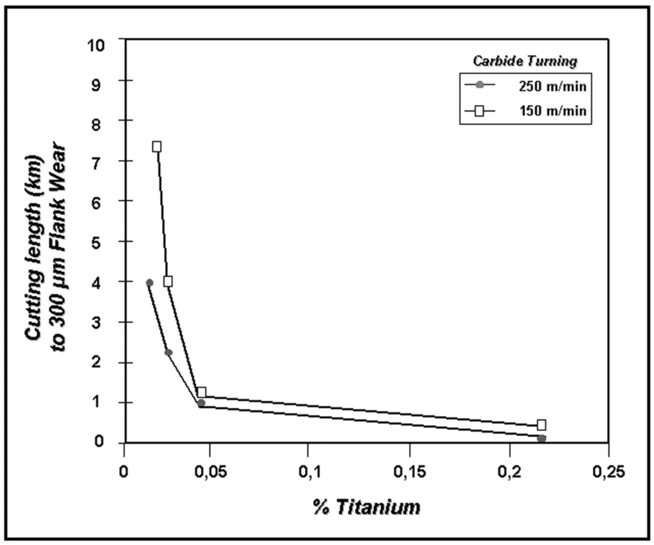

***Figure 3:** The addition of titanium dramatically reduces the tool life of compacted graphite iron during carbide turning.*

Compacted graphite iron can be produced with varying pearlite contents to suit the intended application. Exhaust manifolds require more than 95% ferrite to prevent high temperature growth. In contrast, cylinder blocks and heads are typically produced with a predominantly pearlitic matrix to maximize strength and stiffness. Compacted graphite iron may be specified with 60-80% pearlite to provide approximately the same hardness range (BHN 190-225) as conventional gray cast iron. However, fully pearlitic specifications result in less product variation and provide superior mechanical properties. The mechanical and physical properties of CGI with 70% and 100% pearlite are summarized in Table 1. The data are representative of a microstructure with 10% nodularity, as obtained from separately cast 25 mm diameter arbitration bars.

Table 1
Mechanical and Physical Properties of 10% Nodularity CGI.

Property	Test Method	Temp (ºC)	70% Pearlite	100% Pearlite
Ultimate Tensile Strength (MPa)	ASTM E 8M (25ºC) ASTM E 21 (100ºC & 300ºC)	25 100 300	420 415 375	450 430 410
0.2% Yield Strength (MPa)	ASTM E 8M (25ºC) ASTM E21 (100ºC & 300ºC)	25 100 300	315 295 284	370 335 320
Elastic Modulus (GPa)	ASTM E 8M (25ºC) ASTM E 21 (100ºC & 300ºC)	25 100 300	145 140 130	145 140 130
Elongation (%)	ASTM E 8M (25ºC) ASTM E21 (100ºC & 300ºC)	25 100 300	1.5 1.5 1.0	1.0 1.0 1.0
Unnotched Fatigue Limit (MPa)	Rotating-bending 3000 rpm	25 100 300	195 185 165	210 190 175
Endurance Ratio	Fatigue Limit/UTS	25 100 300	0.46 0.45 0.44	0.44 0.44 0.43
Thermal Conductivity (W/mºC)	Comparative axial heat flow ASTM E 1225	25 100 300	37 37 36	36 36 35
Thermal Expansion Coefficient (µm/mºC)	Pushrod dilatometry DIN 51 045	25 100 300	11.0 11.5 12.0	11.0 11.5 12.0
Poisson's Ratio	ASTM E 132	25 100 300	0.26 0.26 0.27	0.26 0.26 0.27
0.2% Compressive Yield (MPa)	ASTM E 9 (medium length)	25 400	400 300	430 370
Density (g/cc)	Displacement (750x25x25) mm	25	7.0-7.1	7.0-7.1
Brinell Hardness (BHN)	10 mm diameter, 3000 kg load	25	190-225	207-255

PROCESS CONTROL

The control emphasis for the production of CGI engine blocks and heads was placed on the ability to achieve a low nodularity microstructure without allowing the formation of flake graphite. The two key elements in the successful process control were the ability to accurately measure the behavior of the molten iron and to respond to the measured result before the castings were produced. A two-step measure-and-correct production strategy was therefore adopted.

