NEW DEVELOPMENTS IN HIGH PERFORMANCE CYLINDER HEADS: APPLICATION OF LHIP AND SPLIT CYLINDER HEAD CONCEPT

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Abstract

Since specific power output of new engines is increasing, many engine components are facing new challenges. Among these, cylinder heads have to withstand tougher operating conditions in terms of temperatures and loads, which are approaching the limits of present aluminum alloys and of the manufacturing processes currently applied.
The paper discusses two approaches to possibly extend the application of Aluminum alloy heads beyond their present limits: the first is the application of the Liquid Hot Isostatic Pressing (LHIP¨) process aimed to improve the quality of the castings; the second is a novel design concept, split cylinder head, based on the application of different materials in different parts of the head, in order to achieve locally the required material properties.

Riassunto

La tendenza in atto ad aumentare la potenza specifica sui motori di nuova concezione comporta un inasprimento dei livelli di sollecitazione di vari componenti del motore. Tra questi, in particolare, le teste cilindri devono essere in grado di sopportare condizioni operative sempre più gravose, sia in termini di temperatura che di carico, che sfruttano al limite le caratteristiche delle leghe di alluminio e dei processi produttivi impiegati per produrle.
Il presente lavoro analizza due applicazioni che potrebbero permettere di estendere l'utilizzo delle teste cilindri in lega leggera oltre i limiti odierni: il primo è la pressatura isostatica in fase liquida (LHIP), con l'obiettivo di migliorare la qualità dei getti; il secondo è un concetto di architettura innovativa della testa cilindri, basato sulla scomposizione (split) del componente in due parti e sull'utilizzo di materiali con caratteristiche diverse a seconda del tipo ed entità delle sollecitazioni cui devono resistere.

INTRODUCTION

In recent years the main drivers for the evolution of automotive powertrains have come from legislation (exhaust emissions, fuel consumption) and from end user expectations (increased output, better driveability and comfort).
The results of this development process have been the setting of clear trends in terms of:

- weight reduction, due to wider application of light materials;
- increased power density and tendency to downsizing of the engines; future expected values are up to 65 kW/l for Direct Injection Diesel Engines and up to 75 kW/l for boosted Gasoline Direct Injection engines;
- introduction of advanced combustion systems for both Spark (SI) and Compression (CI) Ignition engines.

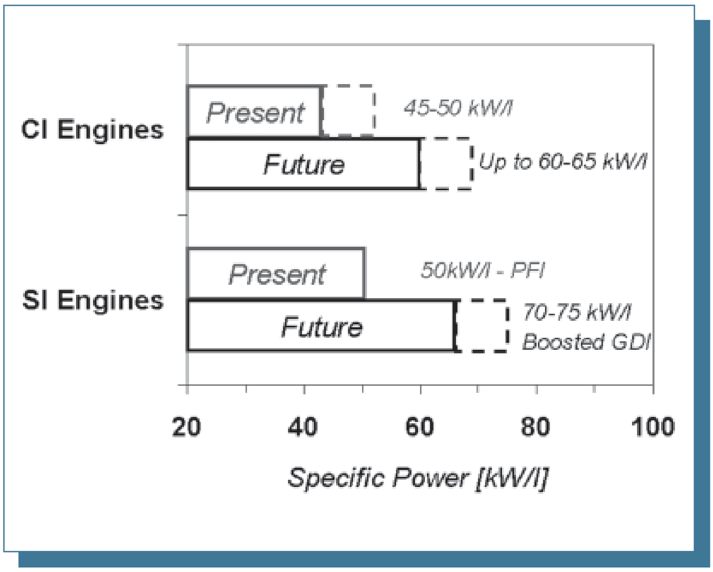

Fig. 1: Future engine trends.

As a consequence of the above described engine development trends, specifications required to aluminum cylinder head castings are becoming more and more severe, due to:

- high power density, resulting in higher operating temperatures;
- 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;
- multi ports layouts and application of advanced combustion systems, leading to very complex geometries and thin cooling water passages.

