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Compacted Graphite Iron – A Material Solution for Modern Diesel Engine Cylinder Blocks and Heads

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The demands for improved fuel economy, performance and emissions continue to pose challenges for engine designers and the materials they choose. This is particularly true in the rapidly growing commercial vehicle sector in India. As road infrastructure improves, and as the need for goods transportation and personal mobility increases, fleet owners will respond by demanding state-of-the-art heavy-duty diesel engines that can carry heavier payloads while providing optimal fuel efficiency.

Based on the European experience, the primary path to achieving improved engine performance is to increase the Peak Firing Pressure (P_{max}) in the combustion chamber. In the European commercial vehicle sector, P_{max} has increased from approximately 180 bar in 1999 to 220~240 bar in 2007. The resulting increase in thermal and mechanical loading have required a change from conventional grey cast iron to Compacted Graphite Iron (CGI) in order to satisfy durability requirements without increasing the size or the weight of the engines. With at least 75% higher tensile strength, 45% higher stiffness and approximately double the fatigue strength of conventional grey cast iron, CGI satisfies durability requirements and also provides the dimensional stability required to meet emissions legislation throughout the life of the engine.

In response to EURO 4 legislation, nine new heavy-duty CGI engines were launched in Europe during 2007. As the same EURO 4 legislation will be phased-in to major cities in India during 2009, the same Peak Firing Pressure solutions and durability challenges will undoubtedly be faced, and the same solutions will undoubtedly be implemented. As a result, it is forecast that the Indian foundry industry will experience a significant up-turn in CGI product development and series production before the end of the decade. Of course, this CGI activity and production experience will also lead toward new opportunities for the export market.

INTRODUCTION

Although Compacted (vermicular) Graphite Iron was first observed in 1948, the narrow range for stable foundry production precluded the high volume application of CGI to complex components such as cylinder blocks and heads until advanced process control technologies became available. This, in turn, had to await the advent of modern measurement electronics and computer processors. Following the development of foundry techniques and manufacturing solutions, primarily initiated in Europe during the 1990's, the first series production of CGI cylinder blocks began during 1999. Today, more than 40,000 CGI cylinder blocks are produced each month for OEMs including Audi, DAF, Ford, Hyundai, MAN, Mercedes, PSA, Volkswagen and Volvo.

Emissions legislation and the demand for higher specific performance from smaller engine packages continue to drive the development of diesel engine technology. While higher Pmax provides improved combustion, performance and refinement, the resulting increases in thermal and mechanical loads require new design solutions. Design engineers must choose between increasing the section size and weight of conventional grey iron and aluminium components or adopting a stronger material, specifically, CGI.

Given that new engine programs are typically intended to support three to four vehicle generations, the chosen engine materials must satisfy current design criteria and also provide the potential for future performance upgrades, without changing the overall block architecture. With at least 75% increase in ultimate tensile strength, 40% increase in elastic modulus and approximately double the fatigue strength of either grey iron and aluminium, CGI is ideally suited to meet the current and future requirements of engine design and performance.

MICROSTRUCTURE AND PROPERTIES

As shown in Fig. 1, the graphite phase in Compacted Graphite Iron appears as individual 'worm-shaped' or vermicular particles. The particles are elongated and randomly

