Applications – Power train – Cylinder heads

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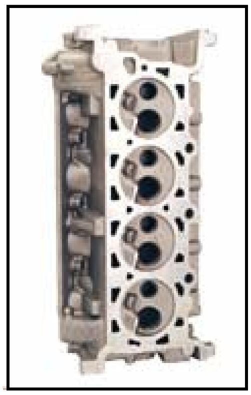
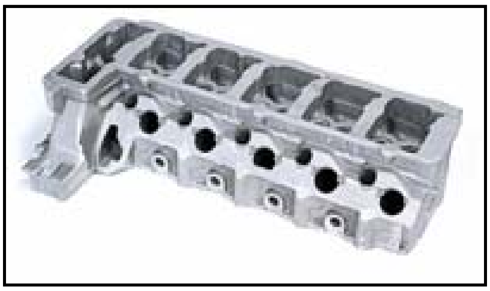
4 Cylinder heads

Source: Nemak

4.1 Introduction

The cylinder head is an integral component of internal combustion engines. It conveys air and gasoline to the combustion chamber and serves as a cover for the cylinders. The main function of the cylinder head is to help the head gasket seal the cylinders properly so that they are able to build enough compression for engine operation. In the vast majority of four stroke engines, the cylinder head mounts the entire valve gear and provides the basic framework for housing the gas-exchange valves as well as the spark plugs and injectors. It also supports the different parts of cooling system.

The cylinder head must be strong and rigid to distribute the gas forces acting on the head as uniformly as possible through the engine block. The combustion gas, the coolant and the lubricating oil flow independently in the cylinder head and follow complex three dimensional routes. Thus cylinder heads are generally produced by gravity or low-pressure die casting. In Europe, grey cast iron cylinder heads have been almost completely replaced by cast aluminium alloys during the past 20 years. Aluminium has the advantages of light weight, high thermal conductivity, and ease of production to close tolerances.

Depending on the engine type, the introduction of an aluminium cylinder block results in a weight reduction of 10 to 20 kg (i.e. at least 50%). But even if the engine block is cast iron, the cylinder head is normally made of aluminium as it allows a more rapid extraction of the combustion heat compared to grey iron. The differing rate of thermal expansion between aluminium and iron creates significant stress levels in the interface region between the block and the head, but this problem can be solved by suitable bolting concepts. Furthermore, compatibility problems with the block become more and more obsolete as the market share of aluminium blocks is steadily growing.

4.2 Design features

The development and production of engine blocks and cylinder heads is often considered to be a core competence of the car manufacturers. With the ongoing substitution of iron by aluminium, the heads and blocks market segment has grown, but there are nevertheless only a limited number of independent competitors besides the OEMs. The reasons are the strong entry barriers that exist for potential competitors.

Engine type

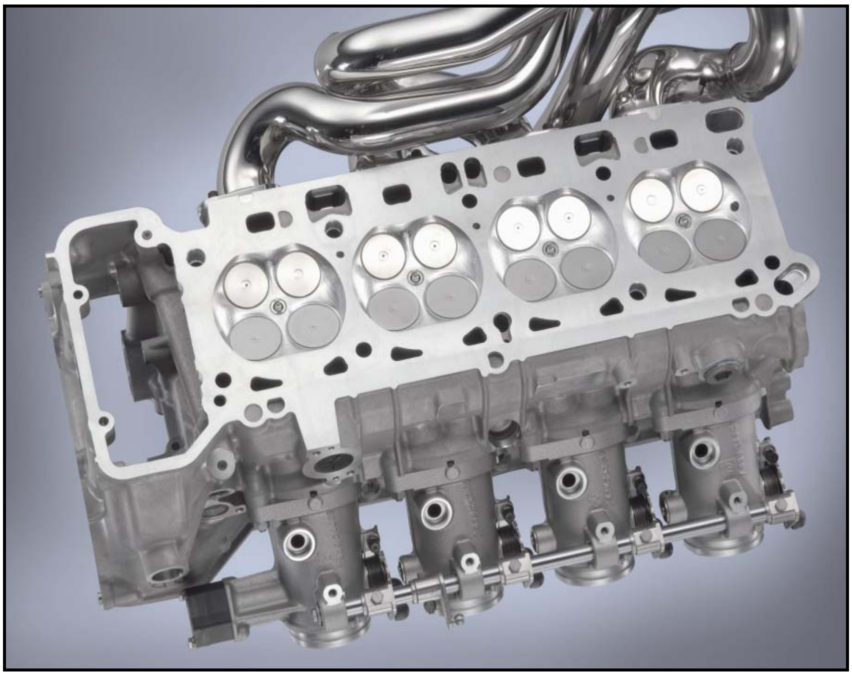
Conventional engines with an „in-line" array of the cylinders have one cylinder head. V-engines generally need two cylinder heads, which may have identical or differing geometry. Provided that the angle between the two cylinder axis planes is not too big (<= 15°), V-engines can also be equipped with only one cylinder head. In this case, the cylinder axis is not perpendicular to the joint face.

