PRODUCTION OF HOLLOW COMPONENTS IN HIGH PRESSURE DIE CASTING THROUGH THE USE OF CERAMIC LOST CORES.

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ABSTRACT

Vehicles lightening is a common goal to all car manufacturers, with the aim to improve fuel economy and reduce CO_2 emissions. It is not always easy, however, to reconcile the use of light alloys and conventional forming or casting technologies with the need to manufacture structural or engine components, with thin walls, complex shapes and adequate mechanical properties.

High Pressure Die Casting (HPDC) of Al alloys, which could be a viable technical and economical way to achieve the expected goals, is generally affected by the difficulty to obtain castings with the required soundness (and thus heat treatable) and, in addition, by the impossibility to achieve hollow sections or to produce parts with undercuts.

Ceramic cores and semi-solid forming technologies are two possible tools that could be used to overcome these problems.

The present paper describes the development of ceramic cores to be used in a prototype single-cylinder engine block, produced in both conventional HPDC and semi-solid casting, that allowed to achieve a closed-deck type geometry of the cooling water-jacket, not generally feasible with this family of casting processes.

In both cases the ceramic cores were able to withstand the mechanical stresses during the die filling (without breakage or changes in shape) and the packing pressure without any significant dimensional change. The castings were then processed with high pressure water jet to remove the cores and finally sectioned to verify the performance of de-coring process.

The suitability of ceramic cores for use in high pressure die casting processes, without any limit to process parameters, and the possibility to remove them with pressurized water have thus been confirmed.

Keywords: HPDC, ceramic core, structural component, hollow section

INTRODUCTION

Fossils fuel consumption and CO_2 emissions related to the transportation sector in EU account for approx. 26% of total man-made CO_2 and passenger cars contribute for 12%; despite the fact that new cars emit significantly less CO_2, emissions from road transport keep rising. This is due to increasing freight transport, the aging car fleet, a lack of traffic management and increased mileage.

The Association of European car manufacturers (ACEA) has agreed with European regulatory bodies a path for the reduction of CO_2 emissions from passenger cars with very challenging objectives.

Among the possible measures to achieve these targets, reduction of vehicle weight can significantly contribute to improve fuel efficiency (100 kg vehicle mass reduction translates into 0.35 – 0.60 l/100km lower fuel consumption).

Increasing use of light alloys in vehicles is one of the keys to achieve weight reduction, but, often, the replacement of Fe-based materials results in a cost penalty that market is not ready to accept.

It becomes therefore more and more important to develop light alloys forming technologies to allow complex automotive components to be produced at the lowest possible cost.

HIGH PRESSURE DIE CASTING FOR ALUMINUM COMPONENTS

Among the casting processes used to produce aluminum components, High Pressure Die Casting (HPDC) represents a very competitive technology, for high production volumes, in terms of cost (low cycle time, use of secondary alloys, near net shape parts), weight reduction (thin walls) and design opportunities.
On the other side it is characterized by some drawbacks that limit its wide potential applications. In particular these limits are related to the manufacture of high performance components or of castings with internal cavities or undercuts (for example structural or engine parts).

Structural components

Most of the aluminum castings used in automotive applications are produced with Al-Si-Cu alloys. These alloys develop high mechanical properties as a result of a full T6 or T7 heat treatment (solution followed by quenching and artificial ageing) which promotes the precipitation of Mg_2Si o $CuAl_2$ intermetallics. Only with this type of heat treatment it is possible to reach yield strength values over 200-250 MPa, usually specified for structural components.
If the casting, though, is not completely free from air inclusions, entrapped in the filling phase (as often happens to HPDC castings), during the solution stage of the treatment air bubbles, due to the low resistance of the alloy at high temperature, will expand to form blisters on the surface of the casting, leading to a reject of the part.

Several technologies for vacuum assisted HPDC have been developed and are currently used to enable the production of air entrapment free, heat treatable, thin walled parts, but they are still not satisfactory if, for structural or design reasons, thicker walls or heavy sections are present in the part, since shrinkage porosity cannot be completely avoided in this case.

Only Semi-Solid Metal (SSM) forming processes allow to significantly reduce these kind of defects in parts with thick sections (up to 20-30 mm).

Parts with undercuts or hollow section

A second significant constraint to be considered when designing HPDC components is related to the need of using steel cores which, since they are connected to the die, have to be pulled out from the casting before it is extracted from the mold. Steel cores are required to withstand the forces generated by the high speed metal flow into the die cavity during the filling and the high pressures (800-1500 bar) applied on the metal during the solidification of the casting.
Such kind of metallic cores does not allow to create undercuts or complex shape cavities into the casting thus limiting the flexibility in the design of the geometry of the part.

For the production of such components, other casting processes like Gravity (GDC) or Low Pressure Die Casting (LPDC) are generally applied. In these cases, since stresses on the cores arising from filling and solidification phases are much lower than in HPDC, due to low metal flow speed and to limited overpressure applied, conventional sand cores can typically be used. Cores are then removed, by mechanical and/or thermal means, after the casting has been extracted from the mold.
Sand cores are compacted and kept together by means of organic or inorganic binders, that are either added and mixed to the sand or used to prepare pre-coated powders, and cured by thermal or chemical action.
The bonding effect among the sand grains generated by such binders is relatively weak, and resulting mechanical properties of these conventional cores are relatively low, so they are not suitable for applications where higher bending and compressive loads are applied.
Even if the bending strength of sand cores can be increased to quite high levels by reducing the grain size of the sand and by increasing the percentage of binder (at the expense of easiness of removal and increase of gaseous emissions), their modulus of elasticity remains relatively low and decreases as temperature rises during the casting process, leading to unacceptable distortion of the core under load and consequent geometrical non conformity of the casting.

Production of complex shaped castings in HPDC may become feasible if special cores are adopted, capable of reaching high enough mechanical properties, in particular in terms of stiffness (high modulus of elasticity), bending and compression strength, to withstand the stresses generated during the HPDC casting process.

The present work is based on the idea of using ceramic materials for which the hardening mechanism and the obtainable structural resistance are mainly based upon a sintering process. In this way it is possible to obtain cores with a wide range of mechanical properties as a function of the sintering temperature, avoiding the limits and problems coming from the conventional organic binders (outgassing, sensitivity to temperature). In the sintering process the single particles of ceramic material are diffusion bonded together, allowing to reach elevated values for the mechanical properties and modulus of elasticity, well over what is reachable with the use of conventional binders and, even more important, to reduce the effect of the increasing temperature.

CORES FOR HPDC: REQUIREMENTS

The main requirements for cores to be used in challenging high pressure casting processes are summarized as follows:

- **Strength to resist standard HPDC conditions**:
    - Ingate velocity (> 40 m/s)
    - Packing pressure (> 1000 bar);

  Typical Semi-Solid Metal forming conditions are usually less severe, in particular for ingate velocity;

- **Shape stability**: the core should not break and keep its shape without distortion or dimensional changes, even during the packing phase when high hydrostatic pressures are applied;
- **Dimensional accuracy**: required to ensure a correct positioning of the core in the mold through adequate core prints;
- **Surface quality**: After de-coring, the surface of the casting will reproduce the roughness of the core, internal circuits of the casting designed for fluids flow (cooling circuits, oil channels) should have low roughness to reduce pressure drop;
- **Complex shape**: The possibility to form cores with complex shape is extremely important to allow the application to a wide spread of components;
- **Clean removability**: the core removal process should be possible with available industrial technologies and should not leave any residuals in the casting.