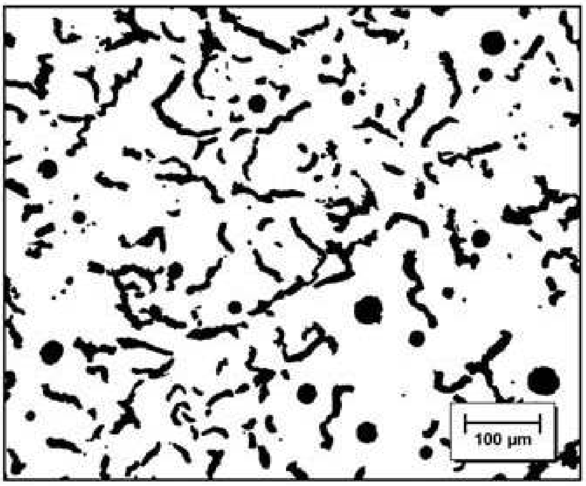

Fig. 1 : CGI microstructure containing 10% nodularity

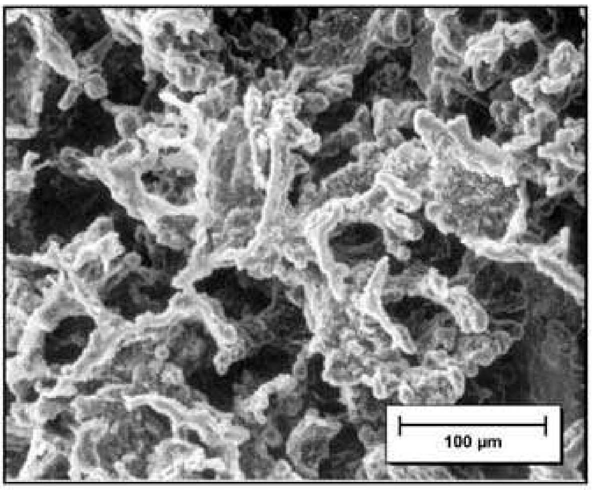

Fig 2 : Deep-etched SEM micrographs show the 3-D coral-like graphite morphology

oriented as in grey 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 (Fig. 2) show that the individual 'worms' are connected to their nearest neighbours within the eutectic cell. The complex coral-like graphite morphology, together with the rounded edges and irregular bumpy surfaces of the compacted graphite particles, results in stronger adhesion between the graphite and the iron matrix, inhibiting crack initiation and providing superior mechanical properties.

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 requirements and the performance conditions of the product. In the case of cylinder blocks and heads, where castability, machinability and heat transfer are all of paramount importance, it is necessary to impose a more narrow specification. A typical specification for a CGI cylinder block or head can be summarised as follows:

- 0-20% nodularity, for optimal castability, machinability and heat transfer
- No free flake graphite, flake type graphite (as in grey iron) causes local weakness
- >90% pearlite, to provide high strength and consistent properties
- <0.02% titanium, for optimal machinability

This general specification will result in a minimum-measured tensile strength of 450 MPa in a 25 mm diameter test bar, and will satisfy the ISO 16112 Compacted Graphite Iron standard for Grade GJV 450. The typical mechanical properties for this CGI Grade, in comparison to conventional grey cast iron and aluminium are summarised in Table 1:

SERIES PRODUCTION REFERENCES

The successful development of CGI production and manufacturing technologies has resulted in series production programs in Europe, Asia and the Americas. A summary of publicly announced CGI programs is provided in Table 2:

The current production volume equates to approximately 500,000 CGI engines per year. Although the current production is limited to diesel engines, and primarily based in Europe, several new programs have been approved and CGI production will expand to other components and other geographical regions. Specific examples include commercial vehicle cylinder heads and V-diesel cylinder blocks for North American SUV and pick-up applications. In consideration of the approved production activities, it is estimated that more than 30 different engine designs, accounting for over two million engines, will be produced during 2010 with either a CGI cylinder block or a CGI cylinder head.

Table 1

Mechanical and Physical Propertiesof CGI in comparison to conventional grey cast iron and aluminium at 20°C

Property	Units	GJV 450	GJL 250	GJL 300	A 390.0
Ultimate Tensile Strength	MPa	450	250	300	275
Elastic Modulus	GPa	145	105	115	80
Elongation	%	1-2	0	0	1
Rotating-Bending Fatigue 20ºC)	MPa	210	110	125	100
Rotating-Bending Fatigue (225ºC)	MPa	205	100	120	35
Thermal Conductivity	W/m-K	36	46	39	130
Thermal Expansion	µm-m-K	12	12	12	18
Density	g/cc	7.1	7.1	7.1	2.7
Brinnell Hardness	BHN 10-3000	215-255	190-225	215-255	110-150

Table 2

CGI Series Production Programs

No.	OEM	Engine Details	CGI Component
1	Audi	3.0 L V6 Diesel	Cylinder Block
2	Audi	4.2 L V8 Diesel	Cylinder Block
3	Audi	6.0 L V12 Diesel	Cylinder Block
4	Caterpillar	Heavy-Duty Engines	Cylinder Liners
5	DAF	12.6 L I-6 Diesel	Cylinder Block
6	DAF	12.9 L I-6 Diesel	Cylinder Block & Head
7	Ford-PSA	2.7 L V6 Diesel	Cylinder Block
8	Ford	3.6 L V8 Diesel	Cylinder Block
9	Ford-Otosan	9.0 L I-6 Diesel	Cylinder Block & Head
10	Hyundai	3.0 L V6 Diesel	Cylinder Block
11	Hyundai	3.9 L I-4 Diesel	Cylinder Block
12	Hyundai	5.9 L I-6 Diesel	Cylinder Block
13	International	11.0 L I-6 Diesel	Cylinder Block
14	International	13.0 L I-6 Diesel	Cylinder Block
15	John Deere	9.0 L I-6 Diesel	Cylinder Liners
16	MAN	10.5 L I-6 Diesel	Cylinder Block
17	MAN	12.4 L I-6 Diesel	Cylinder Block
18	Mercedes	12.0 L V6 Diesel	Cylinder Block
19	Mercedes	16.0 L V8 Diesel	Cylinder Block
20	Renault	3.0 L V6 Diesel	Cylinder Block
21	Volvo	Heavy-Duty Diesel	Cylinder Block