Integration of valves

The cylinder head holds the intake and exhaust valves, thus there may be many designs according to the number and positioning of the valves and the form of combustion chamber**.** In general, two valves are adequate for engines developing up to 35 kW/l, but above this level of power density, more valves are desirable. The increased number of valves offers distinct advantages:

- The spark plug can be more easily positioned close to the centre of the chamber, i.e. the flame path is short and complete combustion is easier to attain. Also the ignition timing can be retarded so that the dwell of the gases at high temperature in the cylinder is reduced.
- The interaction of the two incoming streams of gas can greatly improve mixing, again leading to more complete combustion.
- With two exhaust valves instead of one, the ratio of seat length to area exposed to the hot gases is higher and, therefore, the rate of cooling by conduction through the seats is also higher.

Thus, in modern cylinder heads for high performance engines, three, four or even five valves and possibly two spark plugs have to find place in the flame deck resulting in a continuously decreasing space between the valves. This area also sees the highest temperatures and is exposed to severe thermal fatigue effects when the engine warms up or cools down. In addition, pressed-in valve seat inserts - generally made from sintered powder metal - are essential for aluminium cylinder heads. Consequently, special care has to be taken to avoid local failure due to fatigue cracking. The geometry of the flame deck and the inserted valve seats as well as the surface condition and porosity of the aluminium material play a crucial role regarding crack initiation within that area.



Cylinder head with individual throttle bodies and exhaust manifolds

Source: BMW AG

Type of engine

Cylinder head design should help to improve the swirl or turbulence of the air fuel mixture and prevent fuel droplets to set onto the piston surface or the cylinder wall. Combustion must always take place within a turbulent flow field since turbulence increases the mixing process and enhances combustion.

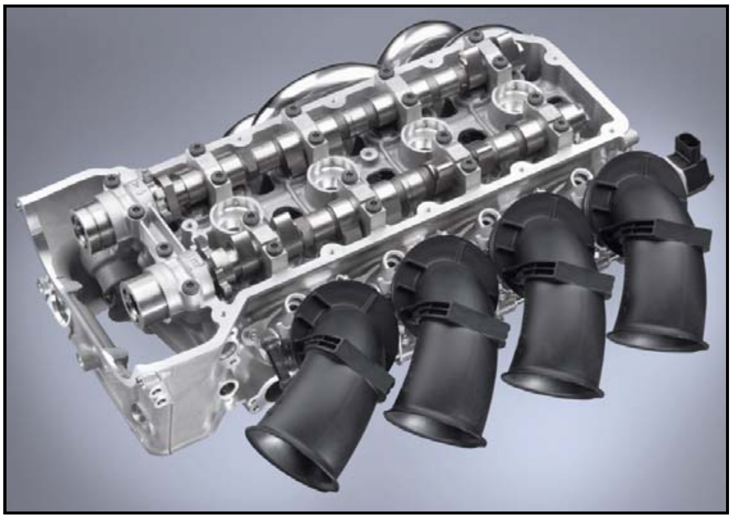
The shape of the flame deck depends very much on the type of engine. Gasoline cylinder heads have bowl shaped cavities in the flame deck, whereas direct injection diesel heads usually have a flat and machined surface which is beneficial when looking at thermal fatigue crack initiation.

Cylinder head of the diesel engine of the Mercedes Benz A class

Source: Daimler AG

Camshaft bearings

The seats for the camshaft bearings may be incorporated into the cylinder head casting. For specially designed heads the camshaft bearings may be incorporated also as a second component produced by high pressure die casting.