The process control is based on the thermal analysis of the molten iron after the initial base treatment with magnesium and inoculant ferroalloys. By evaluating the iron after the base treatment, the thermal analysis result indicates the combined effect of all process variations including charge materials, melting and holding practices, furnace tapping technique, differences in operator habit and the recovery of magnesium and inoculant. Depending on the result of the thermal analysis, corrective additions of magnesium and/or inoculant are added before the castings are produced. To facilitate the two-step strategy, the amount of magnesium and inoculant added in the sandwich base treatment are chosen to intentionally undertreat the iron such that even if all variables combined to result in the highest possible recovery, the base treatment would only arrive at the desired start-cast composition.

The 200 gram thermal analysis sample is obtained by immersing the sampling cup shown in Figure 4 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 approach 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. In order to operate as close as possible to the border between CGI and gray iron, the inner walls of the sampling cup are treated with a reactive coating that consumes active magnesium. The thermal convection currents that develop within the spheroidally shaped sampling cup, rinse the molten iron along the coated walls and cause the reacted metal to collect in a flow-separated region at the base of the cup. The reactive wall coating is designed such that the active magnesium content in the flow-separated region at the bottom of the cup will be approximately 0.003% less than that in the center of the sample. This amount of active magnesium consumption is approximately the same as the amount of fade experienced in fifteen minutes.

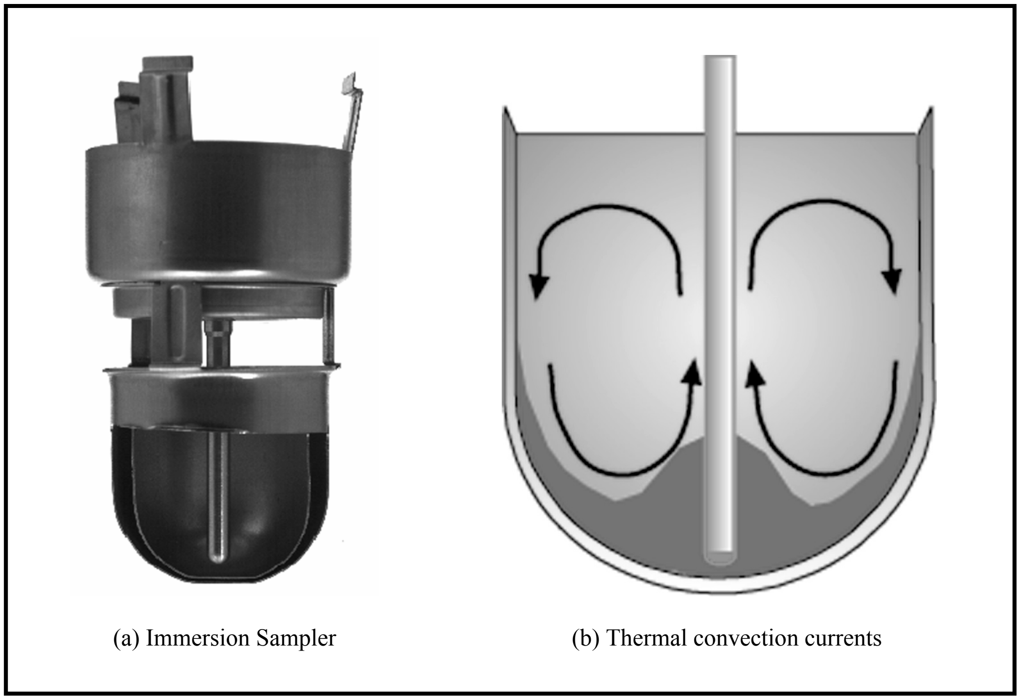

Figure 4:** **The immersion-type sampling probe prevents oxidation of the sampled iron and provides thermal equilibrium between the vessel and the molten iron.

