Lightweight Automotive Diesel Engine Concepts

INTRODUCTION

The continued growth in the number of diesel engines being used in European passenger cars is shown in the registration statistics. Those statistics show that their share in new registrations has almost tripled and is currently at more than 40% over the past 12 years. The key to their popularity is due to the rapid increase in their specific output with simultaneously very high engine torques. Modern passenger car diesel engine provides for an outstanding driving experience, while at the same time consuming very little fuel. The luxury passenger car market segment is not immune to reaping the rewards of these advantages.

The continued demand for high specific outputs is also accompanied by an increase in the required peak pressure.

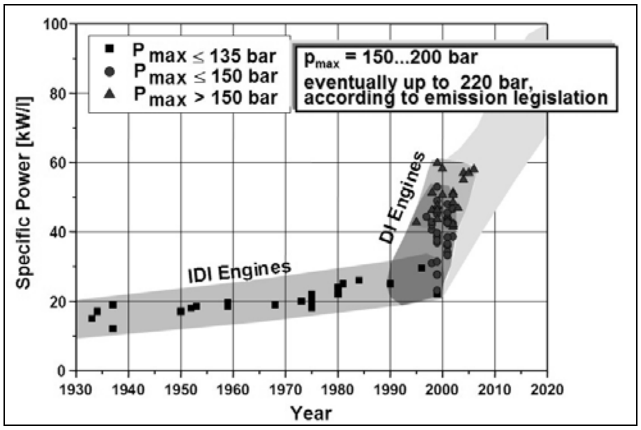

Figure 1: Specific Power and Peak Firing Pressure

Combustion peak pressure increased to a maximum 135 bar by the end of the 1980s. Meanwhile, the specific output relating to the displacement capacity increased only moderately to approximately 25 kW/L. Gasoline engine passenger cars in the same period developed up to approximately 50 to 60 kW/L, more than double the specific power output of a diesel engine. In 1989 Audi released a direct injection diesel passenger car engine for production, which marked a significant increase in the power density of the diesel engine [1]. Gasoline engines achieved similar output densities of up to 60 kW/L, during that short period of approximately 10 years. Accordingly, the maximum combustion pressure increased to about 150 to 160 bar. Modern engines even take values of up to 180 bar into consideration. To achieve these levels, the required component strength must be increased by approximately 10% in order to take tolerances of the engine components as well as those of the fuel-injection equipment into account. Therefore, future product developments must consider a combustion pressure of approximately 200 bar.

Diesel engine specific output is expected to increase as the result of continuous progress improvement. A specific output of approximately 70 kW/L can even be expected by the end of this decade and up to approximately 100 kW/L by the year 2020 are well within reach [2].

COMPONENT WEIGHTS AND MATERIAL PARAMETERS

The design of the new engine design must keep pace with this rapid development. In addition to the requirement for high component loads, permanent demands for a consistent lightweight design must also be taken into consideration. The goal-directed optimization of the component structure and the use of materials adapted to the subsequent application are therefore required [3, 4]. Realization of current components is illustrated in Figures 2 and 3.

The weight of the bare machined cylinder head, with valve seats and valve guides, is indicated without valvetrain components on some of the designs that have been developed.

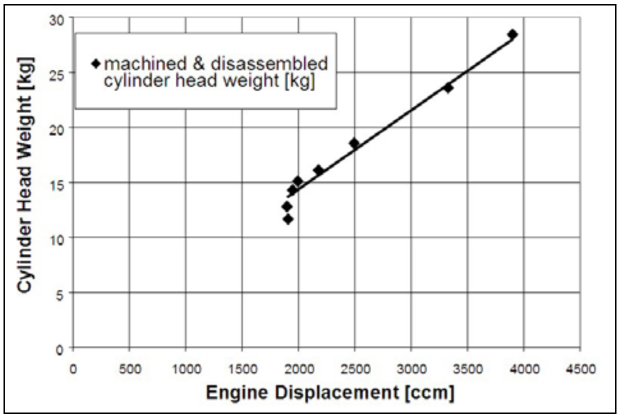

Figure 2: Comparison of Cylinder Head Weight (Aluminum)

All of the illustrated designs that are evaluated utilize aluminum cylinder heads. A two-liter engine will yield a resultant component part weight of approximately 12 to 15 kg. The weight of the cylinder head weight increases proportionally to that of an increase in engine displacement. On V-type engines with high displacements, the weights of both cylinder heads are taken into consideration.