Cylinder head with camshafts and intake trumpets

Source: BMW AG

In order to reduce fuel consumption, recent research activities have concentrated on variable valve actuation. The BMW Valvetronic technology, for example, replaces the conventional throttle butterfly with an electrical mechanism that controls the amount of lift of the individual intake valves on each cylinder. FEV's patented Electromechanical Variable Valve Timing System (EMVT) allows fully variable operation of the intake and exhaust valves with minimal changes to the cylinder heads of gasoline engines. As a result, the conventional camshaft is not anymore necessary for the control of the valves.

New technical developments

As a consequence of the current engine development trends, in particular the tendency to downsize the engines, the cylinder head must meet additional requirements:

- Enable further weight reduction
- Permit increased power densities; future expected performance values are up to 65 kW/l for direct injection diesel engines and up to 75 kW/l for boosted gasoline direct injection engines
- Allow the introduction of advanced combustion systems for both spark (SI) and compression (CI) ignition engines.

Thus the specifications for aluminium cylinder head castings are becoming more and more severe:

- Higher operating temperatures (due to the high power density)
- Increased combustion pressures, meaning higher mechanical stresses (static and dynamic) on the material that combined with thermal cycles may cause significant reduction in fatigue life of the component;
- Designs with multi-port layouts and application of advanced combustion systems, leading to very complex geometries and thin cooling water passages.

In the next generation engines, the combustion pressure is expected to rise to the 180-200 bar range for CI engines and to 100-120 bar range for boosted SI engines, while the maximum combustion chamber wall temperatures, usually found at the bridge between the exhaust valves, might rise well over 250°C and even approach 300°C.

4.3 Material requirements

As a result of the permanent increase of combustion pressures and temperatures, the potential of the common aluminium cylinder head alloys is almost fully exploited. In order to satisfy all the product requirements, optimised casting alloys and a proper control of the as-cast microstructure by the application of sophisticated casting processes are generally necessary.

Strength

The applied aluminium alloys have to offer sufficient strength and hardness at room temperature for machining and assembly. Furthermore, high strength at elevated temperatures (up to 250°C) is crucial to ensure that the engine block-cylinder head assembly can withstand the combustion forces and the forces resulting from thermal expansion and contraction during service cycles without losing tightness of the cylinder head gasket. Creep strength is required in particular for the head gasket area.

Thermal conductivity

The cylinder head can support the high combustion temperatures only due to an efficient cooling. A decisive characteristic for the cylinder head material is therefore a high thermal conductivity. On the other hand, any addition of alloying elements to aluminium for the purpose of increasing strength or creep resistance results in a decrease of the thermal conductivity. Hence, a compromise between the two counteracting targets has to be found.

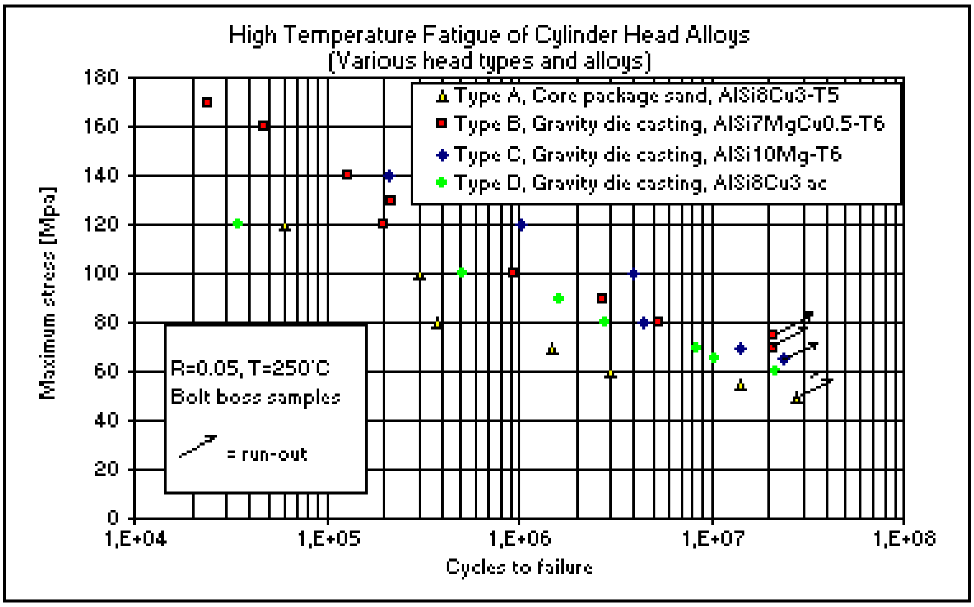
Surface quality

An unimpeded flow of the incoming gas is of major importance for the combustion process. Thus, high demands are made on the smoothness of the surface of inlet and outlet channels. The roughness of the flame deck surface should be minimized as well, because any notches can lead to the initiation of fatigue cracks (see below).