ENGINE DESIGN OPPORTUNITIES

Relative to conventional grey cast iron, CGI provides opportunities for:

- Reduced wall thicknesses at current operating loads
- Increased operating loads at current design
- Reduced safety factors due to less variation in as-cast properties
- Reduced cylinder bore distortion
- Improved NVH
- Shorter thread engagement depth and therefore shorter bolts

During the initial development period in the mid-1990's, much of the CGI development activity was focused on weight reduction. The data in Table 3 provide a summary of weight reduction results obtained in design studies conducted by various foundries and OEMs. The percent weight reduction values in parentheses refer to CGI cylinder blocks that are currently in series production and were published by the OEM. Although these cylinder blocks were never produced in grey iron (weight therefore presented as "xx.x"), the OEM stated that extra mass would have been required to satisfy durability requirements if the blocks were produced in conventional grey iron. While comparisons of the weight reduction potential depend on the size and weight of the original block, the data presented in Table 3 indicate that a weight reduction of 10-15% is a reasonable target for any CGI conversion program.

Since the introduction of common rail fuel injection, the emphasis in CGI engine development has shifted from weight reduction toward downsizing and increased power density. In this regard, the doubling of fatigue strength relative to grey iron and aluminium allow for significant increases in engine loading. One specific OEM study has shown that a 1.3 litre CGI engine package can provide the same performance as a current 1.8 litre grey iron engine. To achieve this increase, the P_{max} was increased by 30% while the cylinder block weight was decreased by 22%. Despite the increase in P_{max}, test rig fatigue analyses showed that the

Table 3
Weight reduction results for CGI vs. grey iron cylinder blocks

Engine Size (Litres)	Engine Type	Grey Weight (kg)	CGI Weight (kg)	Percent Weight Reduction
1.6	I-4 Petrol	35.4	25.0	29.4
1.8	I-4 Diesel	38.0	29.5	22.4
2.0	I-4 Petrol	31.8	26.6	16.4
2.5	V-6 (Racing)	56.5	45.0	20.4
2.7	V-6 Diesel	xx.x	OEM Confidential	(15)
3.3	V-8 Diesel	xx.x	OEM Confidential	(10)
3.8	V-8 Diesel	xx.x	OEM Confidential	(20)
4.0	V-8 Diesel	xx.x	OEM Confidential	(15)
4.2	V-8 Diesel	xx.x	OEM Confidential	(20)
4.6	V-8 Petrol	72.7	59.6	18.0
9.2	I-6 Diesel	158	140	11.4
12.0	V-6 Diesel	240	215	10.4
14.6	V-8 Diesel	408	352	14.2

weight-reduced CGI cylinder block provided a larger safety margin that the original grey iron block, thus indicating that further increases in performance were possible. In comparison to the original engine, the fully assembled CGI engine was 13% shorter, 5% lower, 5% narrower, and 9.4% lighter. This example demonstrates the contribution of CGI to achieve combined downsizing and power-up objectives.

Another consideration of CGI engine design is the ability to withstand cylinder bore distortion. In the combined presence of elevated temperatures and increased combustion pressures, cylinder bores tend to expand elastically. However, the increased strength and stiffness of CGI is better able to withstand these forces and maintain the original bore size and shape. The reduced cylinder bore distortion allows for reduced ring tension and thus reduced friction losses. Additional benefits include reduced piston slap thus improving NVH; reduced oil consumption thus extending oil change intervals; and, reduced blow-by thus preventing torque loss and improving emissions. Table 4 shows comparative bore distortion results for four grey iron and CGI engines with the same design.

