Compacted Graphite Iron for Diesel Engine Cylinder Blocks

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Abstract

The recent trends in diesel engines are discussed, and also the consequences in materials selection for engine cylinder blocks. The increasing demand for higher specific power and the need for weight reduction and decrease of emissions require the use of stronger materials for cylinder blocks, opening a promising space for compacted graphite iron (CGI). The properties of CGI are described, in particular those required for engine cylinder blocks (fatigue strength and elastic modulus). Results of mechanical properties from actual castings are presented. As a result of the mechanical properties improvement, some design opportunities are suggested, in order to decrease the weight of the cylinder block.

Keywords

diesel engines, compacted graphite iron, cylinder blocks

1. Introduction:

In a recent paper discussing CGI uses for engine cylinder blocks and heads, S. Dawson (2001) stated that "the Iron Age is just beginning" and we have taken this statement for the present paper. His point of view, added to those from Rizzo (2001), discloses the enormous CGI potential for manufacturing engine components, especially for diesel engines.

The growth of diesel engines usage for passenger cars has been remarkable in Europe (see Fig. 1), especially after the introduction of the high-pressure common-rail technology (Buchholz, 2003). This growth is surrounded by requirements as: less fuel consumption, emissions reduction , larger power output and torque, and for passenger cars more compact engines are being required due to space limitations. Improved performance, as operation efficiency and engine power density (Fig. 2), are being achieved by the rise of combustion chamber pressures, particularly for diesel engines. For diesel passenger cars, peak cylinder pressures in excess of 160 bar (Heap, 1999) or 180 bar (Vollrath, 2003) can be expected. Heavy-duty truck engines are expected to achieve peak pressures up to 200 bar (Heap 1999, Mohrdieck 2003).

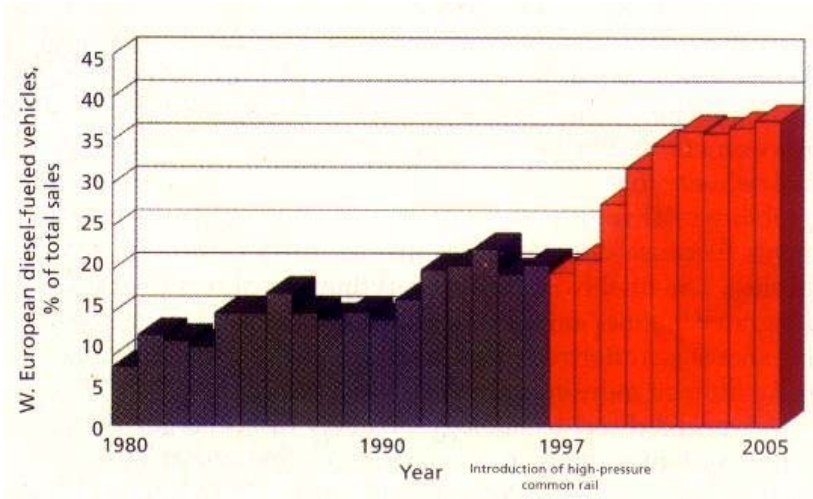


Figure 1 – The introduction of high-pressure common-rail technology in 1997 marked a significant turning point in European sales of diesel-fueled vehicles (Buchholz, 2003).