As shown in Fig.2, maximum combustion pressures and wall temperatures in the combustion chamber of a cylinder head are related to the specific power level of the engine.

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

These new requirements have pushed the casting supplier to develop new process solutions with the aim of increasing the quality of castings, minimizing defects (porosity, inclusions etc.) and improving the microstructure of the material (dendritic arm spacing), in order to achieve better mechanical properties. In addition, Al-Si alloys have been improved to obtain better resistance at high temperatures (up to 250°C), in particular primary alloys with the addition of copper (Cu) have been extensively applied to highly loaded cylinder heads.

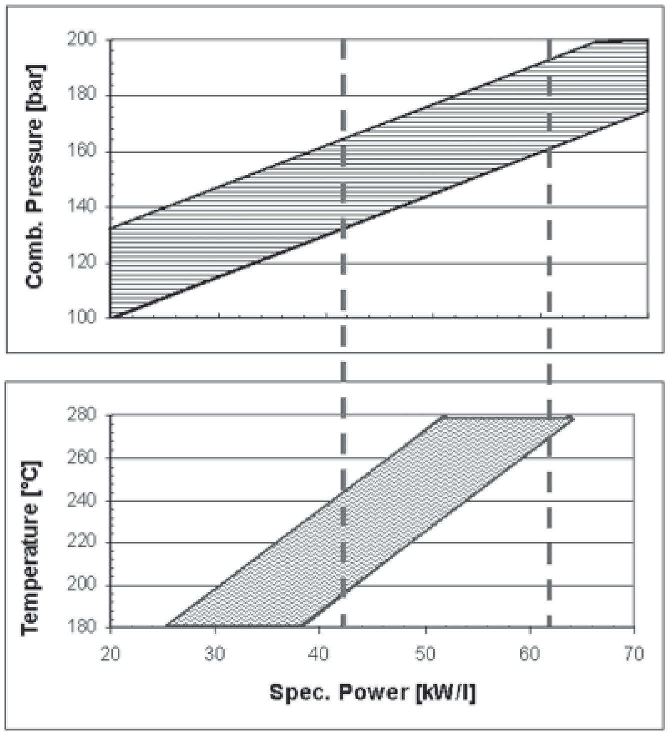

Fig. 2: Next generation engines performances.

Nevertheless these improvements might not be enough to meet future engine performance targets. Moreover the application of alternative aluminum alloys with better high temperature properties (e.g. Al-Cu alloys) is limited by their poor castability, that makes difficult to manufacture complex castings, like cylinder heads, at high production rates.

THE LHIP TECHNOLOGY

Hot Isostatic Pressing (HIP) is a well known manufacturing method that employs high pressure and high temperature to consolidate or to densify materials.

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). HIP is utilized to heal casting defects and voids, to bond similar or dissimilar materials and to form net or near-net-shapes from metals or ceramic powders.

The Liquid Hot Isostatic Pressing (LHIP) is an evolution of the standard HIP process. In this case the medium used to apply the isostatic pressure to the treated part is a liquid (molten salt bath).

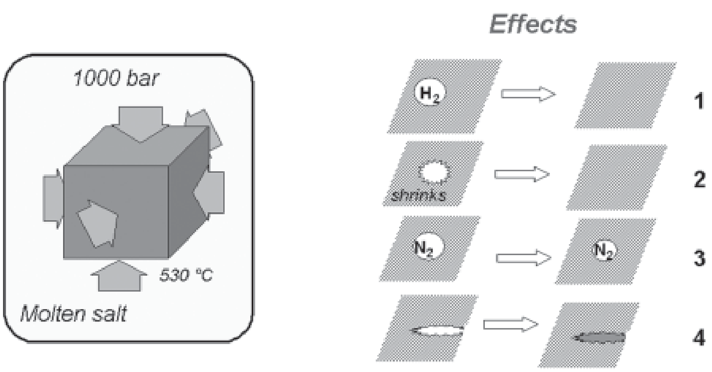

Fig. 3: LHIP: 1) H_2 porosity, 2) Shrinkage, 3) N_2 porosity, 4) Open cavity.