Table 4
Cylinder bore distortion for CGI vs grey iron

Engine Size (Litres)	Engine Type	Improvement % CGI vs Grey
1.8	I-4 Petrol	18
1.8	I-4 Diesel	20
2.2	I-4 Petrol	28
4.6	V-8 Petrol	22

The increased stiffness of CGI also contributes to NVH performance. Although the specific damping capacity of CGI is lower than that of grey iron, the higher elastic modulus stiffens the block, making many webs and ribs redundant. The 40% increase in the elastic modulus of CGI increases the separation between the combustion firing frequency and the resonant frequencies of the block. The net result of this increased separation is that the engine operation becomes quieter. The increase in the first torsional frequency mode and the reduced noise level of several CGI engines tested in semi-anechoic chambers are shown in Table 5, both for passenger vehicle and commercial vehicle engines.

Table 5
NVH results for identically designed CGI and grey iron engines

Engine Size (Litres)	Engine Type	First Torsional Frequency Shift	Sound Pressure Level (dBA)
1.8	I-4 Diesel	+12%	Same
2.0	I-4 Petrol	+8%	-1.0 to -1.5
2.0	I-4 Petrol	+7%	-1.0 to -1.5
2.2	I-4 Petrol	+16%	-1.0 to -1.5
2.4	I-4 Diesel	+9%	-1.0 to -1.5
4.6	V-8 Petrol	+12%	Not Tested
5.8	V-8 Petrol	+18%	Not Tested
12.0	V-6 Diesel	+8%	-0.5 to -1.0
13.8	I-6 Diesel	+8%	Not Tested

Table 6

The Audi 4.2 litre CGI V8 is 4 kg lighter than the Mercedes 4.0 litre aluminium V8

Parameter	Audi 4.2 V8 TDI	Mercedes V8 CDI
Performance (kW)	240	231
Specific performance (kW/litre)	57	57
Torque (Nm @ rpm)	650 @ 1600	580 @ 1600
Acceleration (0-100 km/hr, sec)	5.9	6.1
Bore pitch (mm)	90	97
Overall length (mm)	520	640
Engine weight (kg)	255	259
Power-to-weight (kW/kg)	0.94	0.89

CGI VS. ALLOYED GREY IRON

As the increases in engine loading began to exceed the strength capabilities of conventional grey iron (GJL 25), foundries and OEMs responded by adding alloying elements and hardening agents such as Chromium, Nickel, Copper, Tin and Molybdenum to increase the tensile strength. In order to further increase the strength to fully satisfy the 300 MPa minimum tensile strength objective (GJL 30), some specifications also reduced the carbon content from approximately 3.2% to 3.0% to make the graphite flakes smaller, thus reducing the risk for crack initiation and propagation. While the alloying and reduced carbon content provide a 10-20% increase in mechanical properties, these actions simultaneously consume many of the core advantages of conventional grey cast iron: castability, heat transfer, machinability and significantly, cost.

Castability: During solidification, the formation of graphite flakes in conventional grey iron provides an expansion effect that counteracts the natural shrinkage tendency of the iron. However, the lower carbon content of alloyed grey iron reduces the extent of this beneficial effect. Additionally, many of the alloying elements (Cr, Cu, Sn, Mo) segregate to the last areas of the casting to solidify increasing the sensitivity for shrinkage porosity and carbide formation. The net effect is that the castability of alloyed grey iron, including feeding requirements, is effectively the same as that of CGI. This is particularly true for complex castings such as 4-valve cylinder heads.

Heat Transfer: The addition of alloying elements to grey iron reduces thermal conductivity. Typical alloying levels for GJL 30 (0.3% Cr and 0.3% Mo) reduce the thermal conductivity of grey iron by 10-15%. Further, since grey iron relies on the elongated graphite flakes to provide natural conduits for heat transfer, the lower carbon content of alloyed grey iron also detracts from the heat transfer capability. The net effect is that the thermal conductivity of alloyed grey iron is only about 5% higher than that of a standard pearlitic CGI.

Machinability: The alloying elements added to increase the strength of grey iron also increase the hardness and wear resistance. While the strength of alloyed grey iron is only 10-20% higher than that of conventional grey iron, the hardness can be 30% higher. Depending on the alloy content, the hardness of alloyed grey iron can frequently be higher than that of CGI (Table 1). While there is indeed a significant difference in machinability between conventional grey iron and CGI, the tool life for alloyed grey iron and CGI are effectively the same for many machining operations.

