Compacted Graphite Iron – a material solution for modern diesel engine cylinder blocks

Steve Dawson of Sintercast AB here discusses how the application of CGI can provide new opportunities for reduced weight and package size, power-up, and improved noise, vibration and harshness, NVH. Despite the density difference between CGI and aluminium, the ability to make a more compact cylinder block when using CGI can result in a fully assembled CGI engine that weighs less than an aluminium engine of the same displacement. This design opportunity is illustrated with specific examples of V6 and V8 diesel engines that are currently in production. This report also provides a well-to-wheels energy comparison for CGI and aluminium, showing a favorable profile for cast iron cylinder blocks.

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 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 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, Navistar, Mercedes, PSA, Renault, 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 $P_{\text{max}}$ 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 or aluminium, CGI is well suited to meet the current and future requirements of engine design and performance.

Engine design opportunities

In comparison to conventional grey cast iron, CGI provides opportunities for:

- Reduced wall thicknesses at current operating loads
- Increased specific performance through increased $P_{\text{max}}$ and loading
- Reduced safety factors due to less variation in as-cast properties
- Reduced cylinder bore expansion and distortion
- Improved NVH
- Shorter thread engagement depth and therefore shorter bolts

During the initial development period in the mid-1990s, much of the CGI development activity was focused on weight reduction. The data in Table 2 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 in each case has publicly stated that extra mass would have been required to satisfy durability requirements if the blocks had been 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 1 indicates that a weight reduction of 10-15% is a reasonable target for CGI conversion programs.

Table 1 Weight reduction results for CGI vs grey iron cylinder blocks

<table>
<thead>
<tr>
<th>Engine Size (Litres)</th>
<th>Engine Type</th>
<th>Grey Weight (kg)</th>
<th>CGI Weight (kg)</th>
<th>Percent Weight Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>I-4 Petrol</td>
<td>35.4</td>
<td>25.0</td>
<td>29.4</td>
</tr>
<tr>
<td>1.8</td>
<td>I-4 Diesel</td>
<td>38.0</td>
<td>29.5</td>
<td>22.4</td>
</tr>
<tr>
<td>2.0</td>
<td>I-4 Petrol</td>
<td>31.8</td>
<td>26.6</td>
<td>16.4</td>
</tr>
<tr>
<td>2.5</td>
<td>V6 (Racing)</td>
<td>56.5</td>
<td>45.0</td>
<td>20.4</td>
</tr>
<tr>
<td>2.7</td>
<td>V6 Diesel</td>
<td>xx.x</td>
<td>OEM Confidential</td>
<td>(15)</td>
</tr>
<tr>
<td>3.0</td>
<td>V6 Diesel</td>
<td>xx.x</td>
<td>OEM Confidential</td>
<td>(25)</td>
</tr>
<tr>
<td>3.3</td>
<td>V8 Diesel</td>
<td>xx.x</td>
<td>OEM Confidential</td>
<td>(10)</td>
</tr>
<tr>
<td>3.8</td>
<td>V8 Diesel</td>
<td>xx.x</td>
<td>OEM Confidential</td>
<td>(20)</td>
</tr>
<tr>
<td>4.0</td>
<td>V8 Diesel</td>
<td>xx.x</td>
<td>OEM Confidential</td>
<td>(15)</td>
</tr>
</tbody>
</table>
Although CGI provides significant weight reduction opportunities, the primary driver for new CGI engine development is increased power density, enabled by the doubling of fatigue strength relative to grey iron and aluminium. One specific OEM study has shown that a 1.3 litre diesel engine with a CGI cylinder block can provide the same performance as a current 1.8 litre grey iron engine. To achieve this performance increase, the $P_{\text{max}}$ was increased by 30% while the cylinder block weight was decreased by 22%. Despite the increase in $P_{\text{max}}$, test rig fatigue analyses showed that the weight-reduced CGI cylinder block provided a larger safety margin than 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% less height, 5% narrower, and 9.4% lighter. The ability to decrease the thickness of the main bearings and thus make the cylinder block shorter, means that all of the components that traverse the length of the engine also become shorter and lighter, contributing to the weight reduction of the fully assembled engine.

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 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 reduced friction losses. The improved matching also results in reduced piston slap at cold start, thus improving NVH; reducing oil consumption thus extending oil change intervals; and, reducing blow-by thus preventing torque loss and improving emissions. Table 2 shows comparative bore distortion results for four grey iron and CGI engines with the same design.

Table 2 Cylinder bore distortion for CGI vs grey iron

<table>
<thead>
<tr>
<th>Engine Size (LITRES)</th>
<th>Engine Type</th>
<th>% Improvement CGI vs Grey</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>I-4 Petrol</td>
<td>18</td>
</tr>
<tr>
<td>1.8</td>
<td>I-4 Diesel</td>
<td>20</td>
</tr>
<tr>
<td>2.2</td>
<td>I-4 Petrol</td>
<td>28</td>
</tr>
<tr>
<td>4.6</td>
<td>V8 Petrol</td>
<td>22</td>
</tr>
</tbody>
</table>

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 40–45% 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 the increased separation is that the engine operation becomes quieter.