The isostatic pressure applies a uniform pressure around the casting and anywhere the liquid can go.
The combination of pressure and temperature can eliminate shrinkage and H_2 porosity. Shrinkage porosity will collapse under the force of the pressure. H_2 porosity under pressure and temperature goes into solution. N_2 porosity cannot be definitely closed because nitrogen cannot go in solution in aluminum alloys, once the pressure is relieved porosity opens up again, but with a smaller size. Cracks and open shrink cavities cannot collapse because the LHIP liquid will fill the voids having no effect. Fig. 3 explains how the LHIP process works.

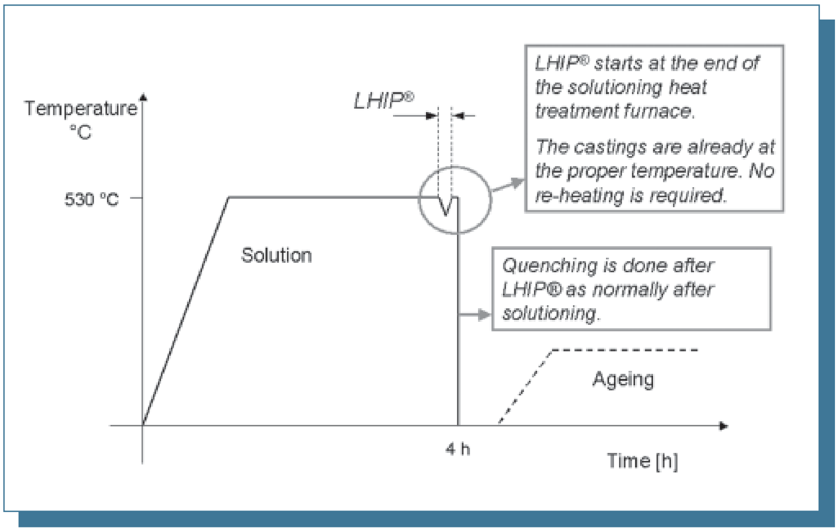

Fig. 4: LHIP included into T6 heat treatment.

A pre-requirement of the process is to have the castings pre-heated at an operative temperature very close to the one of the solution heat treatment. This temperature reduces the yield strength of the alloy, allowing the high pressure to work around the porosity of the casting and to provide the energy for H_2 to enter in solution.
Thus, the LHIP process can be seen as an extension of a conventional solutioning treatment, applied immediately after the castings come out of the solution furnace and just before the quenching. From a production point of view this means that there is no additional cost for re-heating the castings.
The LHIP process has been developed and patented by Metal Casting Technology (USA)[2]. Teksid Aluminum built, under MCT license, the pilot facility, installed at its Technical Center in Borgaretto (Italy). The results shown in this paper were obtained with this pilot plant.
The advantages of liquid vs gas Hot isostatic pressing are:
- Liquid molten salt is virtually uncompressible: a small variation in volume generates very high pressure change
- Short piston stroke for reaching operating pressure
- Fast cycle time (few minutes)
- No explosion hazard (if a component fails