Cost: The shrinkage sensitivity (feeding requirements) and machinability (tool life) of alloyed grey iron both impact the total on-cost of alloyed grey iron compared to normal grey iron (GJL 25). Beyond these operational concerns, consideration must also be given to the cost of the alloying elements. For example, the market price of molybdenum has increased from approximately EUR 5,000 per tonne to EUR 50,000 per tonne since 2004. For a 100 kg casting with a 70% mould yield and a 0.3% Mo content, the molybdenum cost alone is approximately EUR 20 per casting.

NVH: The primary property for the determination of NVH performance is stiffness. While the increase from GJL 25 to GJL 30 provides a 20% increase in tensile strength, the increase in elastic modulus is only about 10%. In comparison, CGI provides a 40% increase in modulus compared to GJL 25. Despite that the specific damping capacity of CGI is lower than that of either of the two grey iron Grades, the increased stiffness of CGI typically results in a reduced noise level of approximately 1.0 dB.

In hindsight, alloyed grey iron was indeed the right material choice for heavily loaded cylinder blocks and heads in 1999, before CGI was proven as a viable high volume material. However, the recent advances in CGI foundry process control and manufacturing technology have established CGI as a proven series production material. As a result, it is no longer necessary to accept the trade-offs associated with alloyed grey iron. Alloyed grey iron brings many of the same challenges as CGI with respect to castability, heat transfer, machinability and cost, but not the benefits. If designers are willing to incur the operational penalties of alloyed grey iron, they should instead specify CGI to realise the full increase in material properties and to realise the full benefits related to engine performance, NVH and durability.

Table 7

Summary of CGI Standards

Country	Issuing Body	Number	Year
International	ISO	ISO 16112	2006
International	SAE	J 1887	2002
Germany	VDG	W 50	2002
USA	ASTM	A 842-85	1997
China	JB	4403-87	1987
Romania	STAS	12443-86	1986

CGI vs. Aluminium

In comparison to aluminium, the mechanical properties of CGI provide opportunities for:

- Smaller package size
- Higher specific performance
- Reduced cylinder bore distortion and improved oil consumption
- No cylinder liners or surface etchant/coating
- Improved NVH
- Lower production cost
- Improved recyclability

Due to the considerable density difference between CGI (7.1 g/cc) and aluminium (2.7 g/cc), it is to be expected that a CGI cylinder block will be heavier than a similar displacement aluminium block. However, because of the higher strength and stiffness of CGI, the main bearing thickness can be reduced to provide a significantly shorter cylinder block. Accordingly, all of the components that span the length of the cylinder block – such as the cylinder heads, crankshaft, camshaft and bedplate – can also be made shorter, and thus lighter. This is particularly advantageous in V-blocks with two cylinder banks. The net result is that a fully assembled CGI engine can indeed have the same weight as a fully assembled aluminium engine. This result is evident from Table 6 which shows that the Audi 4.2 litre V8 TDI based on a CGI cylinder block is actually 4 kg lighter than the Mercedes 4.0 litre V8 CDI aluminium engine.

Even within the in-line sector, it can be shown that the energy intensity of iron vs. aluminium production results in a significant energy penalty for aluminium. With current recycling rates, each tonne of cast iron (grey, CGI or ductile) accounts for an equivalent energy content of approximately 10,500 MJ/tonne. The corresponding value for aluminium is approximately 90,000 MJ/tonne. Assuming that a CGI cylinder block weighs 35 kg and the corresponding aluminium cylinder block weighs 28 kg, the net energy penalty to society for the aluminium block is approximately 2,150 MJ/block.

Given an energy content of 34 MJ/litre for gasoline, the as-cast energy penalty of 2,150 MJ corresponds to approximately 63 litres of gasoline. Further, assuming standard estimates of 0.5 litres of petrol saved for each 100 km and each 100 kg of weight saving, the 7 kg weight reduction provided by the aluminium block over the CGI block would require a driving distance of approximately 180,000 km to payback the energy differential. It is thus evident that government policy makers and OEMs must consider the cradle-to-grave energy balance for society, particularly in countries like India which rely heavily on imported oil.