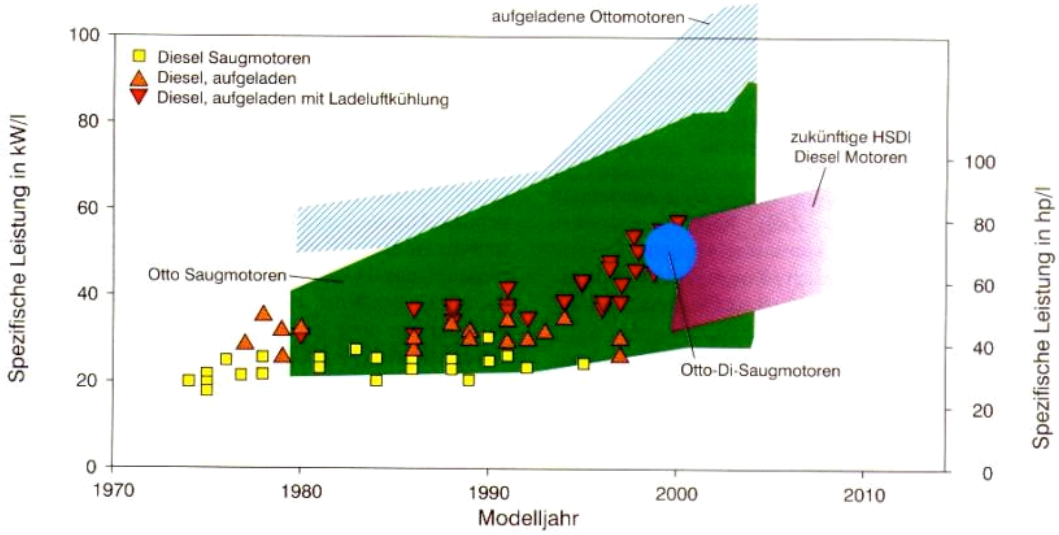


Figure 2 – Increase of the specific power of engines (FEV - Pischinger & Ecker, 2003)

2. The materials scenario:

Aluminum alloys will hardly endure the high pressure numbers mentioned above for cylinder blocks (Martin et all, 2003). Some studies from AVL set limits of 170 bar (for in-line engines) and 150 bar (for V engines) for aluminum in diesel engine cylinder blocks (figure 3, Marquard & Sorger, 1997). A particular weak point of aluminum alloys is their mechanical strength fast drop for raising temperatures. For cylinder blocks, the bulkhead and the bearing caps threads are critical stressed areas (Vollrath, 2003).

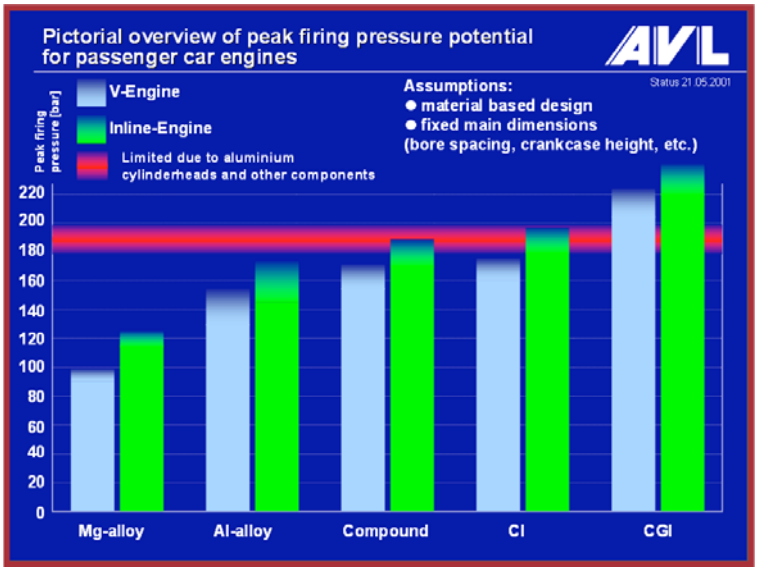


Figure 3 – Peak firing pressure limits for various materials in diesel engine cylinder block (Marquard & Sorger, 1997)

For cast irons, it is possible to obtain tensile strength values from 220 MPa to 550 MPa in the bulkhead area. Those strength values remain stable with increasing temperatures, for example, up to 400^0 C (Vollrath).

Engine blocks design concepts - for cast iron - were developed focusing the local loads acting on each block region (Figure 4 – Vollrath, 2003), and exploiting the mechanical properties of the material.