CERAMIC CORES

The main features of ceramic cores, based on the above requirements, can be summarized as follows:

- **High mechanical properties on demand:**
  Ceramic cores can reach the desired mechanical properties for each specific application thanks to a tailored sintering process. It is not needed to reach always the maximum obtainable resistance, that makes de-coring more difficult.
  A first evaluation of required level of properties may be done with the aid of simulation tools (*Fig. 1*): the mechanical stresses on the ceramic core when molten material is fed inside the mold are estimated by means of numeric methodologies based on results of the casting process simulation, using commercially available software, such as "PROCAST", distributed by ESI Group.
  Once the mechanical stresses on the core have been estimated, a firing temperature for the "green" ceramic core can be established, to give the core a mechanical strength slightly higher than the maximum calculated stresses.

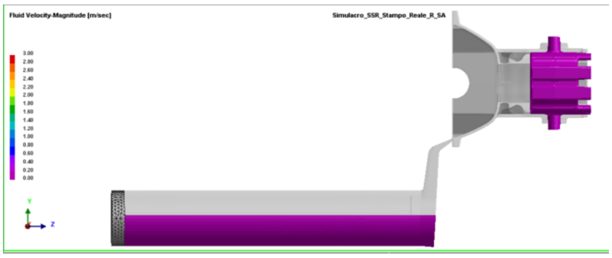
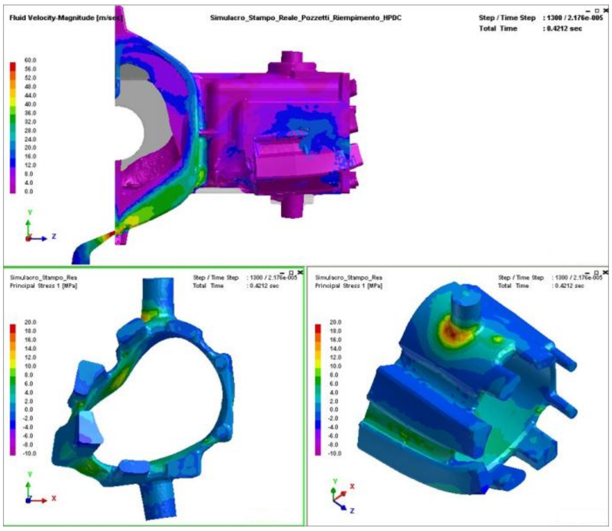


Fig. 1: Simulation of the stress generated on the core by the impact of metal flow during filling of the die

HPDC
$V_{ingate} = 55$ *m/s*
$E_{core} = 4$ *GPa (sand core)*



- **No Binders ► no outgassing:**
  Ceramic cores do not contain any kind of binders, so they do not release gases (generated by the thermal decomposition of organic components of binders) during the casting process. This feature could be extremely interesting also for application to gravity die casting where the pouring time is longer than in HPDC and core gases have more time to form: if not properly evacuated, through the core prints, they could escape through the molten metal with potential damage to the casting due to entrapped bubbles.
  In addition no potentially dangerous organic gaseous compound would be released to the ambient, resulting in a substantial improvement of the working environment.
- **Good-enough dimensional accuracy:**
  Dimensional precision of ceramic cores depends on the type of applied forming process; considering the resulting shrinkage of all the production steps (forming, drying, sintering), it is reasonable to estimate a maximum dimensional tolerance of ± 0.5 %. This average figure might be critical for precise positioning of the core into the die for some applications, but fine tuning solutions can be found for specific cases.
- **Good internal surface of the casting:**
  Roughness of external surface of ceramic cores is very low ($R_a < 2\mu m$), so internal cavities of the casting will have a comparable surface finish. Due to the high compression resistance of ceramic cores no dimensional change has been measured even with extremely high values of packing pressure (tested up to 1800 bar).
- **Complex shapes:**
  It is a very important point since it drives the selection of the forming process for the core. Geometrically simple shapes can, for example, be obtained by axial pressing techniques, with the possibility of using a wide variety of base materials, but, if the shape is complex injection molding processes have to be used, limiting the choice to injectable materials.
- **Easiness of de-coring:**
  It is another key parameter for the choice of the material/process for the core. Both chemical (leaching) or mechanical (high pressure water jet) methodologies are well known and applied for the demolition of ceramic shells in the investment casting process. In the case of cores for HPDC, nevertheless, it is necessary to consider not only the possibly difficult accessibility of internal cavities of the casting, but also the high resistance required to the core, that may create problems for mechanical de-coring.
- **Thermal shock resistance (TSR)**
  The value of this property is in inverse proportion to thermal expansion coefficient of the material. So, depending on the application, the value of this parameter needs to be taken into account for the choice of the material of the core.

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CHOICE OF THE RAW MATERIAL

For the choice of the chemical composition of the material for the cores and of the parameters for the sintering treatment, extensive research and experimental activities have been carried out, using selection criteria based on economical, functional and productive aspects. In particular the following points have been considered:

- Cost of raw materials: very important in view of possible high volume production applications;
- Mechanical properties, as a function of sintering temperature, defined for HPDC application (the most demanding);
- Favorable correlation between mechanical resistance and Young's modulus: for similar levels of bending strength the highest value of elastic modulus is preferable;
- Rheological properties to assess the compatibility with forming process;
- Easiness of mechanical de-coring;
- Compatibility with chemical de-coring (leaching);
- Value of thermal expansion coefficient.

MECHANICAL AND PHYSICAL CHARACTERIZATION OF THE CORES

Chosen ceramic core materials have been experimentally characterized in terms of:

- Density, specific heat, thermal conductivity and thermal expansion coefficient;
- Hardness, bending strength (R_f) and Young's modulus as a function of sintering temperature;
- Required time for mechanical or chemical de-coring

Depending on thickness of the core and on the considered casting process (HPDC, GCD or LPDC), some of these physical properties may become a key for the success of the application: if the core is thin (3-5 mm) and the filling time of the mold is relatively slow (like it happens in GDC or LPDC), then Thermal Shock Resistance (TSR), and consequently thermal expansion coefficient, becomes important; another case is when big cores, heavy and thus with high thermal capacity, are used in GDC or LPDC in areas difficult to fill: in this case it is useful to choose ceramic core materials with low heat diffusivity, which limits heat exchange at the interface between the alloy and the core, preventing the metal to freeze and allowing to fill also thin walls.

DESCRIPTION OF THE APPLICATION

<u>Closed deck cylinder block</u>

The selected demonstrator for the development work on the ceramic cores is a cylinder block, one of the main components of an internal combustion engine, which may account for up to the 4% of the total mass of typical C-segment European car.
Cylinder blocks in Al-alloy are already widely used, in replacement of cast iron ones, for gasoline or small-medium displacement Diesel engines; most of them are produced in HPDC, mainly for cost reasons.

<u>Fig. 2</u> reports the comparison between the mass of the components of two typical engines of approximately 1.6 liters displacement, showing that the potential weight saving obtainable with Al block against cast iron is considerable.