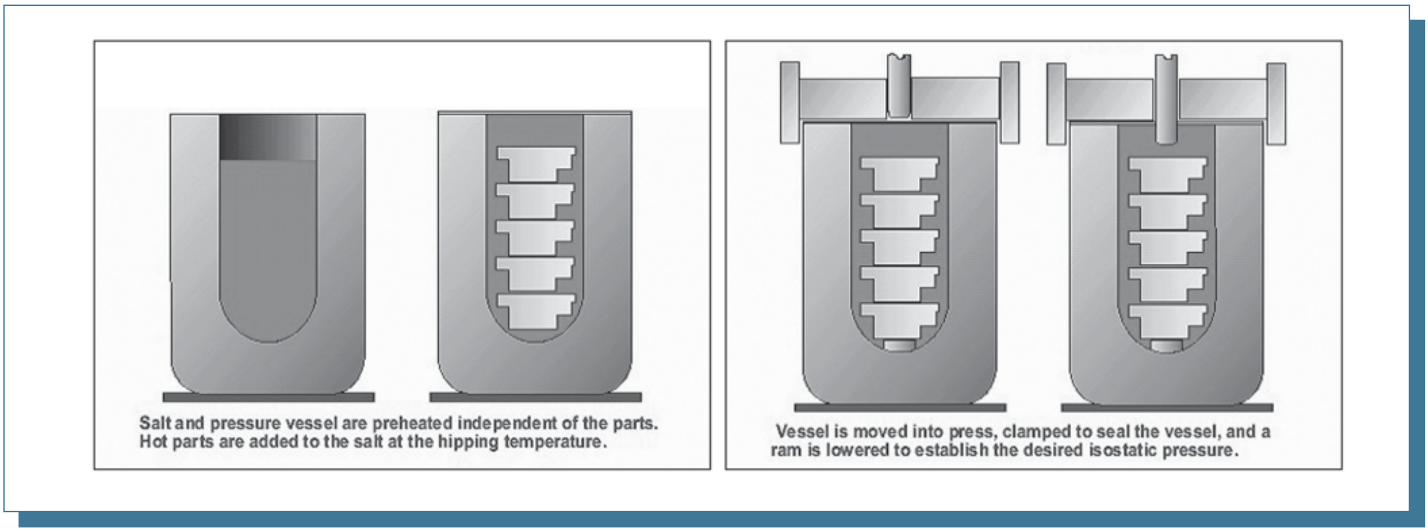

Fig. 5: LHIP process steps.

pressure drops with small spillage of liquid)
- Lower cost
- Possibility to easily include LHIP into T6 heat treatment

Teksid Aluminum has a specific Patent [1], about the integration of HIP in a heat treatment process.
As consequence of porosity reduction, the density on specimens extracted from cylinder head increase. Fig. 6 shows typical densification effects resulting from the application of LHIP.
For example using specimen cast with AlSi7Mg alloy the results obtained in term of density are: as cast 2,614 g/cm^3 after LHIP 2,672 g/cm^3 (2.2%

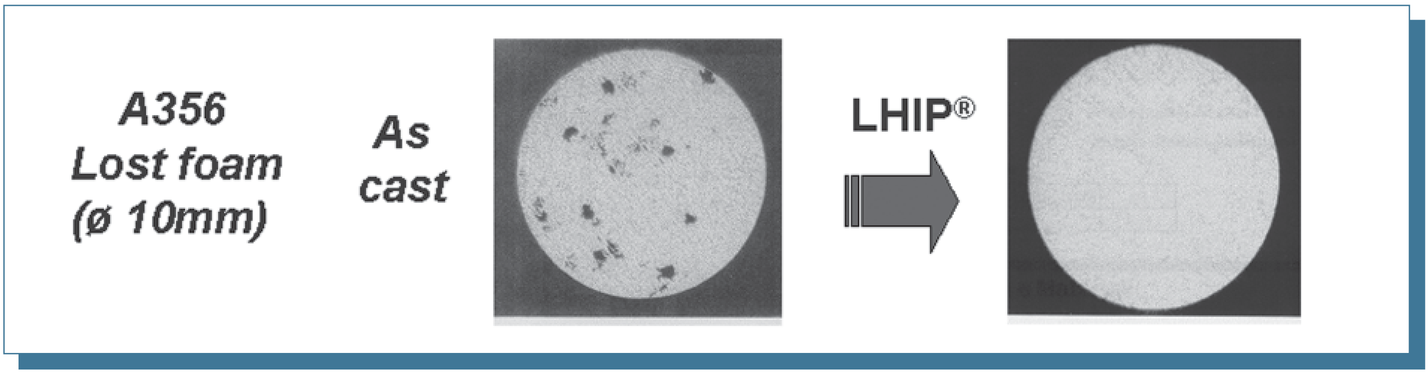

Fig. 6: Porosity of specimen before and after LHIP treatment.