The sampling cup contains two thermocouples in a closed-end protective tube. During production, the thermocouples are extracted and re-used up to 200 times. One of the thermocouples is located at the bottom of the protective tube while the other is located in the thermal center of the sample. The etched cross section of a used sampling cup provided in Figure 5 shows the protective thermocouple tube and the distinct difference between the solidification behavior of the bulk iron and that of the flow-separated region. The loss of 0.003% active magnesium has resulted in the formation of undercooled D-type flake graphite and, due to the reduced diffusion distances, a ferritic matrix. The formation of flake graphite during the solidification in the sampling cup is measurable from the cooling curve of the bottom thermocouple prior to the eutectic minimum. In the simplest sense, the center thermocouple indicates the behavior of the iron at the start of casting while the bottom thermocouple simulates the solidification behavior at the end of casting. The two results are interpolated by the process controller to determine the necessary amount of corrective magnesium and inoculant cored wire additions prior to casting in order to safely prevent flake graphite formation while providing a low-nodularity microstructure for optimal castability.

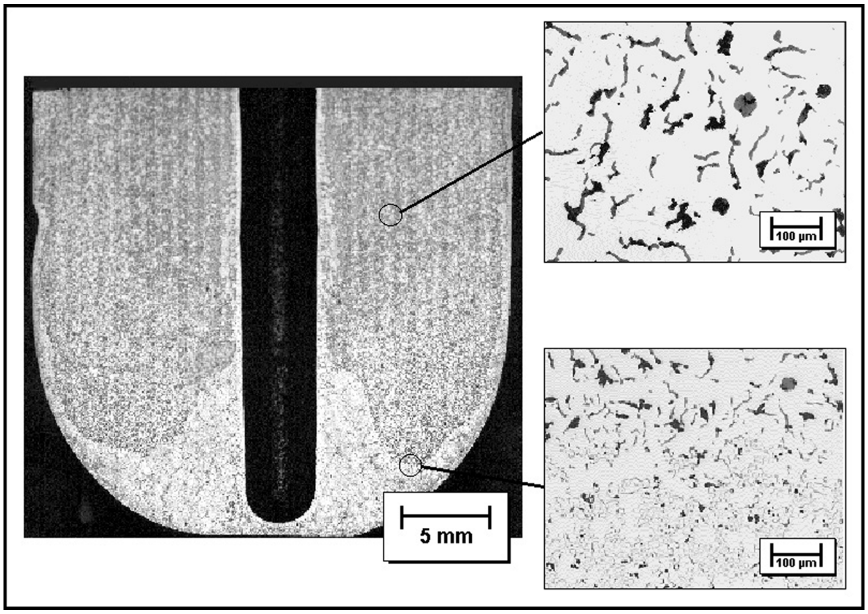

Figure 5: The reactive wall coating consumes magnesium to simulate-fading in the bottom of the SinterCast probe.

To optimize the efficiency of the foundry process, the thermal analysis results for the measured Carbon Equivalent and for dimensionless Modification and Inoculation Index values ranging from 0 to 100 are displayed in real-time as histogram run-charts. Depending on the trend in the run charts, the amount of magnesium and/or inoculant added to subsequent base treatments is changed in accordance with the Standard Operating Procedure to improve process efficiency. The results of each thermal analysis are compiled in detailed Production Summary Reports together with other process data including the amounts of magnesium and inoculant wire fed into each ladle and the sampling and correction times. The reports are automatically generated by the control system and downloaded as Excel® files to be incorporated into the foundry's QS 9000 Quality System to satisfy traceability requirements.

INSTALLATION AND PROCESS FLOW

Based on the initial experiences of prototype block and head production from 1997 to 1999 using portable process control equipment, a full installation of the SinterCast System 2000 was made in the Joinville foundry during March 2000. The installation phase, which lasted for only two weeks, included hardware mounting, system configuration, software calibration, and training of operators and maintenance personnel. The hardware and the overall CGI process flow have been fully integrated into the normal foundry operations and do not interfere with the parallel production of other types of iron.