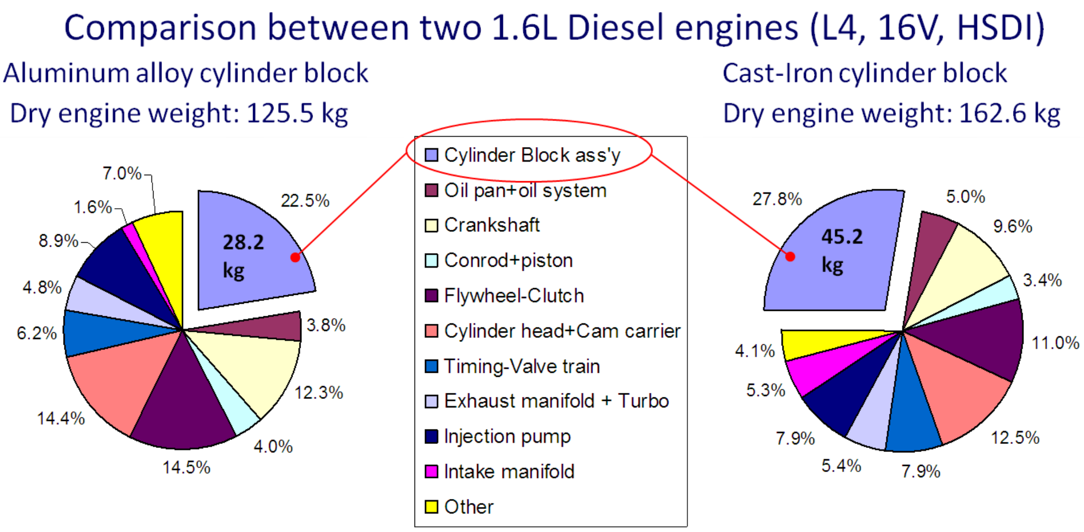

Fig. 2: Potential engine mass reduction using Al alloy cylinder block

There are tough important constraints associated with conventional HPDC technology that limit the possible design of the block and the possibility to extend the application, for example, to diesel engines with bigger displacement and higher power rating. In such engines, at full load, high values of combustion pressure and operating temperatures are responsible of heavy load and stress conditions that require, on one side, high material properties, on the other the possibility to design a very stiff component from the structural point of view, to prevent significant deformation under load; in particular the upper deck should not be completely opened by the water jacket circuit (Closed Deck configuration, see *Fig. 3*) to provide enough support to the cylinders against the side load generated by the piston in its downward stroke.

This kind of geometry of the casting requires the use of a core for the water jacket circuit and cannot be obtained with conventional HPDC in which, the only possible geometry is the so called “Open Deck” configuration, where the water passage around the cylinders is generated by a steel part of the die that has to be pulled out of the casting, leaving the cylinders completely separated from the external structure of the block.

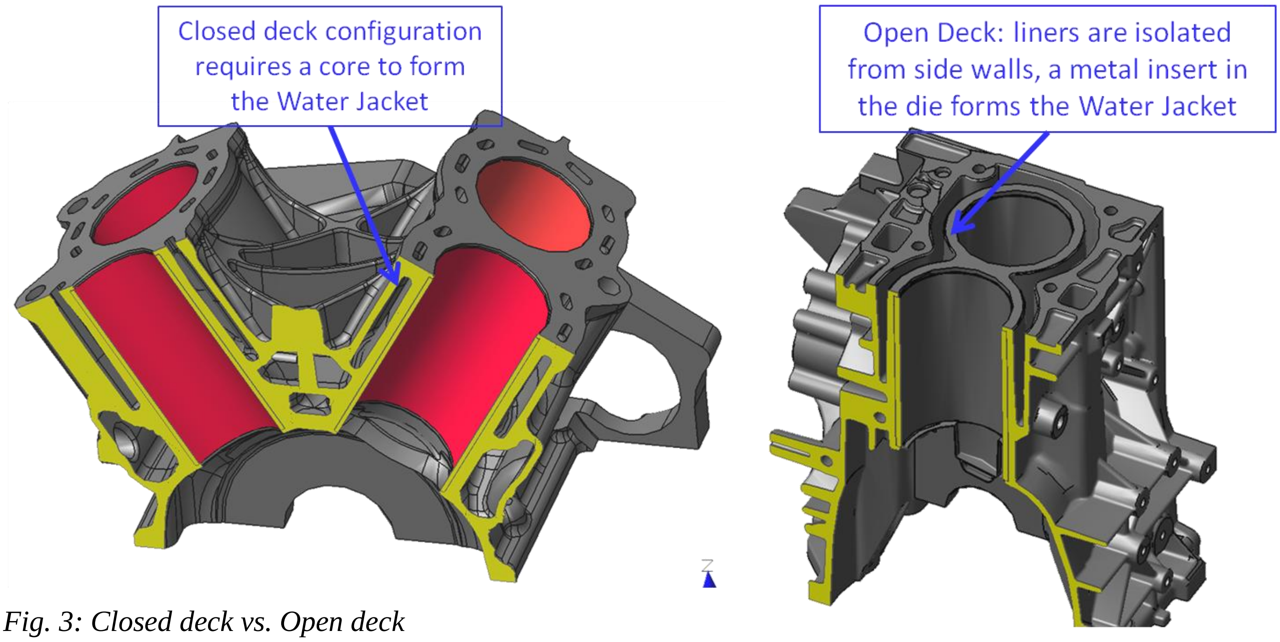

Fig. 3: Closed deck vs. Open deck

Design of the component

For the experimental activity on a real HPDC component, in order to simplify the die and to reduce its cost, it was decided to use as a demonstrator a single cylinder block, based on a section of an existing Diesel 4-cylinder block with closed deck configuration, in which important features of the cooling water passages, like minimum thickness and complex shape, reflected typical conditions found in a real engine.

The ceramic core was designed based on the shape of the water circuit around the cylinder, with protrusions to create the water passages in the top deck. Two core prints were added to provide support for the core in the mold.

The resulting design of the demonstrator (approx weight 3.6 kg) and of the required water jacket core (approx. volume 265 cc, minimum thickness 4.5 mm, mass 0.4 kg) are shown in *Fig. 4* and *Fig. 5.*

At this stage it was decided not to include a cast iron liner insert in the casting.

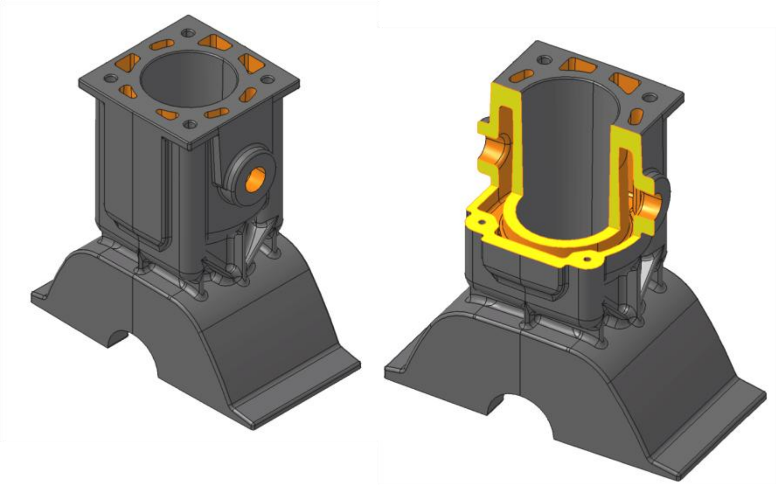

Fig. 4: Closed deck single cylinder block demonstrator

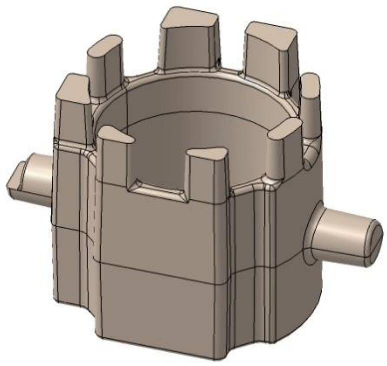

Fig. 5: Water Jacket core

Based on previous experience on similar components, it was decided to cast the part in horizontally, gated from the bottom skirt and with overflows positioned at the parting line of the two slides forming the sides of the monocylinder.

The ingate was designed to be compatible, with simple modifications, to both HPDC and Semi-Solid Metal processes, in order to allow the evaluation of potential improvements in casting soundness associated with the SSM, in view of a possible T6 heat treatment of the part.