increase).
Several tests have been performed to understand the benefits of LHIP®. In Fig. 7 are shown, as an example, fatigue results of specimen extracted from diesel cylinder head.
Measurements show that depending on S-DAS and porosity values, (i.e. different position in the cylinder head) the effect of LHIP® process is to increase fatigue strength and to reduce the dispersion of values.
LHIP found a proper application to Lost Foam castings, because of their higher level of porosity, usually H_2 and shrinkage.
In Fig. 8 the increase of fatigue life resistance at Room Temperature and at High Temperature is shown.
Recently small batches of cylinder heads for aeronautic, racing and for special application engines, have been treated, with excellent results.

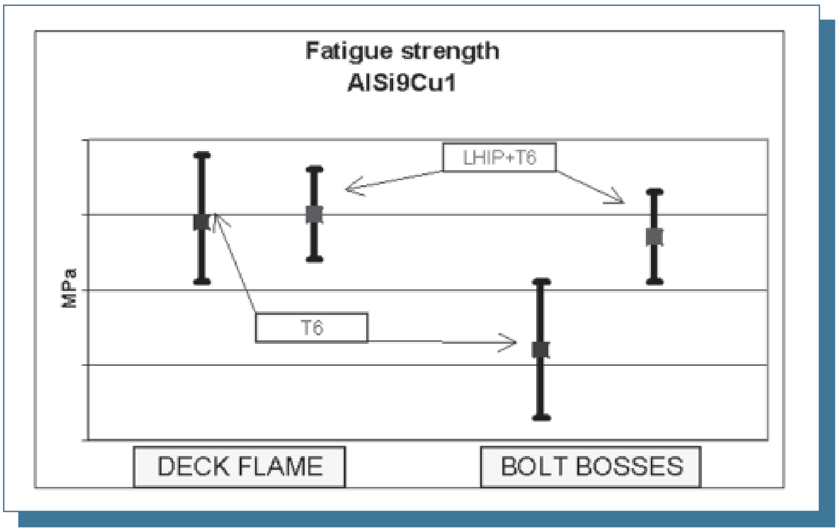

Fig. 7: Results of fatigue tests on SPM cylinder head.

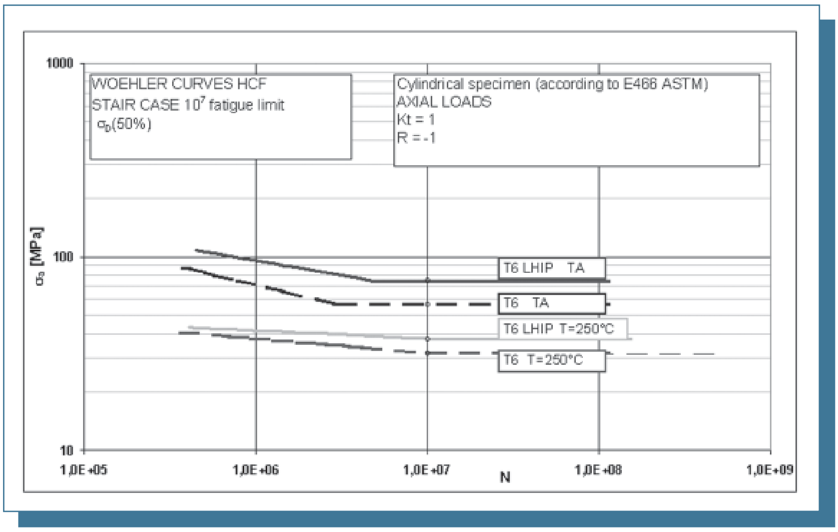

Fig. 8: Results of fatigue tests on Lost Foam (A356) cylinder head.