The hardware installation is comprised of a Sampling Module for mounting the sampling cup and an Operator Control Module to display ladle-by-ladle Carbon Equivalent, Modification and Inoculation results as run-chart histograms. The Operator Control Module also includes a push-button control panel to allow the operator to select the product to be produced, and to interact with the system as required. The Sampling Module and Operator Control Module are mounted on a steel pallet together with a power supply. The power supply filters the mains power and provides 10-15 minutes of back-up power in the event of mains failure to allow a controlled shut-down of the system. The pallet-mounted items are networked-linked to a twin-strand wirefeeder. This electronic link precludes the need for operators to recall results and manually enter the magnesium and inoculant wire lengths into the wirefeeder control cabinet. Together, the pallet-mounted items and the wirefeeder can easily be moved to different production lines by forklift.

The installed System 2000 included a second Sampling Module to allow for anticipated increases in CGI production volume. Each Sampling Module is capable of processing one ladle every 3.5 minutes and, because samples can be processed in parallel, the system allows for production rates that exceed the line capacity. The system also included a laptop PC Customer Access Terminal that allows supervisor-level to access the software menus to create or revise product calibrations, to customize the system, or to download Production Summary Reports.

In the Joinville foundry the CGI production process begins with the melting of a low-sulfur base iron in 18 tonne coreless induction furnaces. Sulfur is maintained below 0.020% using 2 tonne charges containing steel, CGI and/or ductile iron returns and pig iron. Carbon raiser and silicon carbide alloys are used to control the Carbon Equivalent in the furnaces to 4.40-4.50%. The CGI base treatment is performed by the sandwich treatment method, tapping directly from the melting furnaces. The treatment size has been varied between 800-1100kg depending on the size and number of castings poured. Standard 5% MgFeSi and Ce Mischmetal alloys are used in the base treatment process. The MgFeSi alloy amounts for CGI production are much less than those used in ductile iron treatments thus allowing the base treatment to be performed directly in the pouring ladles without excessive splash or loss of Mg recovery. An alloy pocket constructed in the pouring ladles also helps to maintain a consistent and acceptable Mg recovery. Base treatment in the pouring ladles has reduced iron temperature losses and Mg-oxidation due to reladling and has provided a sound basis for wirefeeding corrections following thermal analysis.

Following base treatment, the thermal analysis sample is obtained by immersing the sampling cup in a representative sample of iron spooned from the ladle and the iron is transported to the wirefeeder correction station positioned near the desired molding line. While the sample solidifies, the ladle is deslagged and positioned beneath the splash lid and fume extractor for wirefeeding. The thermal analysis results for Carbon Equivalent, Modification and Inoculation are automatically compared to the calibrated values for the casting to be produced and corrective additions of Mg and inoculant cored wire are automatically determined. The operator is prompted with a simple Green/Red button selection to activate the wirefeeding. After wirefeeding the ladle is transferred directly to the molding line to begin casting. Deslagging and further sampling are not required. Prototype castings have been produced in the Joinville foundry on both the Künkel Wagner molding line (100 molds/hour, 1100x850x350mm flask size) and the BMD molding line (75 molds/hour, 1100x850x350mm flask size).

Following the initial experiences in the Joinville foundry, the System 2000 has been successfully transported to and operated in the recently acquired Mauá Foundry in São Paulo. A similar CGI production process has been established using an 8 tonne induction furnace and a 16 tonne arc furnace for base iron preparation and pouring on the Jolt/Squeeze molding line (1473x1143x460mm flask size). Production plans have been formalised to construct a high volume CGI series production line for up to 350,000 flasks per year in the Mauá facility.

PROTOTYPE BLOCK AND HEAD RESULTS

To date, a total of fourteen different castings have been produced in CGI for process validation and OEM customer evaluation. With the exception of one bedplate casting, which had a 0-50% nodularity specification, all of the CGI castings were produced with a 0-20% nodularity specification. Each of the fourteen parts were cast in the existing gray iron patterns without incidence of internal porosity or surface shrinkage defects. The various CGI prototype parts are listed in Table 2.

Table 2
Summary of prototype castings produced in compacted graphite iron.