High- and low-cycle fatigue

Cylinder heads are exposed to high-cycle fatigue (HCF) due to the combustion cycles and to low-cycle fatigue (LCF) resulting from thermal expansion and contraction during start-up and stop of the engine. Critical HCF areas are on the water jacket side of the flame deck wall because of the prevailing cyclic tensile stresses, while LCF may primarily cause cracks in the thin-walled valve bridge areas which are at the same time exposed to the highest temperatures within the cylinder head.

LCF strength is partly related to the static strength at high temperatures which in turn is strongly influenced by the alloy composition. However, HCF strength can only be slightly influenced by the alloy composition. In this case, the cast microstructure, the presence of casting defects (in particular porosity) and the surface quality are the dominating parameters. The application of an alloy with defined ductility seems to be advantageous since some studies indicate that better low cycle fatigue behaviour is related to a higher ductility when small material plastifications are allowed.

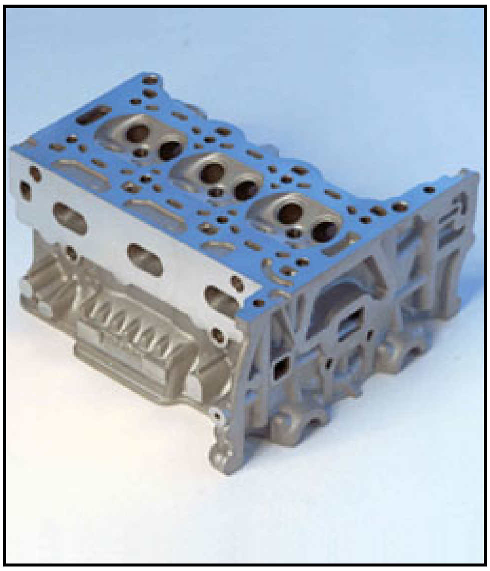


Fatigue properties at 250 °C for different types of cylinder heads and alloys

Source: Hydro, former VAW

Castability

The castability of an alloy is generally improved with increased Si content, while Cu additions, which are required for high temperature strength, have a negative effect on the feeding behaviour. Insufficient feeding could lead to defects in the as-cast structure, in particular porosity. The presence of such defects would be critical in those regions of the cylinder head which are exposed to high cycle fatigue, i.e. the area between the valves in the flame deck or the walls between the flame deck and the water jacket.



Cylinder head for a 3 cylinder engine, gravity die casting

Source: Hydro, former VAW

4.4 Alloy composition and heat treatment

The alloy selection for cylinder head castings requires the consideration of various criteria, some of them similar to those used in case of engine blocks. Many cylinder head castings undergo a heat treatment with a subsequent aging. In this case, potential aging effects during operation of the engine over a long period have to be considered too.

The best combinations of strength and ductility are offered by casting alloys with low iron content such as AlSi7Mg0.3 (A356). Therefore, in the past, most cylinder heads were made from primary aluminium alloys. But also alloys which can be produced using recycled aluminium (i.e. with a slightly increased impurity content) such as AlSi10Mg or AlSi7Mg still provide sufficient ductility. Due to the poor high temperature performance of this type of alloys, new Cu- or Ni-containing alloys have been developed specifically for high performance diesel cylinder heads (e.g. AlSi7MgCu0.5, AlSi9Cu1Mg and AlSi7MgCuFeNi). They provide higher strength at elevated temperatures while maintaining ductility and fatigue performance. Cylinder heads produced with these alloys are usually applied in the T6 condition.

For moderately loaded cylinder heads of gasoline engines, also foundry alloys like AlSi8Cu3 or AlSi6Cu4 (similar to A380.2 and A319, respectively) can be considered. They are widely used for cylinder heads produced in the gravity casting processes. The T4 and T5 conditions are favoured whereas the as-cast (F) condition may cause problems due to insufficient dimensional stability and hardness, the latter being most important for ease of machining.