The comparative weights of diesel engine blocks are illustrated in Figure 3.

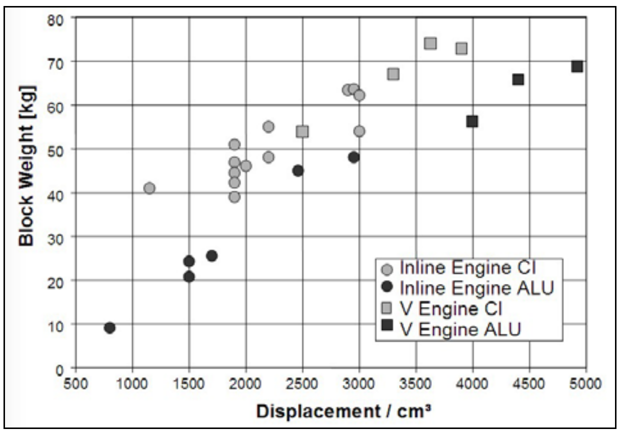

Figure 3: Comparison of Block Weight (HSDI Engines)

Figure 3 also shows the different engine block materials used for both the inline and V-type-engine designs. The comparison of inline engines, having the same displacement, clearly illustrated aluminum cylinder block's weight advantage. Similarly, light-alloy V-type engine blocks are also lighter, i. e. the difference is about 15 kg, being almost independent of the engine displacement. Given this information, an assumption could be made that iron blocks have a higher peak pressure potential than aluminum blocks. However, this assumption is not confirmed, based upon closer examination of the construction. Endurance of up to 180 bar combustion pressure can be achieved in some iron as well as some aluminum engine blocks. Construction of the cast iron blocks consists of two materials, lamellar iron (GJL) and vermicular graphite iron (GJV). A comparison of the material properties is needed prior to completing the investigation of different design concepts for diesel cylinder heads and engine blocks. Figure 4 illustrates the material properties used in their construction.

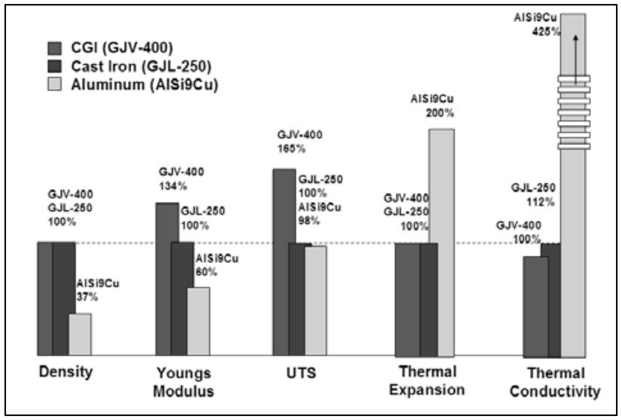

Figure 4: Material Properties

Cast aluminum alloys have a tremendous advantage in their low specific weight. This alloy's density is only about 37% of that of cast iron materials. However, the advantages of iron materials can be seen through a comparison of the Youngs Modulus and the tensile strength. The material strength of GJL is similar to that of aluminum and its stiffness is higher than aluminum by more than a factor of 1.5. The material strength of GJV is approximately 65% higher than that of aluminum and its stiffness is more than double that of GJL. The results shown in the diagram are applicable at room temperature. However, comparative strength values highlight further advantages for iron materials while under operating temperatures [5]. Additionally, thermal expansion and thermal conductivity are essential to the operating behavior and design of the engine. Significant advantages in cooling and heat conductivity can be gained by using aluminum. However, aluminum's high thermal expansion becomes a detriment when it is used as a block or cylinder head material, due to the high component part temperatures occurring during engine operation that produce high thermal tensions and deformations. Specific attention (detailed CAE-computations) in the process of the design must be given to these effects, regarding function and component loads [6, 7 and 8].

Aluminum's greatest advantages are that it is a lightweight material with low density, as opposed to the higher strength values of iron materials. It is this inconsistency that creates the need for a variety of engine designs and the use of different materials.

CAE-computations are used to analyze several designs in greater detail in the text that follows. The goal of that investigation is finding a design that is suitable for higher peak pressures, while taking the lightweight design requirements into account.

CYLINDER HEAD - POTENTIAL CONCEPTS

Extensive investigations and analyses were completed on a modern 2.0L diesel engine, concerning the structure-mechanical load limits of the basic cylinder head as well as those of concept variants.