SPLIT CYLINDER HEAD

This concept is based on the idea of splitting a cylinder head into two parts, each one made by using the best combination of material and manufacturing process, with the aim of optimizing their cost and mechanical resistance.
The two parts are then joined together to form a single, multi-material component. [3].
This concept could find application on heads for Diesel engine to increase specific power and withstand high pressures and temperatures of operation.
Cylinder head characteristics produced according to this concept, are described following with the aid also of Fig. 9 and Fig. 10.
With reference to the figures. 9 and 10, a cylinder head 1 is made of a slice 2, the lower surface of which faces the combustion chambers CC of the cylinders of the engine, draw in a block B (schematically illustrated in the figures). The slice 2 is crossed by openings 4a, in which are drawn the seats for the induction valve (not illustrated), and other openings, among which openings 4b for the seats of exhaust valves (not illustrated) and openings 4c for the passage of the liquid of cooling.
Since the lower surface of the slice 2 should face the combustion chambers CC, it will preferably be realized with an high temperatures resistance material. On the other hand, since the structure of the upper part 3 is relatively complicated, it is preferably obtained by cast aluminum or other

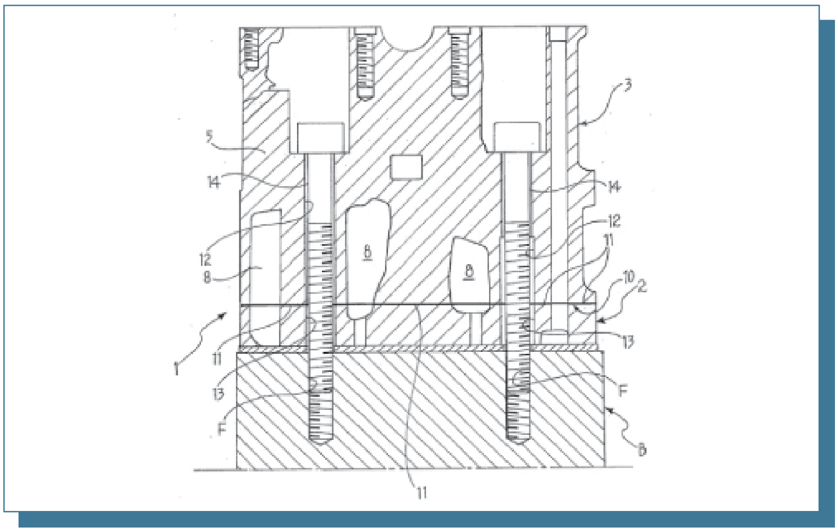

Fig. 9: Split cylinder head section.

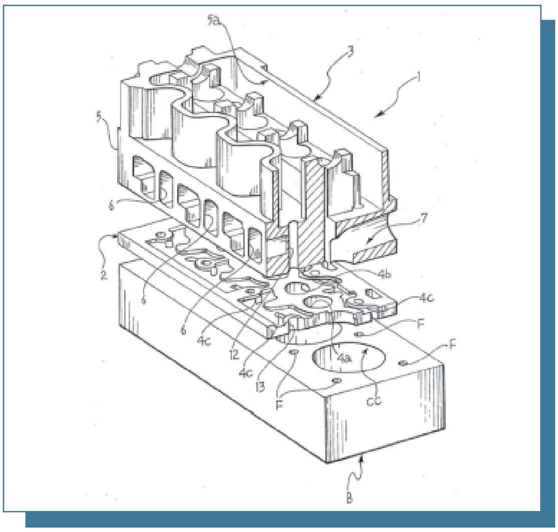

Fig. 10: Split cylinder head: exploded view.