Commonly and occasionally used alloys and heat treatments for cylinder heads
(composition of the casting according to EN 1706)

Alloy	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Used Tempers
EN-AC-AlSi8Cu3 1)	7.5-9.5	0.8	2.0-3.5	0.15-0.65	0.05-0.55	0.35	1.2	0.25	F, T4, T5
EN-AC-AlSi6Cu4 2)	5.0-7.0	1.0	3.0-5.0	0.2-0.65	0.55	0.45	2.0	0.25	F, T4, T5
EN-AC-AlSi7Mg0.3	6.5-7.5	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi7Mg 3)	6.8-7.2	0.45	0.15	0.35	0.25-0.65	0.15	0.15	0.05-0.20	T6
AlSi7MgCu0.5 4)	6.5-7.5	0.19	0.4-0.6	0.10	0.25-0.45	0.03	0.07	0.08-0.25	T6
EN-AC-AlSi9Mg	9.0-10.0	0.19	0.05	0.10	0.25-0.45	0.03	0.07	0.15	T6
EN-AC-AlSi10Mg(Cu)	9.0-11.0	0.65	0.35	0.55	0.20-0.45	0.15	0.35	0.15	T6

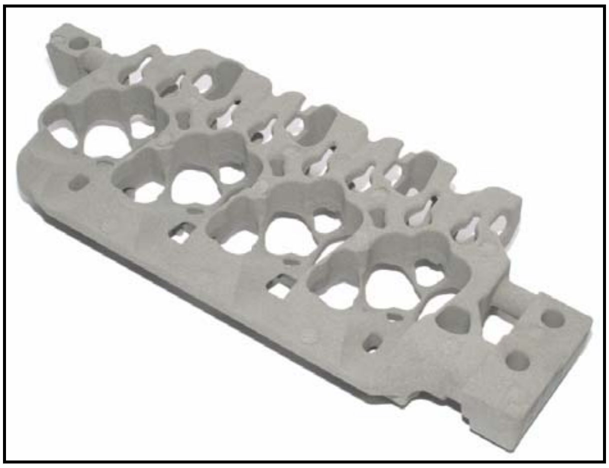
1) A380.2, VDS 226 3) LM25 2) A319, VDS 225 4) not standardized

In practice, the applied alloy composition is optimized depending on the specific cylinder head design and casting conditions. It is important to find a compromise between high temperature strength, ductility and fatigue performance while maintaining reasonable material cost by tolerating certain levels of impurities.

The performance requirements of highly loaded cylinder heads have pushed the suppliers of aluminium castings to develop new process solutions with the aim of increasing the quality of the cast components, minimizing the number of casting defects (porosity, inclusions etc.) and improving the microstructure of the material (dendritic arm spacing). Nevertheless, the current engine development trends leading to higher operating temperatures and increased combustion pressures ask for new alloy developments. Although the performance of the standard Al-Si casting alloys could be significantly improved by the addition of Cu (and other alloying elements) to obtain better resistance at high temperatures (up to 250°C), these improvements might not be enough to meet future engine performance targets. The application of alternative aluminium alloy systems with better high temperature properties (e.g. Al-Cu alloys) will have to be considered, although their applicability is limited by their poor castability which makes it difficult to manufacture complex castings, like cylinder heads, at high production rates.

4.5 Applicable casting processes

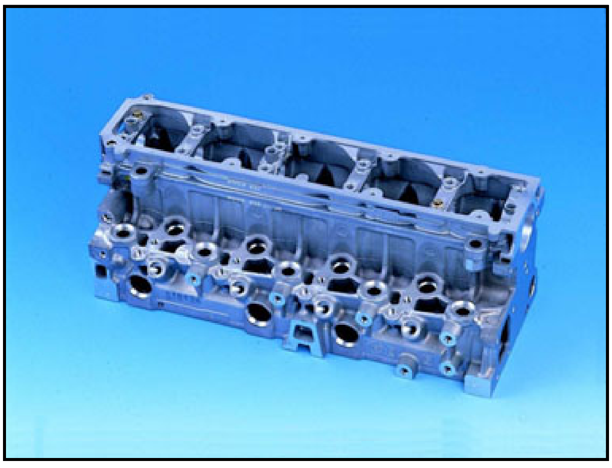
Different casting processes using sand moulds or, preferentially, metal dies are applied for the production of aluminium cylinder heads, each offering advantages and disadvantages. The channels for the combustion gas, the coolant and the lubricating oil are cast hollow using sand cores installed in the holder mould. For this reason, the high-pressure die casting cannot be used because the sand cores are fragile and would not endure the high injection pressure of molten aluminium.