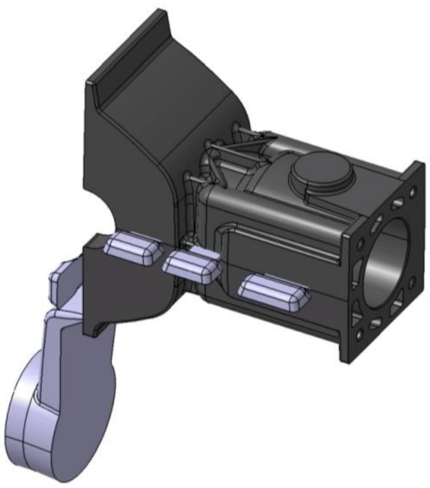

Fig. 6: Casting with ingate and overflows

The total weight of the casting, ingate and overflows, shown in *Fig. 6*, resulted in approx. 4,8 Kg.

Among the various proposed methods for producing Semi-solid slurry *on demand*, just before the injection into the mold, the Semi Solid Rheocasting (SSR™), developed by IDRA under MIT license, was chosen mainly because, usually, it can be integrated into existing HPDC cells without requiring big changes to the layout of the machine.

According to this process, slurries ideal for semi-solid forming can be produced by stirring during the first small fraction of solidification, provided that stirring is combined with rapid heat extraction.

Operationally, these conditions are fulfilled by using a

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hollow mixer (a bar of graphite, internally cooled) dipped into a ceramic cup containing the appropriate quantity of metal alloy required by the component. After a few seconds, depending on the amount of metal in the cup, however in the order of 8-15 seconds, the mixer is removed from the cup while the semi-solid metal continues to cool quiescently to a given fraction solid (during the transfer to HPDC machine) and then it is poured into the shot sleeve for the casting forming.

The Alloy selected to cast the part is the UNI EN-AC 46000 - AlSi9Cu3(Fe), widely used for HPDC components and for cylinder blocks in particular.

Design of the die

The prototype HPDC die was designed to be as simple as possible to reduce the cost, nevertheless all the main features typical of production tools were included in the die, like: simple cooling circuit, ejector plate and two slides needed to form the external shape of the single-cylinder block.
It was built using pre-hardened 1.2312 (P20) tool steel, with the aim of allowing the casting of some hundreds of parts before needing maintenance.
Particular care was given to the study of a reliable system to keep the water jacket core, which is positioned by hand into the die, in place before the die is closed; this task required quite a lot of adjustments since different materials and sintering conditions used for the ceramic cores led to significant variations in the final dimensions of the inserts.

Some details of the die are shown in *Fig. 7*.

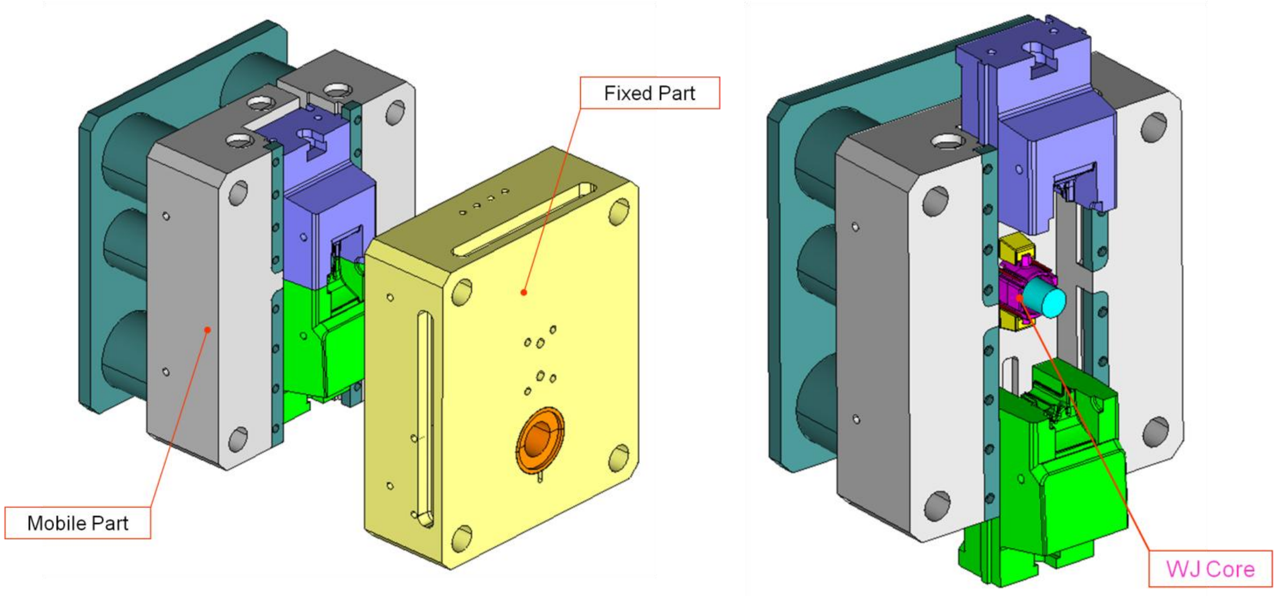


Fig. 7: Prototype HPDC die for single cylinder block

EXPERIMENTAL ACTIVITIES

Ceramic core development and production

The first development phase of ceramic cores was done using plaster molds, but since dimensional stability of cores produced with this technology was not satisfactory, the company SACMI, selected for the development of cores, designed and manufactured a prototype mold suitable for a core forming process representative of those used for serial production (high production rate).
For the first test sessions 4 different chemical compositions were used, along with 2 sintering temperature levels in order to get a complete screening on raw materials in terms of suitability to injection process and to verify the easiness of removal at increasing levels of strength of the core. Materials with different rheological properties, but capable of supplying adequate strength have been considered.

Once this screening has been completed, cores to be used in casting trials have been produced with a limited variety of materials. A sample of ceramic core is shown in *Fig. 8*

Based on the consideration that, at least when using the SSR process, the stresses on the cores during mold filling should be relatively low, also sand cores formed at Teksid Aluminum core shop with conventional techniques, like shell-molding, have been included in the experimental evaluation plan (*Fig. 9*). These sand cores have been coated with the aim to prevent aluminum infiltration under high packing pressures.

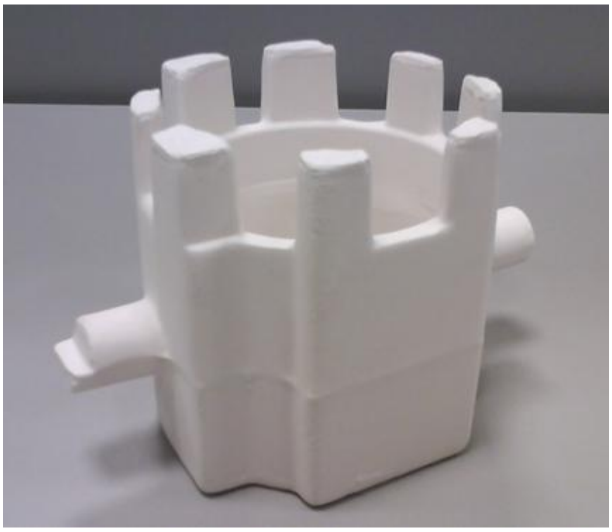


Fig. 8: Ceramic core

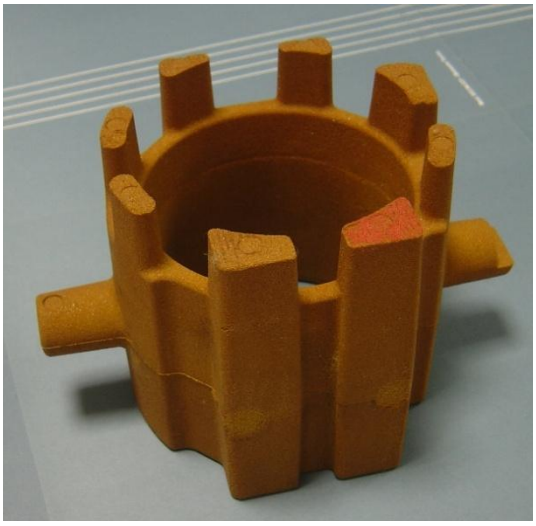


Fig. 9: Sand core (shell molding), before coating

Casting trials

Extensive casting trials have been performed, using both standard HPDC process and SSR, at first at the tool manufacturer then at a HPDC foundry where an IDRA SSR device was available.