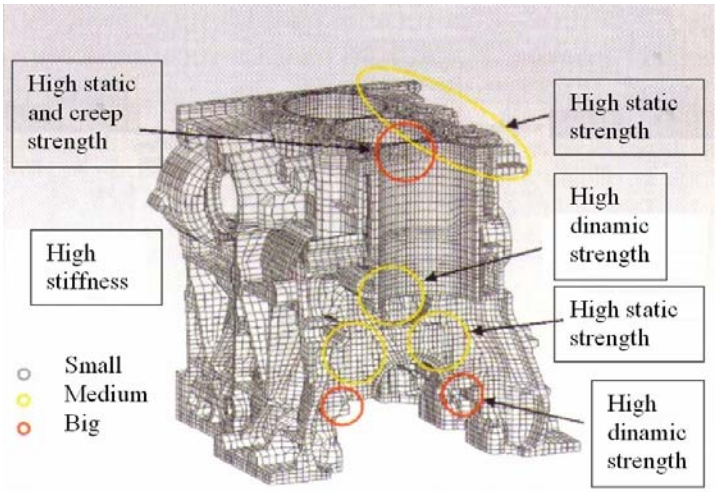


Figure 4 – The one-dimensional era of engine design is finished. The current approach considers the loads acting at each point of the engine block. (Vollrath, 2003)

The concepts listed below are shown in Figure 5 (Marquard et all, 1998):

- varying topdeck thickness
- varying liner thickness
- horizontal trussbar are integrated to the topdeck
- vertical trussbars act as oil return and blow-by passages
- thread bosses for the cylinder head are integrated to the water jacket deck
- reduced thread depth

- decreased water jacket height
- wide crankcase venting holes
- hollow main bearing walls
- reduced oil pan flange thickness
- bearing cap designed as U-profile

The use of these concepts allows considerable block weight reduction. For instance, for a turbocharged 2,0 L diesel engine, the block weight was reduced from 42,8 kg to 29,5 kg. For a turbocharged gasoline engine, the block weight was reduced from 38,5kg to 28,5 kg (Vollrath, 2003).

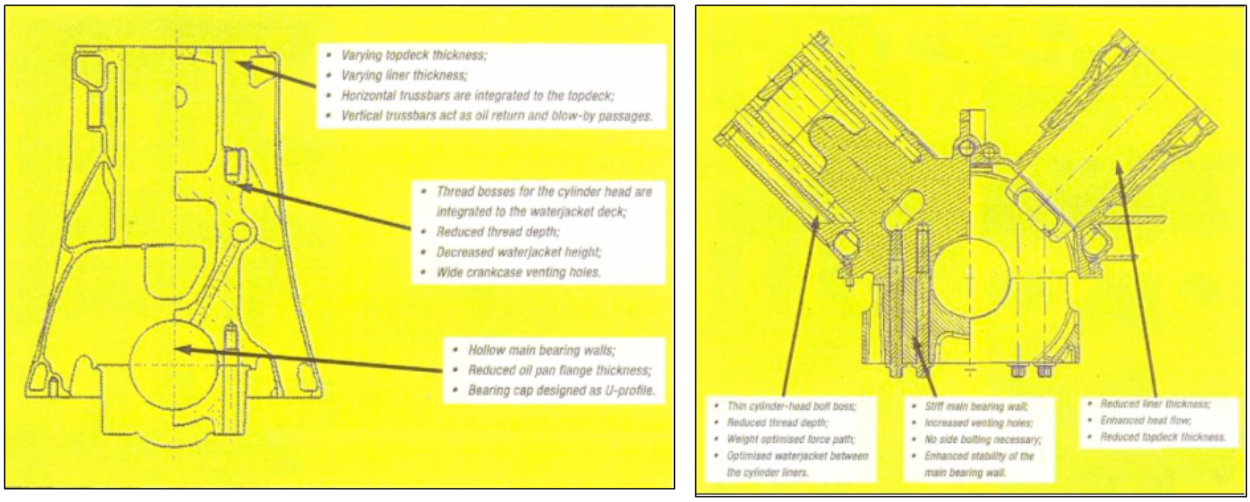


Figure 5 – Cross-sections through cylinder and main bearing wall (Marquard et all, 1998).
a) In-line 4-cylinder diesel engine *b) V8 diesel engine*

Nowadays it is already a reality the production of cylinder blocks with 3.5 mm wall thickness. Figure 6 shows the example of the capabilities, regarding the current wall thickness practice at Tupy Fundições.

Some other examples of tendencies in OEMs from Europe:

- Audi: manufactures 2,8 million engines per year; 85% cast iron and 15% aluminum alloys engine blocks. The forecast according to this company is that direct injection diesel engines will be made from gray iron, and in near future, from CGI. For gasoline engines, with 20 bar average pressures, the engine blocks should be made from gray iron. For other engines, aluminum blocks should be used (Vollrath, 2003).