**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. 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% to make the graphite flakes smaller, thus reducing the tendency 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 the 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 during solidification, thus preventing torque loss and improving emissions. The net effect is that the castability of alloyed grey iron, including feeding requirements, is effectively the same as that of CGI.

**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 by 10-15%. Further, since grey iron relies on the elongated graphite flakes to act as 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 stiffness 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 30-40% higher. Depending on the alloy content, the hardness of alloyed grey iron can frequently be higher than that of CGI. 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 alloying elements including chromium, nickel and molybdenum.

**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, which typically leads to noise reductions of approximately 1.0 dB. Alloyed grey iron brings many of the same challenges as CGI with respect to castability, heat transfer, machinability and cost, but it only provides a fraction of the material property benefits. If designers are willing to incur the operational penalties associated with alloyed grey iron, they should instead specify CGI to realise the full increase in material properties and operational benefits related to engine performance, NVH and durability.

**CGI vs Aluminium**

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


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- 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
- Lower life cycle energy consumption and CO₂ emissions
- Improved recyclability

Due to the considerable density difference between CGI (7.1 g/cc) and aluminium (2.7 g/cc), CGI cylinder blocks will be heavier than aluminium blocks of a similar displacement. However, the higher strength and stiffness of CGI allows significant reductions in the thickness of the main bearings resulting in a 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 – also become shorter and lighter. This is particularly true in V-type cylinder blocks where there are two cylinder banks. The net result is that fully assembled CGI engines can be significantly lighter than aluminium engines of the same displacement. This result is evidenced by the V6 and V8 CGI engines produced by Audi. The Audi 3.0 litre V6 CGI engine is 130mm shorter and 15kg lighter than the Mercedes 3.0 litre V6 engine based on an aluminium cylinder block. Likewise, the Audi 4.2 litre V8 TDI, based on a CGI cylinder block, is 120mm shorter and 4kg lighter than the Mercedes 4.0 litre V8 CGI aluminium engine. This result shows the importance of comparing the weight of the fully assembled engine rather than the weight of the cylinder block, particularly for life cycle energy and fuel saving calculations. It can also be shown that the energy consumption of iron vs aluminium production results in a significant energy penalty for aluminium. Perhaps surprisingly, the melting of iron requires 600 kWh/tonne while the melting of aluminium requires 1,100 kWh/tonne, despite that the melting temperature of cast iron is around 1150°C while that of aluminium is around 650°C. This is due to the magnetic properties of ferrous materials which provide better coupling with the electromagnetic induction melting techniques used in foundries. However, the biggest difference in the energy consumption between iron and aluminium occurs in the production of the virgin material, where the energy consumption for primary aluminium production (which is manufactured via an electrolysis process rather than a melting process) is almost ten times higher than that of iron or steel.

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 4-cylinder CGI block weighs 33kg and that the corresponding aluminium cylinder block weighs 28kg, the net energy penalty to society (based on the block weight differential rather than the assembled weight differential that will be less than 5kg) 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 100km and each 100kg of weight saving, the 5kg weight reduction provided by the aluminium block over the CGI block would require a driving distance of approximately 250,000 km to payback the energy differential; more than 10 years of normal driving (15,000 miles/year). If the weight differential for the fully assembled engine was only 3kg, this increases the breakeven distance to 450,000km; more than 18 years of driving.

The energy penalty associated with aluminium can also be expressed in terms of the equivalent well-to-wheels CO₂ reduction. Based on the 3kg weight reduction for the fully assembled engine, every one million aluminium engines corresponds to an energy penalty equivalent to 350,000 barrels of crude oil and approximately 90,000 tonnes of CO₂ emissions. It is thus evident that government policy makers and OEMs must consider the full energy balance for society, particularly in countries that rely heavily on imported oil.

**Conclusion**

The properties of compacted graphite iron relative to grey iron and aluminium provide many opportunities for improved engine design and performance, both in passenger vehicles and commercial vehicles. Since the onset of CGI cylinder block production in 1999, CGI has been established as a viable high volume engine material. Indeed, CGI has effectively become the standard material for V-type diesel engine cylinder blocks, with 13 of the last 15 V-diesel passenger vehicle engines being specified with a CGI cylinder block. Likewise, CGI is becoming more widespread in the commercial vehicle sector, with every European heavy-duty engine manufacturer having at least one CGI engine in its line-up. Perhaps the most compelling statistic regarding CGI is that, every OEM that has a CGI engine in production today, either has more than one engine in production, or is in the process of developing additional CGI engines.

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