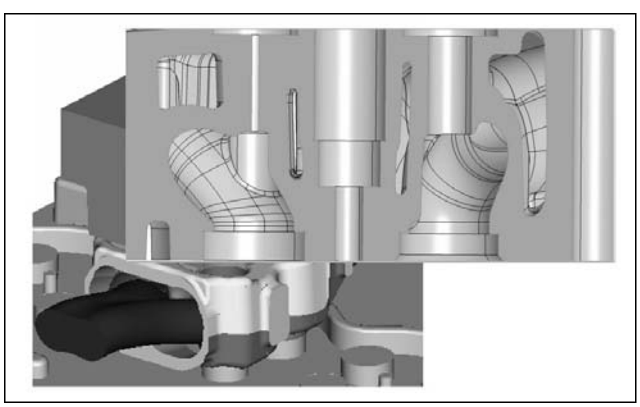

Figure 5: Conventional Cylinder Head Design

The construction of the core and a cross-section of the basic cylinder head are illustrated in Figure 5. A conventional cylinder head design was selected, with aluminum construction, parallel valve arrangement and central injectors. The layout of the cylinder head's combustion system provides for 50 kW/L power density, common in today's market, and 160 bar thermodynamic peak pressure. Compensation for the usual series tolerances of fuel ignition equipment was taken into consideration; however, the design was laid out for 180 bar peak pressure. For a precise routing of coolant, the one-piece water core was partially separated by transverse bulkheads between the cylinders (FEV Helix-U concept).

The highest operating loads occur below the exhaust ports and in the flame deck on both sides of the bulkheads between two cylinders and in both cases locally in the transition radii to the fire deck (figure 6).

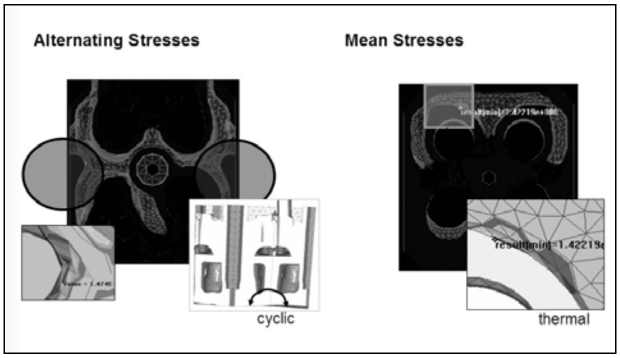

Figure 6: Locations of High Stresses

Due to differences in thermal expansion, the right point is dominated by mean stresses. The left point is, owing to the cyclic ignition pressure, under a stronger dynamic load. In order to quantify the potentials regarding the load limits for future requirements, further design variants were investigated at increased peak pressures:

- Variant 1: cast AISi alloy with intermediate deck

  On the level of the lower end of the valve guides, the water core was separated horizontally by means of an intermediate deck (figure 7).

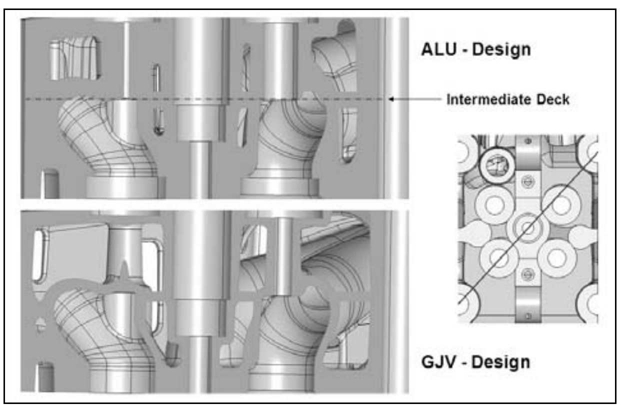

Figure 7: Cast Iron Design versus Aluminum Design

  The gas force was increased to 200 bar mechanical design pressure.

- Variant 2: cast GJV with intermediate deck

The basic construction was appropriately converted to a GJV-thin-walled casting, by intentionally dispensing with separate valve seat rings (figure 7).

In order to reduce the unavoidable disadvantages in weight, compared to the AISi-basis, the GJV cylinder head variant was also designed with a two-piece water core. Besides the structural advantages of the intermediate deck, material-saving undercuts can also be shown that way, which additionally helps shortening the local heat conduction paths. The gas force was further increased to 220 bar mechanical design pressure.