Component	Detail	Tupy Part Number	Casting Weight (kg)	Parts/ Mold	Mold Weight (kg)
Cylinder Head	6,0 liter I6	25.04.006	55,1	2	158,2
Cylinder Head	5,9 liter I6	81.04.013	91,2	2	243,5
Cylinder Head	7,3 liter V8	81.09.004	57,5	2	135
Cylinder Block	I4	81.12.001	49,3	4	244
Cylinder Block	5,9 liter I6	81.04.010	152,6	1	195
Cylinder Head	5,9 liter I6	81.04.005	70	1	102
Cylinder Block	4.1 liter I4	25.01.013	123	1	165
Bearing Cap	4,1 liter I4	20.20.017	12,8	7	141
Timing Cover	4,1 liter I4	-		1	
Bedplate	I4	80.46.004	36	6	270
Cylinder Block	1 liter I4	25.07.003	37	4	213
Cylinder Block	12.0 liter I6	BR460	392	1	430
Cylinder Head	12.0 liter ind.	25.04.014	16	3	67
Cylinder Block	7.3 liter V8	81.09.003	150	1	207

Depending on the needs of the product, the castings were produced with different pearlite contents according to ASTM A842-85 grades 300 to 450. All castings were produced from a similar base iron chemistry containing approximately 0.45% manganese. Depending on the specification of the casting, the pearlitic grades were stabilized by ladle additions of metallic copper and tin to achieve 0.45-0.60% Cu and 0.05-0.08% Sn. These additions were sufficient to provide 70-90% pearlitic matrices with 190-240 BHN. For the specific case of the ferritic-pearlitic 12.0 liter individual cylinder head and the bedplate, the base iron copper and tin contents of 0.004% and 0.006% respectively were sufficient to satisfy the 30-50% pearlite specification. As shown in Figure 6, both tensile strength and Brinell hardness vary linearly with pearlite content. This linear behavior has also been shown to exist in specimens obtained from test bars [3].

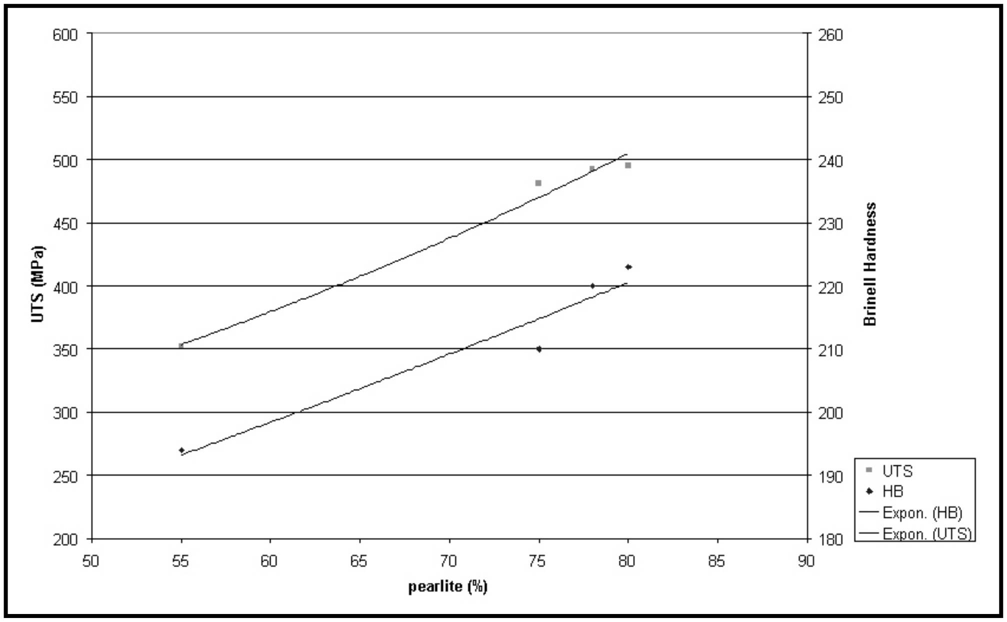

Figure 6: Ultimate tensile strength and hardness as a function of pearlite content.