Details of the four trial sessions are summarized below:

- The first two sessions have been performed at the tool maker casting shop, with the main aim to fine tune the die, in particular in the area where the ceramic core is supported, and to define baseline process parameters of the conventional HPDC process. In these phases 4 different types of raw ceramic materials have been tested.
- The third session, at a third party foundry, using the SSR^{TM} process on a conventional 1200 Tons HPDC machine equipped with the stirring system for the production of semi-solid slurry supplied by IDRA. In this session 2 types of raw ceramic materials, with 2 levels of bending strength, have been tested.
- In the fourth session, performed during 2 days, cores produced with only one ceramic material, but with 3 different levels of bending strength have been tested using both conventional HPDC (injection temperature of the liquid alloy: 680 °C) and SSR^{TM} (injection temperature of the semi-solid alloy: 580 °C).
  In detail, in this session, 140 ceramic cores, sintered to 3 temperature levels in order to get 3 ranges of mechanical properties, centered on the following reference values, were used:
  n. 40 cores with $R_f = X_{min}$
  n. 80 cores with $R_f = X_{mean}$
  n. 20 cores with $R_f = X_{max}$
  The value X_{mean} has been chosen as a reference for both HPDC and SSR^{TM} processes.

  In addition to the 140 ceramic cores, also other 125 sand cores have been prepared, 100 of which made with the shell-molding forming process (pre-coated sand) with optimized strength (R_f = 6-12

MPa), and 25 produced with experimental inorganic binder (R_f = 7 MPa). All these sand cores, as already mentioned, have been treated with different types of coating in order to prevent molten aluminum to infiltrate between sand grains.

Table 1 summarizes the range of process parameters tested in the trials:

Table 1

Process	Velocity @ ingate [m/s]		Packing pressure [bar]	
	Typical	Max	Typical	Max
HPDC	35	55	900	1800
SSR™	3.0	5.7	900	1800

For most of the castings produced the packing pressure (the actual pressure on the metal during the 3rd phase) was kept in the range 800-900 bar, in line to the typical range used for the production of HPDC cylinder blocks, but, in order to verify the limits of the various types of cores, some parts have been cast with higher pressures, up to 1800 bar.

Some pictures taken during the try-out sessions are reported in *Fig. 10* - *Fig. 13*

Fig. 10: Casting as extracted from the die

Fig. 11: Parts produced in the try-outs

Fig. 12: Single cylinder block with ceramic core after gating removal and deflashing

Fig. 13: Die open, ready for the introduction of the WJ core

RESULTS AND DISCUSSION

The analysis of the results has mainly concentrated, on one side, on the performances of the cores in terms of structural behavior, resistance against metal infiltration, deformation and removal; on the other side, on the quality of the prototype cylinder block castings as far as regards soundness, microstructural features and suitability for heat treatment.

Structural behavior of the cores

Several parts, coming from the above described trial sessions, have been analyzed, either by sectioning or by X-Ray, to verify the integrity of the core after the casting process. The results can be summarized as follows:

Ceramic cores:

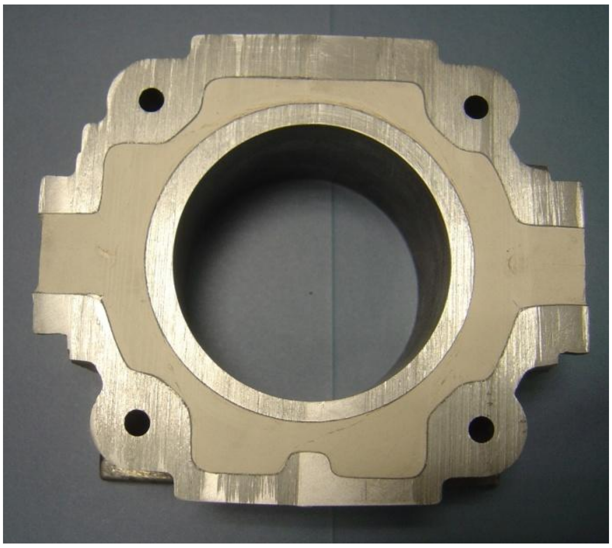
Fig. 14

R_f / Process	X_{min}	X_{mean}	X_{max}
HPDC	o	+	+
SSR™	+	+	+

- Bad: many broken cores

o Fair: few broken cores

\+ Good: no broken cores



Sand cores:

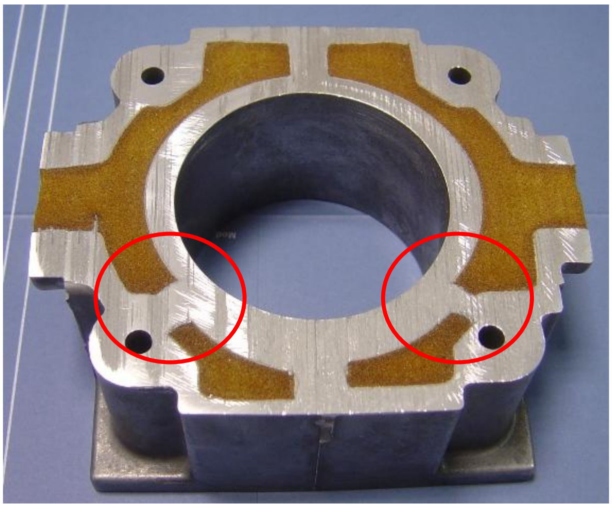
Fig. 15

Binder / Process	Inorganic R_f = 7 MPa	Organic R_f = 12 MPa
HPDC	-	o
SSR™	+	+

- Bad: many broken cores

o Fair: few broken cores

\+ Good: no broken cores



As expected, limited values of bending strength are acceptable to avoid core breakage, only when the SSR process is used, where the injection speed of the metal is extremely low (< 5 m/s at the ingate).

If conventional HPDC is used, where the metal speed at the ingate may reach 40 m/s or more, stronger cores are required to withstand the impact of the metal flow.

Resistance against infiltration

Ceramic cores:

Analyzing by naked eye sections of the castings (see *Fig. 14* for example) there is no evidence of infiltration of metal into the core, regardless of which casting process is used (HPDC or SSR™).
This result is not surprising since sintering temperatures close to those of "*full density*" have been used and expected residual porosity was limited (< 15%). Low value of residual porosity after sintering was one of the selection criteria for the base material for ceramic cores.

However, at a deeper metallographic analysis, done with optical microscopy on samples after de-coring, a layer of *cermet* material, of approx 100 µm thickness (depending on the porosity of cores), can be found on the aluminum alloy surface in contact with the core. This layer is shown in *FIG. 16*.