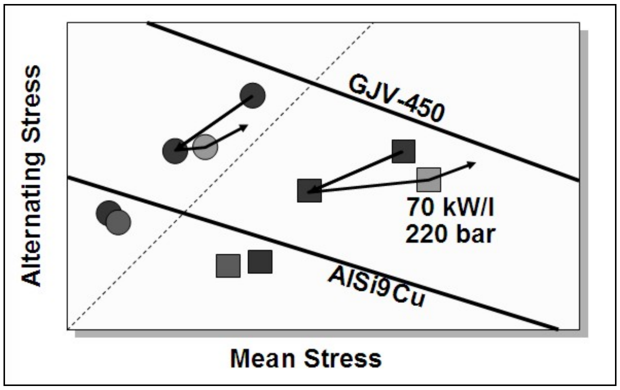

Figure 8: Potential of Design Variants - Haigh Diagram

In the Haigh-diagram (figure 8) a comparison of results of the investigations are illustrated. The square symbols mark the strong mean-stress that occurs below the exhaust ports. The ○-symbols, however, point to the bottom area of the bulkheads dominated by the cyclic gas pressure. For a qualitative valuation of the local safety factors taken against fatigue breakage, the global material characteristics for AlSi9Cu and GJV-450 are indicated, without being able to give attention to local influencing factors (e.g. taking the local temperature or the tension gradient into consideration) in this form of representation.

Comparing the aluminum basic design with its intermediate deck variant, the insertion of the intermediate deck allows the permissible peak pressure to be increased by 20 bar, and even provides slight advantages in fatigue fracture safety. The intermediate deck has not only positive effects on the stress concentration below the exhaust ports, but additionally helps to reduce dynamic stresses even more , despite the gas force being increased to 200 bar. This is due to the capability to take up the thermal expansion in the form of shear stress and to evenly transmit it into the global structure.

The GJV-variant's intermediate deck higher absolute tensions occur as expected. However, due to the clearly higher material strengths, again despite the increased gas force to 220 bar compared to the AlSi-alloy, do not appear to be at a disadvantage. Due to the worse thermal conductivity of GJV, the maximum temperature in the flame deck increases by >100°C. However, the modified structure shows component temperatures (eg. in the injector seat) that are comparable to or even lower than temperatures of the AlSi-basis, because of very short heat conductivity paths in the thin-walled design.

Therefore the target values mentioned at the beginning for the next generation of premium diesel engines in principle can be achieved with the GJV concept under structural points of view.

Lastly the Low Cycle Fatigue (LCF) is examined. The thermal load increases almost equally with the higher power density, leading to a drastic increase in flame deck temperatures. For high output requirements peak temperatures of >400°C are to be expected for GJV-constructions. However, in the modern commercial vehicle sector these values are considered normal and can definitely be controlled. The temperatures are also in connection with the higher combustion pressures. For AlSi alloys, peak values of >280°C are to be expected. In connection with the diesel engine's typical peak pressures, it will probably be more difficult to control these turbocharged gasoline engine-similar values for today's common AlSi-alloys.

POTENTIAL CONCEPTS FOR THE CYLINDER CRANKCASE

A further potential application for GJV is offered in the cylinder crankcase. The increase in power density leads to increasing thermal and mechanical requirements, which are faced with the demand for light weight construction.

For the consistent utilization of the advantages of a high-tensile material FEV Motorentechnik GmbH, Aachen has developed a light weight concept that contains the cylinder block as a short-skirt design (figure 9).

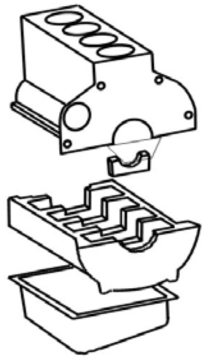

Figure 9: Lightweight Bottom End Concept

In the high stress areas of the crankcase, this concept uses an iron material. The lower end of the crankcase is closed with a light metal ladder frame. The highly stressed areas of the crankcase are:

- The stopper support of the head gasket in the top deck (especially the interbore area)
- The bolt boss connection for the cylinder head bolts
- The bulkhead of the cylinder block
- The threads where the main bearing bolts to the bulkhead

As a result, the cylinder block to achieve the high peak pressure requirements may be constructed in GJL, GJV, or an aluminum block with the highly stressed areas specifically re-inforced with cast iron inserts.