The ultimate tensile and yield strengths for the CGI castings and the corresponding tensile strengths for gray iron parts produced in the same molds are shown in Figures 7 and 8. On average, the pearlitic parts shown in Figure 7 provide a 90% increase in tensile strength relative to their gray iron counterparts. All tensile results were obtained from test bars sectioned directly from the same locations in the gray iron and CGI castings.

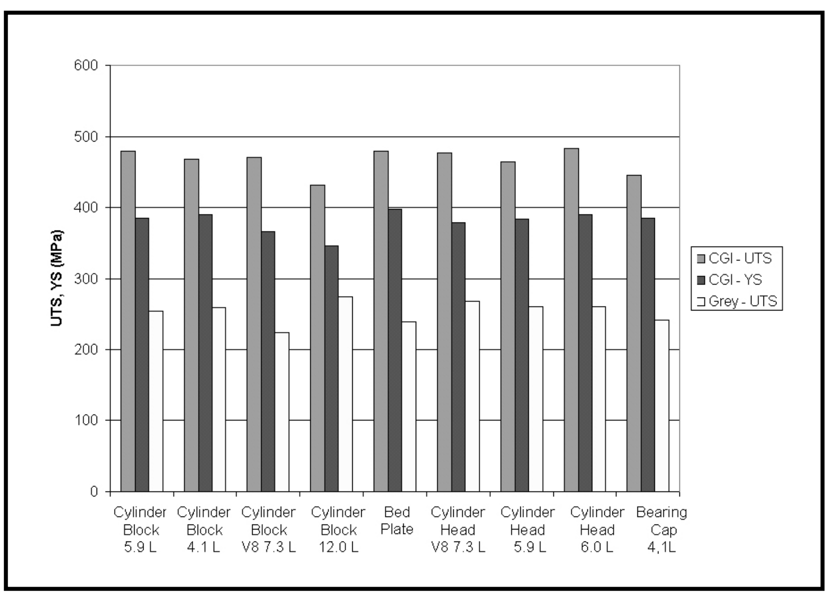

Figure 7: Ultimate tensile strength for pearlitic parts ASTM Grades 400-450.

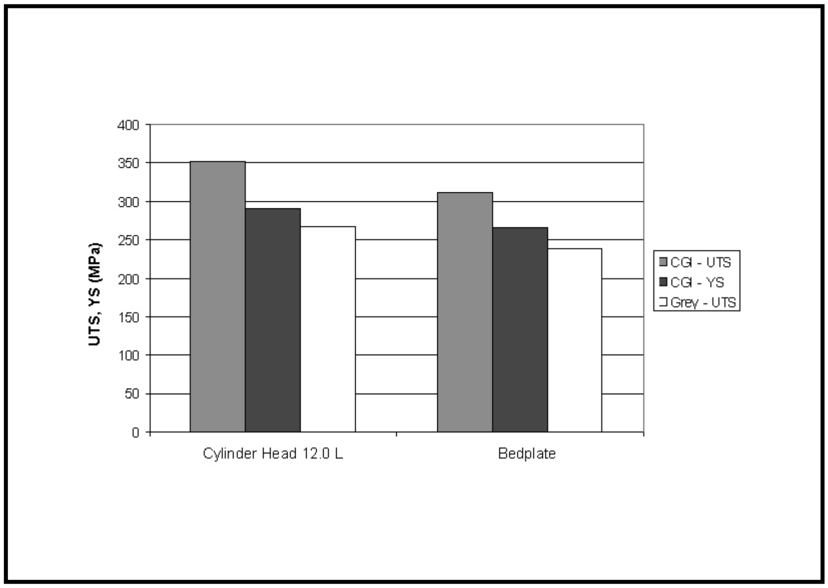

Figure 8: ***Ultimate tensile strength for ferritic-pearlitic parts ASTM Grade 300-350.***

Representative values of the elastic modulus of CGI were obtained for specimens sectioned from the 12 liter engine block and from Y-blocks and cylindrical test bars. The data shown in Figure 9 indicate that the elastic modulus is relatively insensitive to changes in section thickness or cooling rate. Typical elastic modulus values for CGI are approximately 150 GPa while the elastic modulus for gray iron samples extracted from the same region of the casting is approximately 100-110 GPa.