DESIGN CONSIDERATIONS

All CGI cylinder blocks for passenger car applications are produced with a minimum wall thickness of 3.5 mm (-0.5, +1.0). This is the same as for conventional grey cast iron and confirms that CGI has sufficient fluidity to fill complex state-of-the-art moulds. Given that the minimum wall thickness for CGI is the same as for grey iron (dictated by sand moulding considerations) the weight reduction opportunity is not based on minimum-wall thickness capabilities. Rather, the weight reduction opportunity for CGI cylinder blocks is based on re-designing the relatively thick load-bearing walls of the casting. For example, the reduction of a main bearing wall from 20 mm to 15 mm provides a significant weight reduction, without infringing on foundry process capability. In contrast, a reduction of the water jacket from 3.5 mm to 3.0 mm may exceed process capability and yet only provide a small weight reduction. The higher strength of CGI allows designers to reduce weight by focusing on the relatively thick load-carrying regions of a casting that are not yet limited by moulding considerations. Although every kilogram is important in a casting, and thick and thin sections must both be addressed, the most effective contributions to weight reduction are those made to the thick sections, as enabled by the improved mechanical properties of CGI.

When specifying grey or ductile iron, design engineers know that uniform graphite shape is critical to maintaining mechanical properties. In grey iron, the presence of degenerate graphite forms such as undesirable D-Type graphite result in a 20-25% reduction in mechanical properties. Similarly, 'crab-shaped' graphite or exploded nodules reduce the strength and stiffness of ductile iron. Based on these experiences, designers may be inclined to specify a uniform graphite structure in CGI. However, while 0-20% nodularity structures are required in performance-critical sections to optimise castability, thermal conductivity and machinability, higher nodularities can actually benefit the outer structural regions of a casting. The natural tendency of CGI to solidify with higher nodularity in the faster cooling sections may result in the thin outer walls (less than ~5 mm) having up to 50% nodularity. Where the thin sections are not thermally loaded and do not require extensive machining, the higher nodularity only serves to increase the strength, stiffness and ductility of the castings. CGI microstructure specifications should therefore focus on performance-critical sections such as the cylinder bore walls and main bearings and, whenever possible, take advantage of the increased nodularity in thin wall areas.

Thermal fatigue failures in grey iron are often rectified by adding material to reinforce strength and stiffness. However, the lower thermal conductivity of CGI causes thermally loaded CGI components to operate at higher temperatures. Therefore, if a CGI component experiences thermal fatigue, particularly in material substitution applications based on existing grey iron designs, the solution may lie in reducing - not increasing - wall thicknesses to improve heat transfer. It is also important to optimise the design of the cooling water channels to ensure that the cooling water is introduced as close as possible to the heat source to maximise the cooling efficiency. Because of the higher elastic modulus and lower thermal conductivity of CGI relative to grey iron, it is clear that the thermal stress loading in a similarly designed CGI component will be higher than that in the grey iron component. Ultimately, the ability for CGI to provide improved durability requires that the strength increase is greater than the increase in thermal load, thus providing a net benefit. In some cases, this will require an improved design of the water channel.

STANDARDS AND TERMINOLOGY

Several national and international organisations have developed and published standards for CGI. These standards specify the CGI Grades in terms of the tensile strength and the microstructure, expressed as percent nodularity. The currently available standards are summarised in Table 7.

Historically, CGI has been known by the names “Compacted Graphite Iron” and “Vermicular Graphite Cast Iron”, with the “compacted” terminology primarily being used in English speaking countries and the “vermicular” terminology predominating in most other languages. Most recently, during 2006, the new ISO standard for CGI was published using the combined name: “Compacted (Vermicular) Graphite Cast Iron”. The ISO designation for CGI has been abbreviated as “GJV” and five Grades have been specified based on the minimum ultimate tensile strength obtained in separately cast test pieces, including: GJV 300 (ferritic), GJV 350, GJV 400, GJV 450 (pearlitic) and GJV 500 (alloyed).

Beyond the standards issued by the national and international organisations, several OEMs have also established their own internal CGI Specifications, including: Audi, BMW, Caterpillar, Cummins, DAF Trucks, DaimlerChrysler, Ford, General Electric, General Motors, Hyundai, John Deere, Opel, Rolls Royce Power Engineering and Volkswagen, among others.

CONCLUSION

The improved mechanical properties of Compacted Graphite Iron relative to grey iron and aluminium provide many contributions to the design and performance of internal combustion engines for passenger and commercial vehicles. Since 1999, series production experience has established CGI as a viable high volume engine material. Perhaps the most compelling statistic regarding CGI cylinder blocks is that no OEM has only one CGI cylinder block in its line-up. Without exception, every OEM that has launched the production of a CGI engine has also proceeded to develop, approve or launch additional CGI engines.