The essential goal for the design, besides the control of material stress, is to keep the distortion of the cylinder liner and the main bearings as low as possible, in order to guarantee safe engine operation under tribological aspects. At both points the crankcase interacts with rotating or oscillating components, with force transmission taking place through the engine oil lubrication. Discontinuities in the oil film aggravate the oil pressure build-up and should be avoided or reduced. In addition, the cylinder liner distortion also influences the leakages at the combustion chamber (blow-by), which are emission-relevant and must also be minimized.

In order to achieve the high acoustic goals common in engine construction today, further measures are required. Here, the FEV concept suggests an aluminum ladder frame as an essential feature. From the acoustic point-of-view and for weight reduction, a frame as high as possible is considered to be optimal, which ideally encloses the complete area below the crankcase. The effect of the frame results from the stiffening of the crankcase longitudinally as well as in a crosswise direction. This leads to a reduced movement of the side walls of the crankcase, thus lowering the noise radiation. The frame concept can, without restrictions and supporting measures, be combined for stiffening the crankcase (e.g. by means of ribs).

The area of the flywheel housing portion of the ladder frame can be stiffened up with ribs, which essentially contributes to the reduction in powertrain bending, i.e. reduces the deflection (oscillation) of the complete drive unit (crankcase and gear box).

Compared to GJL, it is possible that with GJV the cast-on main bearing cap is separated from the crankcase by a fracture split operation. Afterwards, the fracture surface is suitable for positioning the cap relative to the crankcase, so that it is not necessary to take further measures to put it into place.

A further element of the acoustic concept is the use of a sheet metal oil pan, which can be acoustically isolated. The use of sandwich material or a coated oil pan is also possible.

The detailed design of the crankcase strongly depends on the strength of the materials used. This is clearly shown a comparison of the main bearing design for GJV and GJL (figure 10).

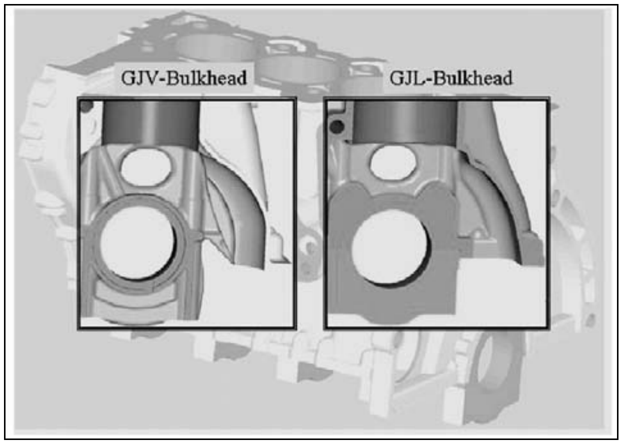

Figure 10: GJL and GJV Block

In order to obtain high peak pressures with low deformation, definitely more material is required with GJL, which strengthens the complete bearing housing. The design of the bolt bosses is definitely more solid. Also, the passage above the bearing required for the longitudinal ventilation in the crankcase has been reduced, compared to GJV, which may lead to increased pumping losses. In principle, a cross section as large as possible is required, so that the weight of the bulkhead can also be reduced. The optimized design in GJV offers identical stiffness, i. e. the same functionality at a lower weight.

A hybrid design is an alternative to the use of iron materials for the diesel engine crankcase. Here, an insert, often made of spheroidal cast iron (GJS), is used for carrying the bolt forces of the main bearing cap and cylinder head connections. The pre-cast inserts are premachined for positioning and can be used for all kinds of cast aluminum. In principle a permanent connection turns out to be difficult. As a result of the different thermal expansion of aluminum and cast iron materials, shearing stress occurs on the surfaces, which already after a short time or a low stress reversal show a tendency for detachment. This problem results in the requirement of a sufficient dimensioning of the inserts to carry and transfer the tensile forces by themselves. Therefore, aluminum, apart from taking the contact forces of the insert, mainly serves the purposes of closing off the crankcase towards the surroundings, guidance of gas, water and oil and the support of accessories. The inserts are not necessarily connected with each other. That way the aluminum structure must guarantee the global stiffness of the cylinder crankcase, which is necessary for good acoustic behavior. The optimization of the aluminum structure requires effective CAE methods for the simulation of the sound radiation and the powertrain bending.

In principle, the hybrid structures are suitable for inline engines as well as for V-type engines. Lightweight design is in particular required for the reduction of the engine weight in large-volume V-type engines in premium vehicles. Large diesel engines represent the heaviest aggregate in a vehicle platform, so that the lightweight design measures of this engine mean corresponding weight advantages for the vehicle itself. In this situation the hybrid design offers the greatest potential; therefore, the increased costs are accepted.