- MAN: for truck engines, the peak firing pressures will grow according to Fig. 7. For Euro 3, a peak firing pressure of 150 bar will be enough, while for Euro 4 (2005) the peak firing pressure will be increased up to 180, and for Euro 5 (2008) values of 200 bar will be necessary (Vollrath, 2003).
- Deutz: for the new engine 2014, gray iron grade 300 and section thickness of 5,0 mm are adequate for 195 bar peak firing pressure. For higher pressures, CGI will be necessary, despite the increasing costs of foundry and machining processes involved (Vollrath, 2003).
- Daimler Chrysler: for 2009, it is forecast for gasoline engines exhaust gas temperatures up to 1050 C; for diesel engines, it is expected peak firing pressure up

to 200 bar and exhaust gas temperatures up to 850 C (Mohrdieck, 2003). One of the first CGI parts at Daimler Chrysler Germany will be a diesel engine cylinder head, in CGI Grade 400.

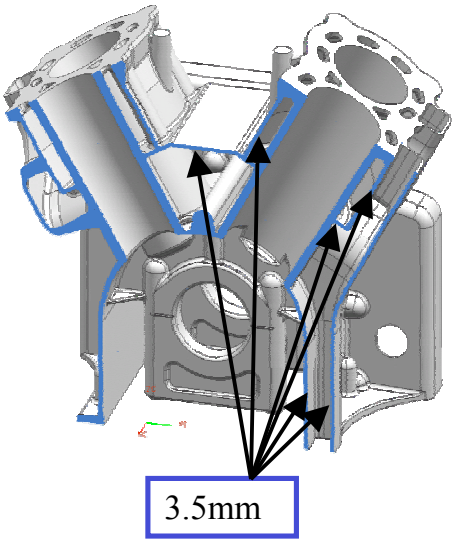


Figure 6 - Current wall thickness for Cyl. Blocks in CGI in production at Tupy Fundições.

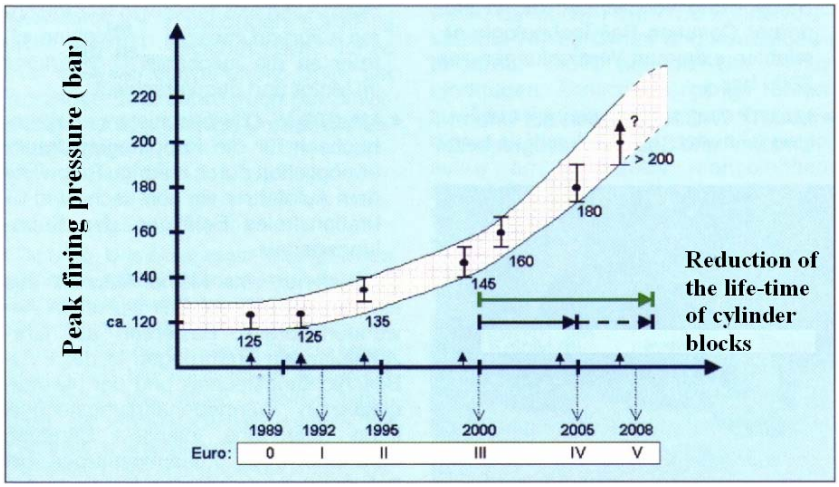


Figure 7 – In order to fulfill emissions standards requirements, the peak firing pressure in truck engines must surpass 200 bar, according to MAN (Vollrath, 2003).

3. CGI – a new combination of properties:

As shown in Fig. 8, the compacted graphite iron graphite particles 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. The compacted graphite morphology inhibits crack initiation and growth and is the source of the improved mechanical properties, as compared to gray iron. 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 and thermal conductivity (Guesser et all, 2001). It is usual to set a limit of 20% nodularity for

CGI specifications. Table 1 shows mechanical properties of CGI, with grades from 300 to 500 MPa.