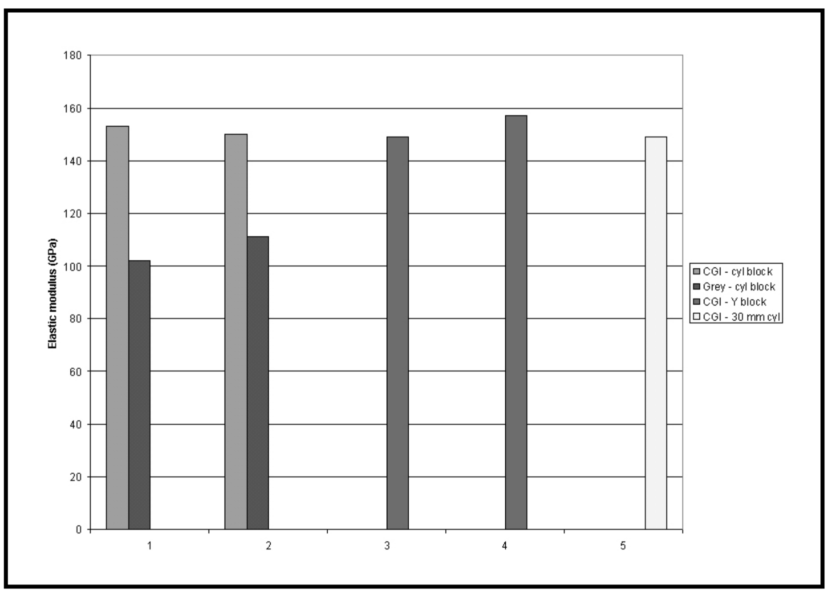

Figure 9: ***Elastic modulus of CGI and gray iron samples from the main bearing of the 12.0 liter cylinder block and from test pieces.***

The microstructure of compacted graphite iron is influenced by cooling rate, with faster cooling rates promoting an increase in nodularity. While cooling rates generally correlate well with wall thickness, mold filling patterns also influence the cooling rate, especially in complex castings such as cylinder blocks. As a result, some 3 -5 mm walls located near in-gates may actually cool more slowly than thicker walls located elsewhere. For most cylinder block castings, walls thicker than approximately 5 mm will cool slowly enough to meet the 0-20% nodularity specification in the presence of good process control. Thinner walls, which are typically restricted to outer walls, webs or ribs, may contain 30-50% nodularity, which is not detrimental to either castability or performance. The influence of wall thickness on microstructure and mechanical properties is illustrated for a 1.0 liter I-4 cylinder block in Figure 10. This figure shows that even for a small block casting, with a relatively small thermal mass, the nodularity in the 4.5 mm wall is only 25% while that in the 9 and 24 mm walls is 15% and 10% respectively. In consideration of the machining stock that is applied to as-cast components, it is evident from this example that all performance and machining critical sections including cylinder bores, main bearing, top deck and pan rail behave as "thick walls" and, with proper process control, can be held within the 0-20% nodularity specification.