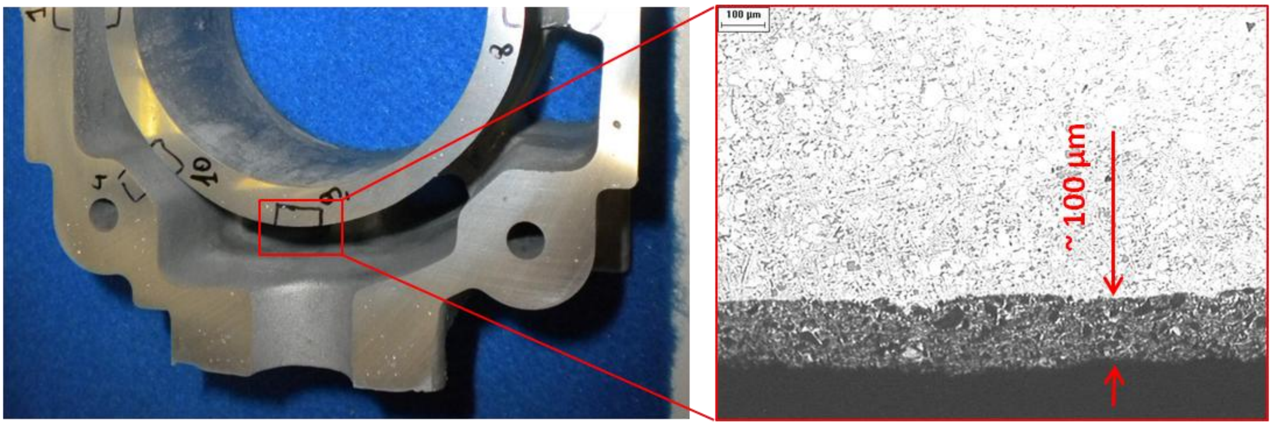


Fig. 16: Cermet layer at Al-ceramic core interface

This layer shows no tendency to detach, but, because of its hardness, it might generate a premature wear of machining tools if this surface had to be machined. In such event a coating applied on the surface of the core should be employed, to act as a mechanical barrier against infiltration.

Sand cores:

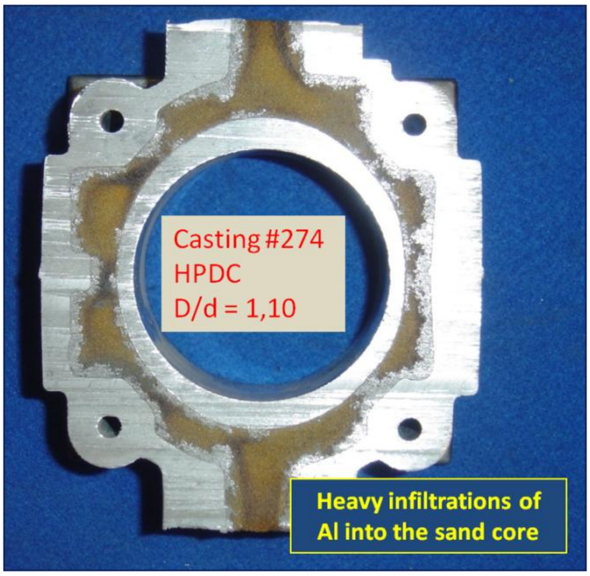


Fig. 17: Aluminum infiltration into sand core

Despite the use of refractory coatings, sand cores made with organic binders showed a strong tendency to get infiltrated by the aluminum alloy (see *Fig. 17*). This effect was more evident in HPDC cast parts, probably due to lower viscosity of the completely liquid metal, than in SSR™ castings.

The application of refractory coatings gave better results in combination with inorganic binder, even if the problem was not completely eliminated.

For both types of sand cores, the resistance to infiltration remains one of the weak points, and even if solutions can probably be found (e.g. impregnation + multiple layer coatings), a lot of development and fine tuning work would be needed before a robust process is established.

Deformation during the casting process

Based on the results of the first casting session, particular attention was given to the evaluation of possible deformation of the cores resulting from the stresses generated during the filling, compactation and solidification of the casting.

Several measurements have been made on sectioned parts to evaluate the distortion, induced by the casting process, in the various types of cores tested: in particular it was noted that, consistently, the castings analyzed showed a deformation of the water jacket, in direction normal to the core prints, for which the cross section perpendicular to the axis of the liner, instead of being circular was elliptical. A typical example is shown in *Fig. 18*.

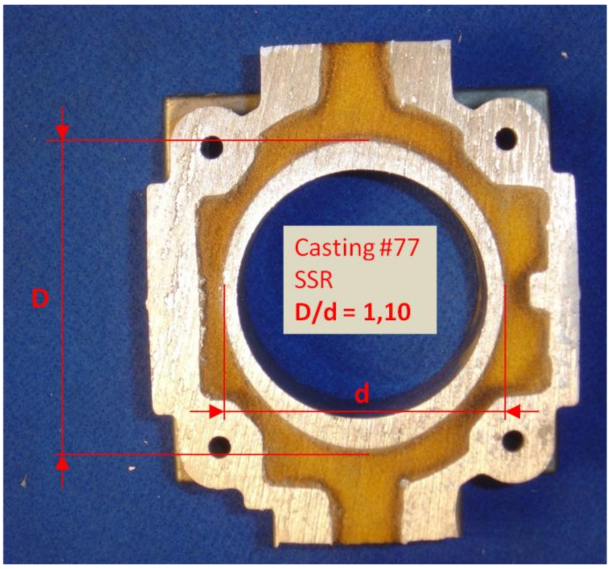


Fig. 18: Sand core deformation

To assess the amount of deformation of the cores, a distortion index was calculated as the ratio between the 2 axis of the elliptical section: D/d. In addition also the out of roundness parameter, defined as (D-d)/2 was considered.

The highest distortion values were found when sand cores had been used, with values of D/d up to 1.10 (meaning a percent difference of nearly 10% between the 2 axis) and out of roundness > 3 mm.

On the other side ceramic cores behaved significantly better, showing differences lower than 2% between the 2 axis, which is in line with the manufacturing tolerances of the cores.

The different behavior between sand and ceramic cores, even if in some cases their bending strength level are similar, can be explained with the difference in their Young's modulus which is higher for the latter (less deformation under the same load). In addition, since this parameter is measured at ambient temperature and cores with organic binders are much more sensitive to the temperature increase, in the actual conditions found during the casting such cores are even more penalized.

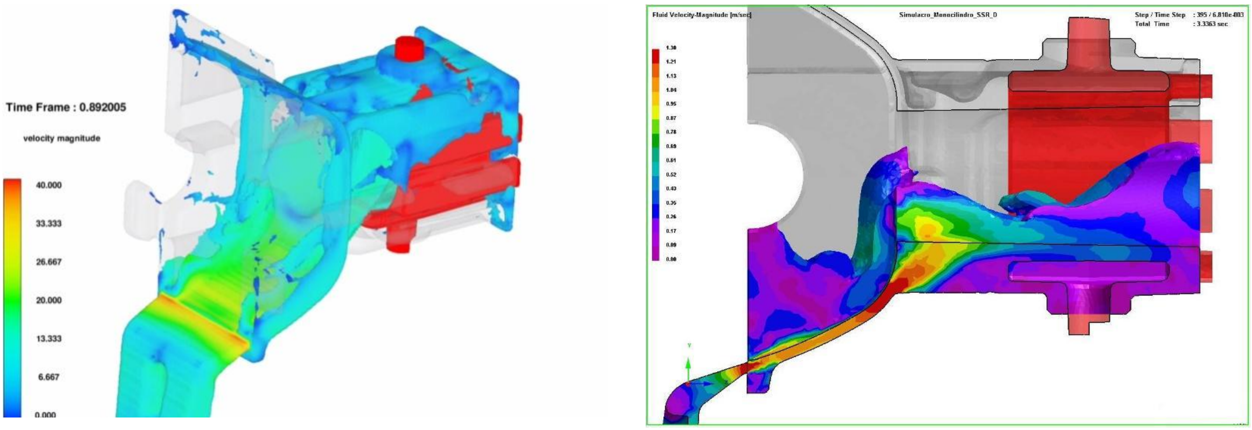


Fig. 19

a) *Filling in HPDC: metal arrives on the core from the top*

b) *Filling in SSR: metal flows in the cavity from the bottom*

It should be noted that distortion values were correlated both with the packing pressure (higher pressure, bigger distortion) and the type of casting process: SSR^{TM} seems to generate more deformation than HPDC with similar level of packing pressure. The explanation in this case may be related to differences in the way the cavity is filled and to the exposure time of the core to the high temperature of the incoming metal. *Fig. 19* shows how the simulated cavity filling patterns are different between SSR^{TM} and HPDC.