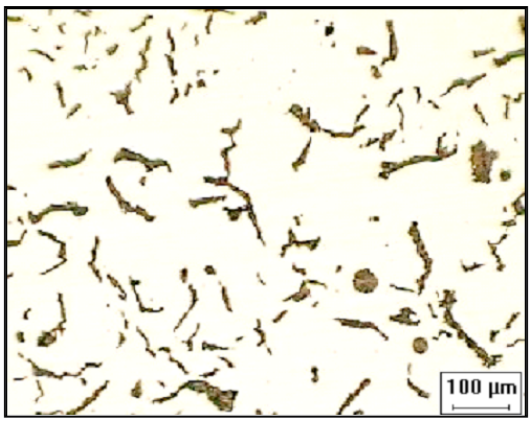


Figure 8 – CGI typical microstructure: 5% nodularity, 9% graphite, 265 particles/mm^2.

Grade	UTS (MPa)	YS (MPa)	E (%)	HB 30 (typical results)
EN-GJV-300	300-375	220-295	1,5	140-210
EN-GJV-350	350-425	260-335	1,5	160-220
EN-GJV-400	400-475	300-375	1,0	180-240
EN-GJV-450	450-525	340-415	1,0	200-250
EN-GJV-500	500-575	380-455	0,5	220-260

Table 1 - CGI Grades – German Standard VDG Merkblatt W50 (2002)

Typical mechanical properties for cylinder blocks and cylinder heads are shown in Figure 9. The results allow the comparison between CGI and gray iron. It can be seen the increase on tensile strength, moving from gray iron to CGI.

CGI also shows a higher elastic modulus, when compared to gray iron. The results in Figure 10 were obtained from two sources: test bars and main bearings of a 12.0L cylinder block. The increase in elastic modulus, from 100 GPa for gray iron to 150 GPa for CGI, results in slighter cylinder bore distortion as reported by Tholl et all (1996), therefore reducing oil consumption and emissions.

Results of fatigue strength tests can be seen on figure 11, comparing gray iron grade 250 and CGI grade 450, samples from an I6 5.9L diesel cylinder block. The fatigue limit for the gray iron is 62-79 MPa, depending on the carbon content, while for the CGI the fatigue limit is 175 MPa. The raise of fatigue strength allows the designer to reduce the cylinder block weight.

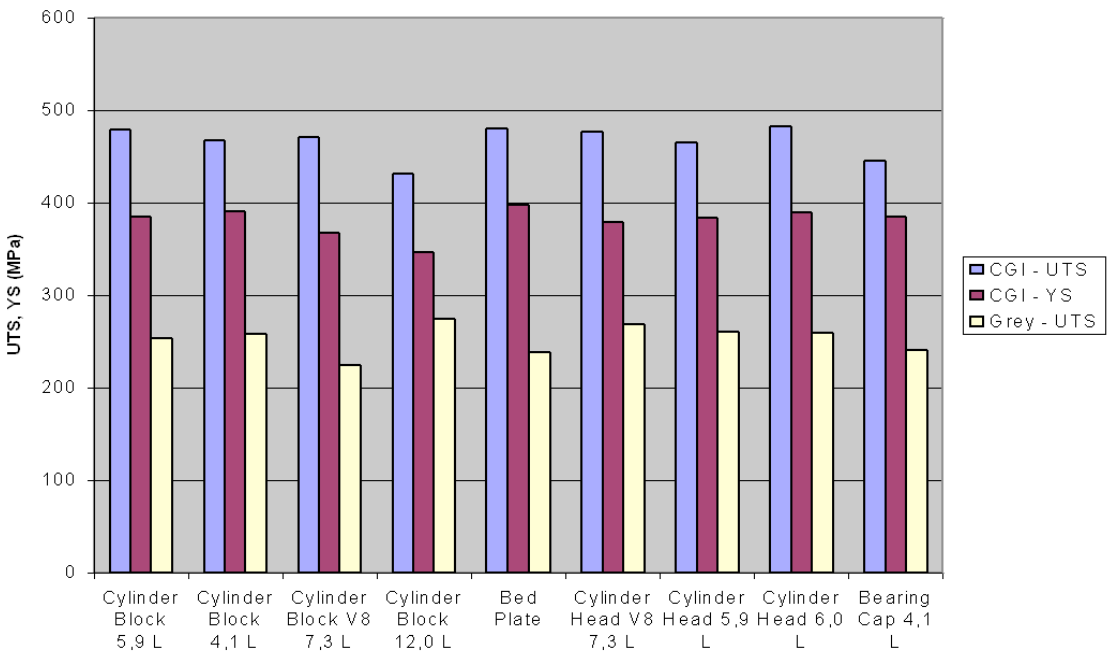


Figure 9 - Mechanical properties of gray iron and CGI grades 400-450. 195-230 HB. Samples taken from the castings (Guesser, 2003).