light alloy, for instance through processes of gravity or low pressure casting. Between the two parts there is a layer of adhesive material (11) with sealing property, placed on the plane of junction 10 on the areas of mutual contact, that should to be able to provide, after the bolt bosses 14 are tightened, a seal that prevents the communication among the conducts that cross the head, eventually with the aid of a metallic gasket 15.
Such adhesive, with the aid of properly located dowel pins, has also the function to maintain together the two parts, to allow the manipulation of the cylinder head and its assembling on the cylinder block, without relative movement between them.
As it can be appreciated, in comparison to a traditional unique casting, the cylinder heads produced according to this concept, allows to make the lower part (of limited thickness), without the necessity to use sand core, and to simplify and strengthen the sand core that make the passages in the upper part of the head. In this way it is possible to draw passages for the cooling fluid that optimizes the cooling in some critical zones (for instance between the valves), and distribution oil channels of complex form. Besides it is possible to eliminate the dispersion due to the positioning tolerances of the water core within the mold, improving uniformity of thickness of the walls and, consequently, of the thermal flow towards the cooling circuit.
Another important advantage of this solution is that without the water core, we also eliminate the possibility to have fatigue cracks starting from the core joint flash of division plan in the cooling circuit (Fig. 11).
Such a cylinder head could suitably be used, for instance, in an automotive engine. In fact, for the manufacture of the upper part of the head, it is possible to use an aluminum alloy or similar, of relatively low cost and with low mechanical characteristics, even in engine with high thermo-mechanical stress as many direct injection diesel engine of the last generation. The part that interfaces with the block, bearing the greater part of the thermal stress, will be manufactured instead with an alloy of high performances (such as the AU5GT or AlCu4TiMg), eventually using a production process that, due to the simple shape of the part, can use alloys usually not easily castable in complex form.

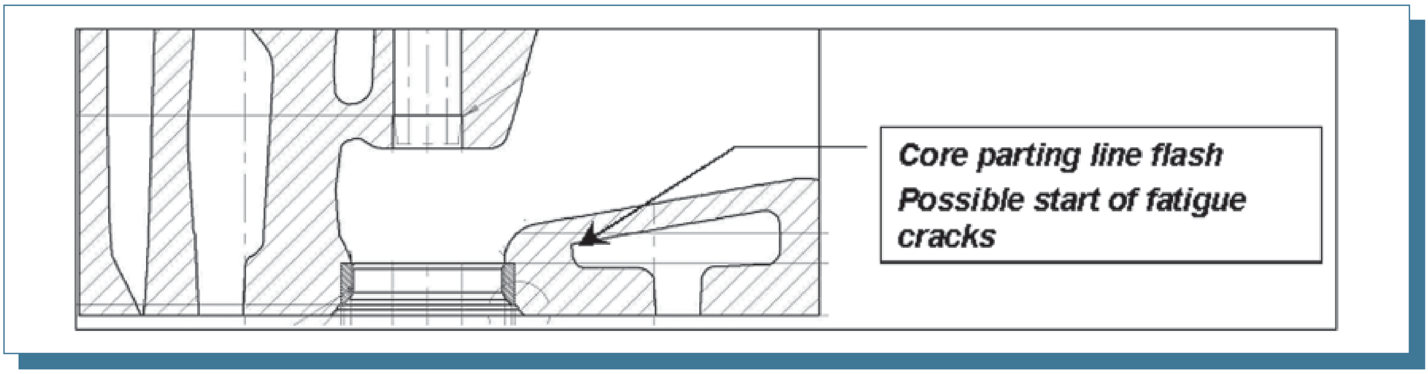

Fig. 11: Section of port and water core.

The targets that we planned to reach at the end of the project are:
- Evaluation of unitary cost of cylinder heads produced with this concept in comparison to those produced with the traditional process of casting.
- The performances of the engine with such innovative heads.
- The real functionality, of prototype heads produced with this innovative solution

(verified through duration bench tests of significant number of heads).

We estimate that, at same conditions of all the other performances (including weight), the head produced with the new system could be economically competitive with conventional ones.

The reasons that justify such expectations are essentially the following:

- The cylinder heads used on high performances Diesel engines are in primary Al alloy (expensive), while with the new production cycle, at the same weight of the machined component, a significant reduction of the need of the valuable alloy in the casting (only deck flame).
- The upper part of the head, the one obtained by melting and not in direct contact with the cylinder, can be made with an alloy of lower characteristics and therefore of lower cost.
- We believe that the complete heat treatment of the whole head will not be necessary, but only of the deck flame (lower weight, lower volume).
- The coremaking cycle, will be simpler because simpler will be, from the point of view of the drawing, the cores that will have to be formed, this will strike again in a sure reduction of the cost of the necessary cores and therefore of the general cost of the part.
- These cost reductions should compensate the machining and assembling cost of the split cylinder head.