Ceramic core removal (de-coring)

After a preliminary screening and tests of available technologies for the removal of the ceramic cores from the casting, High Pressure Water Jet (HPWJ) was selected, because of its capability to destroy also fairly tough materials, and fully tested in the experimental phase of the project.

A prototype core removal station (shown in *Fig. 20*), capable of semi-automated operation, has been designed and built with the aim of fully understanding not only the potential technical limits of this technology, but also the process and production parameters (like time required for the core removal, water and energy consumption and so on) required for a reliable cost evaluation of the operation.

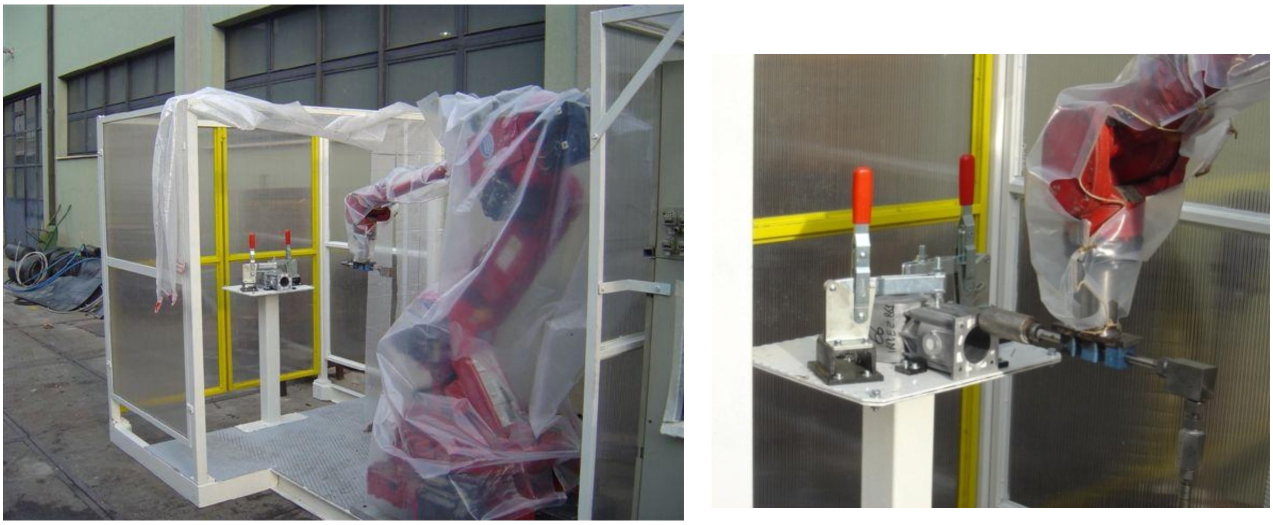


Fig. 20: Set-up for High Pressure Water removal of cores

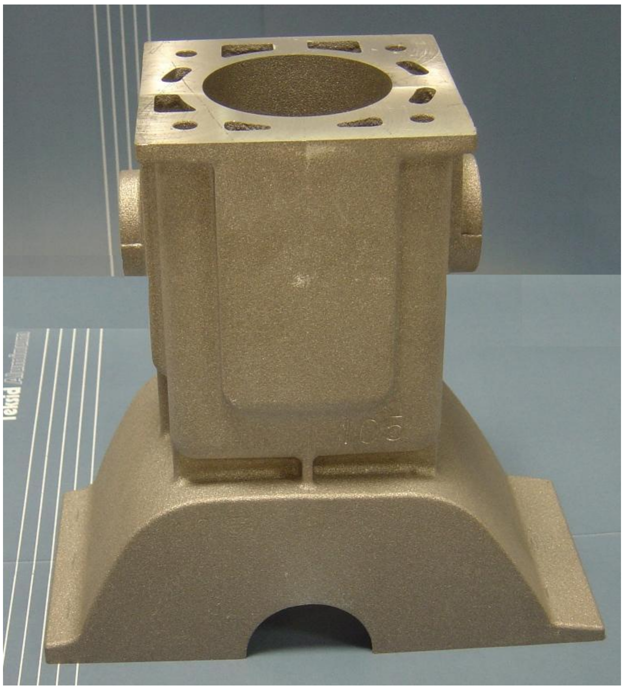
The station is equipped with a system for positioning and clamping of the part to be treated and with a robot that brings a special tool capable of carrying 2 types of high pressure nozzles, one for first rough core removal and a second for final cleaning. The nozzles are then connected with flexible tubes to a suitable high pressure pump (pressures up to 2000 bar have been tested during the cleaning sessions). The robot follows a programmed cycle that allows to apply the water jets, properly "*shaped"* by each nozzle, on all the openings where the core comes out from the surface of the casting.

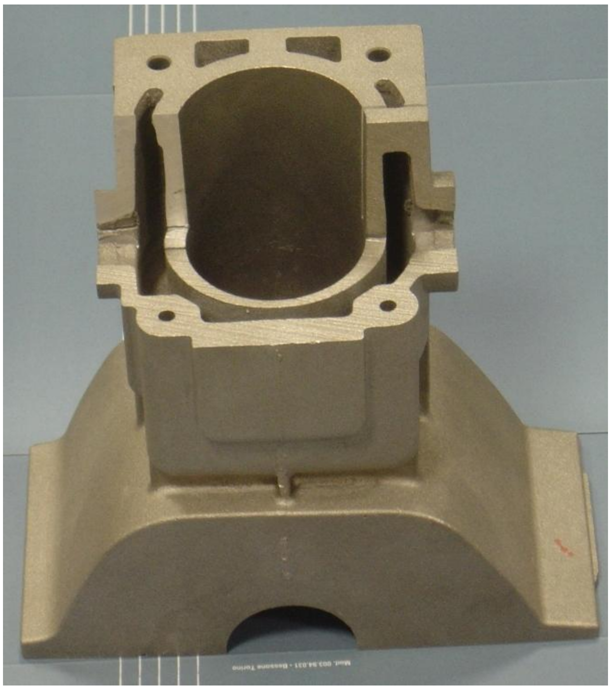
Particular care is requested for a proper design of these openings (position, number and dimensions) to allow for a complete removal of the core.

With this set-up several castings have been processed with various sets of process parameters (water pressure and flow rate, type of nozzle) until satisfactory results have been achieved: ceramic cores with $R_f = X_{max}$ (the highest strength tested) have been destroyed and completely removed from the cylinder blocks.

Also parts cast with sand cores needed to be treated with this process, since, due to the relatively high core strength achieved, conventional mechanical or thermal shake out process did not work properly.