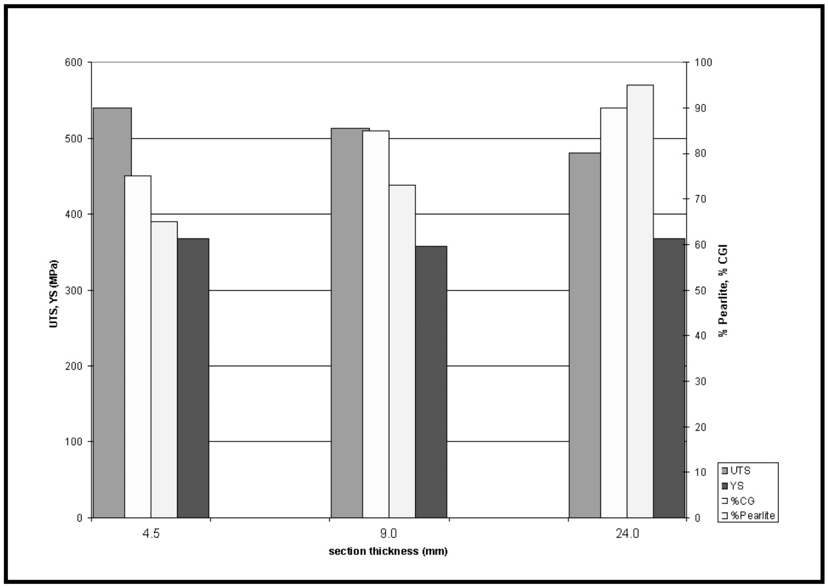

Figure 10: Tensile strength and microstructure as a function of section thickness in a 1.0 liter I-4 cylinder block.

The residual stress has been measured using strain gauges for In-line and V-type cylinder blocks and cylinder heads with in-mold cooling times ranging from 1.5 to 4.0 hours. The measured micro-strain values for a 7.8 liter V-8 block with 1.5 hours in-mold cooling are compared to typical results from the standard gray iron production castings in Table 3. It is evident from these data that the differences between the two materials are not significant and this is confirmed by dimensional measurements which show no difference between the CGI and gray iron castings after machining. Assuming a micro-strain of 500, and taking into account an 80% increase in tensile strength (from 250 to 450 MPa) and a 40% increase in elastic modulus (from 110 to 150 GPa) for CGI over gray iron, the ratio of residual stress-to-ultimate tensile strength is approximately 0.20 for both materials. From the direct micro-strain measurements and calculations it has been confirmed that no process modifications are required for the transition from gray iron to CGI series production.

Table 3
Residual Micro-strain measurements for 7.3 liter V-8 Cylinder Blocks Cast in CGI and Gray Iron.

Measurement Location	**Residual Strain (10^{-6})**	
	CGI	**Gray (Prod'n)**
Inside cylinder No. 3	+261	+506
Inside cylinder No. 4	+267	+480
Main bearing No. 2	+320	+577
Pan rail, crank No. 3	-564	-1029
Pan rail, crank No. 6	-523	-1076
Side face, near hole	-56	-76
Side face, near hole	-123	-74
Firedeck, between cyl. 3 and 5	-68	-96
Firedeck	-811	-743
Firedeck	-434	-500

Note: (+) tensile, (-) compressive

CONCLUSION

Following the production of compacted graphite iron exhaust manifolds since 1992, and prompted by OEM customer enquiries for CGI cylinder blocks and heads, Tupy initiated a programme to extend its production capability in 1997. Since that time, a total of fourteen different blocks, heads and bedplate components have been successfully produced in CGI using existing gray iron tooling and core processes. All parts have been produced in the 0-20% nodularity range in compliance with the ASTM A842-85 specification.

In order to meet the more stringent production demands of complex castings such as blocks and heads, which must be produced without the use of titanium to facilitate high volume machining, the foundry adopted an on-line measure-and-correct process control strategy. The process control system is integrated into the existing process flow and is operated by the normal foundry operators. The consistency in the as-cast products has resulted in an average 90% increase in tensile strength and 40% increase in elastic modulus compared to gray iron components cast from the same patterns.

REFERENCES

Dawson, S., "Compacted Graphite Iron: Mechanical and Physical Properties for Engine Design", *VDI Conference on Materials in Powertrain (Werkstoff und Automobilantrieb*), Dresden, Germany, (October 1999)

Dawson, S., Hollinger I., Robbins, M., Daeth, J., Reuter, U., and Schmidt, H. "The Effect of Metallurgical Variables on the Machinability of Compacted Graphite Iron", *Presented at SAE International Congress*, Detroit, (March 2001)

Warrick, R.J., Ellis, G.G., Grupke, C.C., Khamseh, A.R., McLachlan T.H. and Gerkits C., "Development and Application of Enhanced Compacted Graphite Iron for the Bedplate of the New Chrysler 4.7 Liter V-8 Engine", *SAE Paper* pp 99-144