The possibility to use, for the slice that will contain the combustion chamber, a material that has a good resistance to high temperatures, should allow to reach higher peak of pressure in the cylinders, up to 200 bar and higher operating temperatures.

TESTING OF SPLIT CYLINDER HEAD

Prototypes of the cylinder heads based on this concept have been built, based on existing geometry, with the aim to verify different alternatives for the sealing between the two parts. High temperature resistant silicon has given so far a good result.

A prototype of a split cylinder head is at present under bench test in a firing engine.

The test cycle has been studied also to verify the present solution for the sealing, especially in exhaust ports area, alternating periods of max rpm, max torque, max power with thermal shocks.

After more than 100 hrs of operation reached, no leaks or failures have been detected and the performance of the engine has always been comparable to the standard one. Tests are going ahead, with the target of reaching 300 hours of operation before disassembling the head and evaluating the conditions of the sealing.

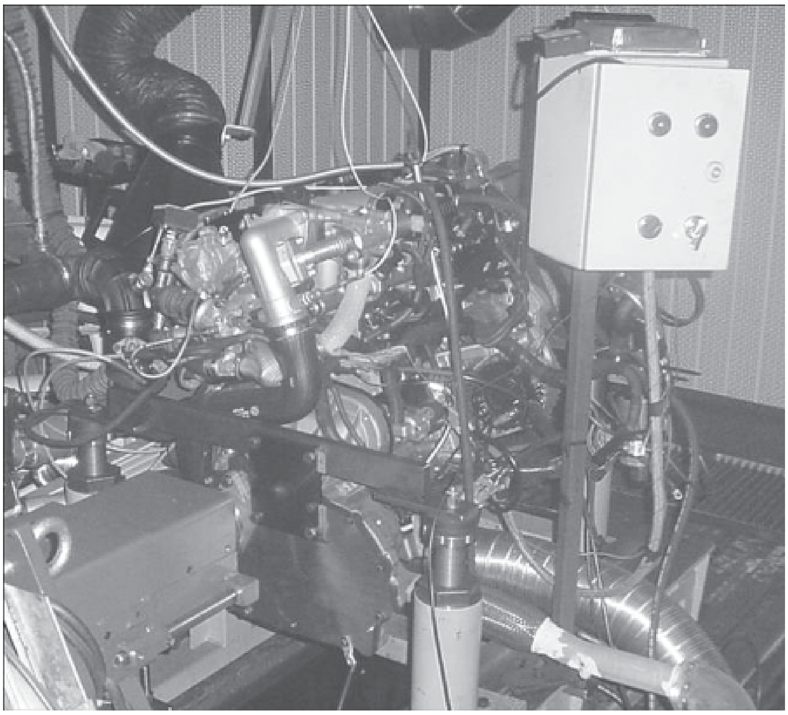

Fig. 12: Bench test on prototype head.

CONCLUSIONS

Engines of the next future will reach very high levels of specific power output, creating new challenges for many engine components, in particular for cylinder heads.

Teksid Aluminum is working in several directions to meet highly demanding specifications required for new aluminum cylinder heads: improvement of conventional casting processes to reduce defects, to refine microstructure and to increase mechanical properties; selection and application of alloys capable of withstanding higher operating temperatures and loads; development of new technologies or conception of new design solutions.

Application Liquid Hot Isostatic Pressing and multi-material cylinder head concept have given some interesting preliminary results and offer potential for further developments.

REFERENCES:

[1] US Patent 6,524,409 B2 – Method for hot isostatic pressing and heat treatment of light alloy castings.

[2] US Patent 5,340,419 – Method and apparatus for densifying an article.

[3] WO Patent application 03/062621 – A cylinder head for an internal combustion engine.

[4] Metallurgical Science & Technology, Vol.19 No.1, June 2001.