Sand cores with inorganic binders increase dimensional conformity and jointing quality of technically complex castings

Source: Honsel

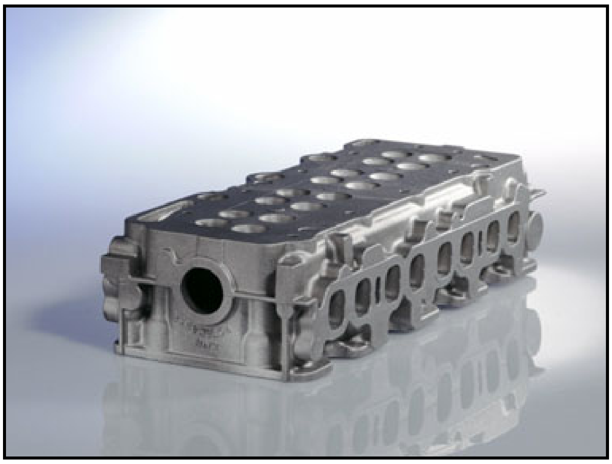
Gravity die casting is worldwide the traditional casting process for cylinder heads. Depending on the position of the casting in the mould, the process enables to achieve a high solidification rate in the flame deck region resulting in a fine microstructure with low porosity, and hence good mechanical properties. With the application of sand cores, a very sophisticated cooling water-jacket with a complex geometry of can be realised.



HDI diesel cylinder head produced by gravity die casting, alloy EN-AC-AlSi7Mg0.3, T6 temper

Source: PSA

The Rotacast® process, a variant of the gravity die casting method, provides even higher cooling rates in the flame deck area and at the same time a higher productivity due to a smaller volume of feeders and runners.



Isuzu diesel 4-cylinder head produced with the Rotacast® process, alloy EN-AC-AlSi7Mg / T6 temper

Source: Hydro, former VAW

Low pressure die casting provides similar benefits as the conventional gravity die casting process. Additionally there is nearly no process scrap (feeder, etc.). However, due to the fact that the machinery is blocked during the entire solidification time, the total cycle time is relatively high, which in turn decreases productivity.

The lost foam casting process is predestined for castings with very complicated and complex geometries which is in fact the case for water jackets in cylinder heads. But apart from the need of perfect mastering of the process, the safe avoidance of porosity in important areas (e.g. flame deck) can be a problem, because the implementation of local cooling in the lost foam process is difficult.

4.6 Future developments

Application-specific optimizations of aluminium alloys and casting processes, including an improved control of the local solidification conditions, are ongoing and will enable continuous improvements of the performance characteristics of the cylinder head.

Another approach looks for an improvement of the quality of the casting by the subsequent elimination of defects. Hot Isostatic Pressing (HIP) is a well known method that employs high pressure and high temperature to “heal” porosity and other casting defects. In the conventional HIP process the pressurizing medium is typically a gas and the process is carried out at elevated temperatures for specific time periods (normally several hours per cycle). Another possibility is Liquid Hot Isostatic Pressing (LHIP) where the medium used to apply the isostatic pressure is a liquid (molten salt bath).

A further idea is to split the cylinder head into two parts, each one made by using the best combination of material and manufacturing process. The lower part of the cylinder head facing the combustion chambers could preferably be realized with a high temperatures resistant alloy. Without the necessity to use sand core, a high performance alloy such as AlCu4TiMg, which is not easily castable in complex forms, could be used. For the upper part of the head, it is then possible to use an aluminium alloy with excellent castability. In comparison to a traditional single casting, it would also be possible to simplify and strengthen the sand core that make the passages in the upper part of the head and to draw passages for the cooling fluid that optimizes the cooling in the critical zones (for instance between the valves).

Considering the many advantages offered by aluminium in cylinder head applications, a substitution of aluminium by other materials is not likely for the moment.