The comparison of functional parameters and costs for a direct-injection diesel engine with four cylinders and 2.0L displacement for the materials GJV, GJL and an aluminum hybrid structure with GJS inserts is shown in figure 11.

4-Cyl. 2,0L 400.000 per year	GJV	GJL	AL
Nom.Wall Thickness	3.5mm	3.5mm	4.5mm
CONCEPT	•Short Skirt •Ladder-Frame •Sheet Metal Oil Pan •Cracked Main Bearing	•Short Skirt •Ladder-Frame •Sheet Metal Oil Pan	•Short Skirt •Ladder Frame •Sheet Metal Oil Pan •Insert Design/CI Liner
Total Block Weight	Down To 90%	100%	80% - 70 %
Max. Peak Pressure	200 bar	200 bar	200 bar
Space Between Liner	8 mm	8 mm	10 mm
Manufacturing Costs	138 %	100 %	162%

Platos

Figure 11: Comparison GJV-GJL-AL 4-Cyl. 2.0L

For the materials GJL and GJV, a general wall thickness of 3.5 mm and for aluminum a wall thickness of 4.5 mm is used as a basis. The crankcases are all designed for a suitable peak pressure of 200 bar and correspond to the FEV lightweight concept. The advantage of the low engine block weight of GJV, compared to GJL, at almost identical dimensions, is paid for with additional costs of approximately 38%. The hybrid structure offers a clear weight advantage of about 20% to 30%; however, it requires a bigger space to accommodate the design, as the required land widths between the cylinders are higher. A clear disadvantage is currently represented by the costs, which are approximately 62% higher than that of GJL. This is caused by the higher costs for raw parts, which are additionally increased by the casting process of the inserts. The costs, apart from that, are essentially more favourable because processing light metal blocks are increased by the mixed machining operations of hybrid structures. Therefore, in the end the trade-off between weight optimization and production costs essentially decides the selection of the crankcase material.

CONCLUSIONS

Future performance requirements for direct-injection diesel engines, considered from a mechanical standpoint, are represented by modern design concepts that are appropriate for the different materials. The fatigue limits for the thermomechanical loading capacity of pure aluminum designs will be reached, without further development of AISi cast alloys. Converting a modern four-cylinder production engine, with a cast lamellar iron block and an AISi cylinder head, to GJV or a hybrid structure of AISi with cast-in inserts would result in higher peak pressure suitability for the cylinder crankcase. However, higher manufacturing costs would result from the conversion. Increasing the engine's power density from the potential downsizing, would result in additional weight and packaging advantages. Prior to making changes in the engine's material, the structural design of the cylinder head would also require modification, e.g. in the form of an intermediate deck in the water jacket. State-of-the-art or future trends for the materials used in engine crankcases and cylinder heads are summarized in figure 12:

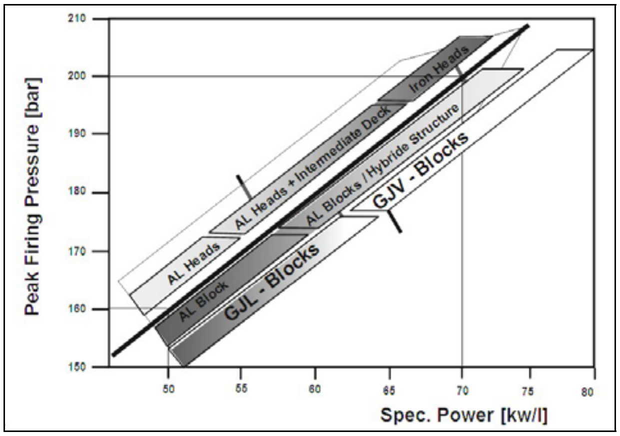

Figure 12: Conclusions

- Very high cylinder peak pressures of up to 200 bar are required for a continuous increase in output from HSDI diesel engines. New design solutions for cylinder heads require an aluminum intermediate deck. Iron materials for the crankcase and cylinder head may be at an advantage under conditions with peak pressures above 200 bar.
- Extremely light HSDI crankcases, especially in engines with higher displacement capacities (e.g. V6 and V8), will utilize aluminum iron hybrid designs or vermicular graphite iron.
- To arrive at an individual solution, the decision will be a trade-off between cost and weight.

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