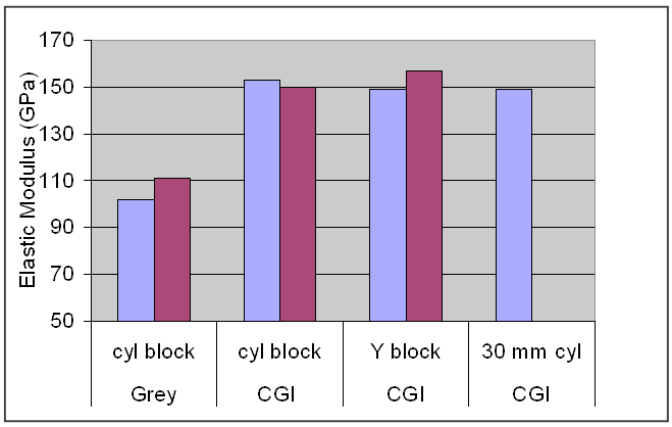


Figure 10 – Elastic modulus of gray iron and CGI grade 400. 12.0L I6 cylinder block (Guesser, 2003).

As a result of mechanical properties improvements, a design study conducted by AVL Austria (Sorger & Holland, 1999) has evaluated downsizing opportunities for a 1.8 L diesel engine cylinder block, converting from gray iron to CGI. The benefits of this conversion included:

- 9% reduction in overall weight of the finished engine
- 22% reduction in weight of machined cylinder block
- 15% reduction in overall length of the finished engine
- 5% reduction in both; height and width of the finished engine

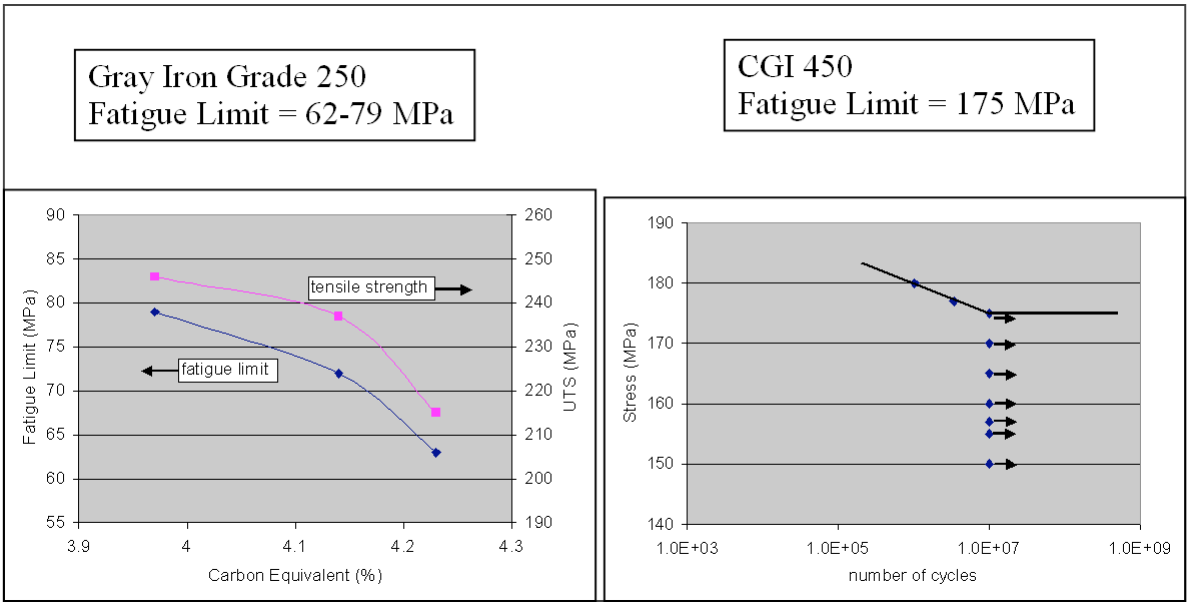


Figure 11 - Fatigue Limit results for an I6 cylinder block – 5.9 L – 150 kg. Samples from the main bearings, push-pull test (R = -1, 10 Hz). Gray Iron Grade 250, 100% pearlite, 210-250 HB, CrCuSn. CGI Grade 450. 2-4% nodularity, <2% ferrite. 230-255 HB. (Guesser, 2003).

4. Some Examples of Engines with CGI Cylinder Blocks:

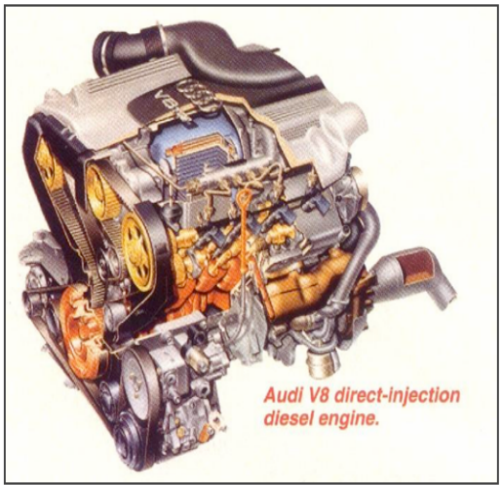
BMW V8 (Birch, 1999; Luchner, 1999)

- power output -180 kW (245 hp) at 4000 rpm,
- maximum torque of 560 N.m between 1750 and 2500 rpm
- acceleration 0-100 km/h in 8.4 s
- fuel consumption 9,9 litres/100 km
- maximum injection pressure of 135 MPa
- adjustment of turbochargers by electric motors
- two intercoolers
- four-valve combustion chambers with the injection nozzle located in the middle

CAD front view of BMW's V8 direct-injection engine.

Audi V8 (Birch, 1999; Kassack, 2000)

- 3,3 L V8
- 165 kW
- 480 N.m of torque available from 1800 to 3000 rpm.
- direct-injection common rail
- cylinder pressures up to 160 bar
- variable turbine geometry turbochargers

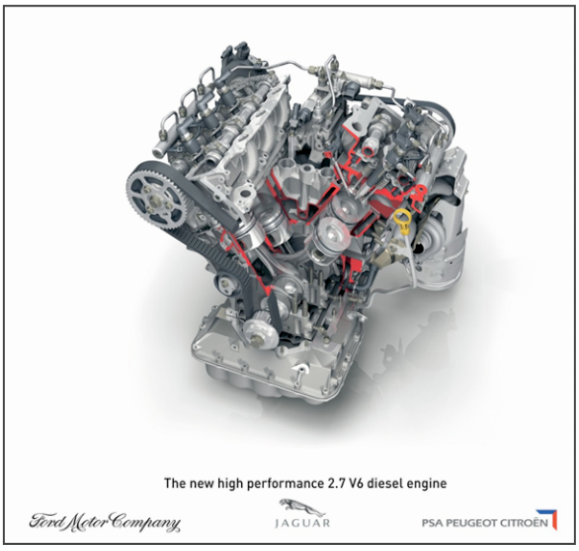


DAF XE390-C (Lampic-Opländer, 1999)

- I6 12,6L
- 1050 kg
- 390 kW
- 2350 N.m at 1100 to 1500 rpm
- emissions according to Euro 3

Ford PSA Jaguar V6

- 2.7L V6 Diesel
- 202 kg
- up to 152 kW
- up to 440 N.m
- common-rail direct injection
- twin turbochargers
- cylinder block in CGI 450



The Ford PSA V6 is the first high volume engine with a CGI cylinder block to be manufactured. Production started in Oct. 2003. The cylinder block is produced at Tupy Fundições, Plant Joinville – Brazil, using the SinterCast technology to control the liquid metal. Some machining operations (super cubing) is also being made at Tupy.

5. Conclusions:

The use of CGI in engine parts is just starting, but already shows its potential for the auto industry. Diesel engines cylinder blocks are the first natural candidates for development, but there are many studies aiming to cylinder heads and also to gasoline engines cylinder blocks. The increasing demands for light-weight design and for emissions reduction promise new opportunities for CGI.

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