Pictures of a complete and a sectioned cylinder blocks after the de-coring process are reported in *Fig. 21*, showing the complete removal of the ceramic core achieved.





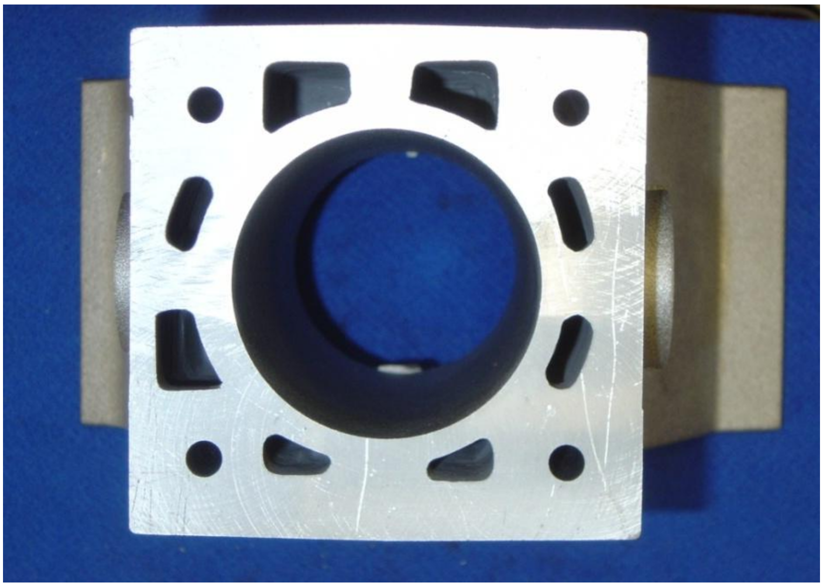


Fig. 21: Single cylinder block after de-coring

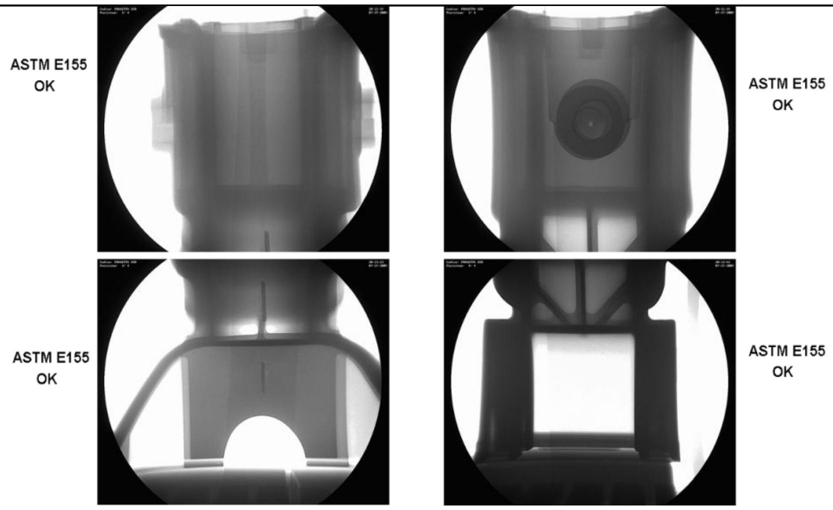
<u>Quality of the castings</u>

Even if the optimization of the casting process was not among the priorities of the experimental phase, the quality of some of the cylinder blocks produced in the casting trial sessions has been assessed with X-Ray analysis.

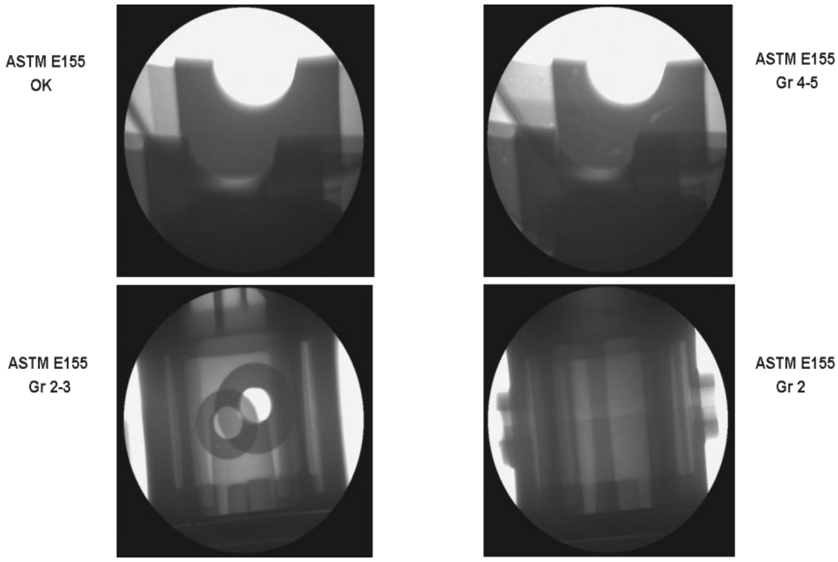
The results confirmed that an excellent soundness of the casting can be achieved, with an appropriate set of process parameters, with the SSR™ and that an acceptable quality in terms of porosity can be obtained also

with HPDC, even if at a lower level than SSR™.
Some X-Ray images of typical SSR™ and HPDC cylinder block samples are reported in *Fig. 22*.

It is important to underline that the use of cores did not limit in any way the setting of HPDC process parameters (in particular 2nd phase piston speed or 3rd phase overpressure), in comparison to what would have been used in a similar casting in conventional HPDC without cores.



a) X-Ray inspection of a SSR™ *casting*



b) X-Ray inspection of a HPDC casting

Fig. 22: X-Ray analysis of SSR (a) and HPDC (b) castings

Full heat treatment test

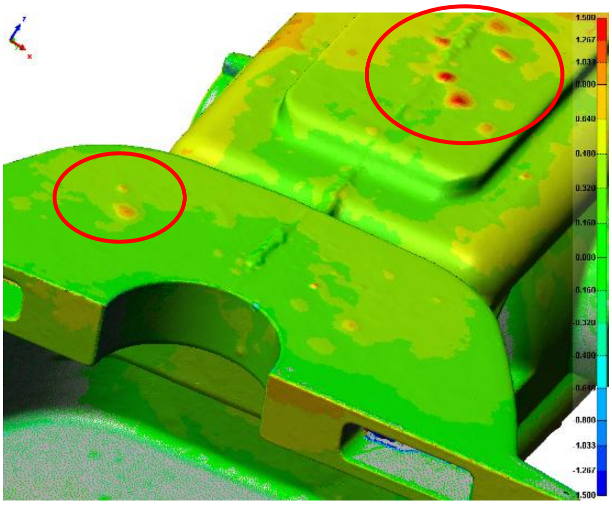
Two cylinder blocks, one cast in HPDC and one cast in SSR™, have been solution heat treated (4 hours at 470°C) in order to check the possible formation of blisters on the surface of the parts.

Before and after the solution treatment the external surfaces of the parts have been scanned with a 3D optical scanner based on structured light technology. Even small geometrical differences can be detected by the comparison of the two scans, pointing out the formation of blisters or distortion of the part. A color scale is used to show the result of the comparison:

- Green: same geometry or small differences (< 0.4 mm);
- From yellow to red: excess material from the baseline scan;
- From light blue to blue: less material than the baseline scan.

The results, reported in the following figures, put in evidence that in the HPDC casting after solution treatment (*Fig. 23-a*) blisters, with height up to 1.5 mm, appeared in various positions, while the surface of the SSR^{TM} casting appears free from significant defects (

Fig. 23-*b*).



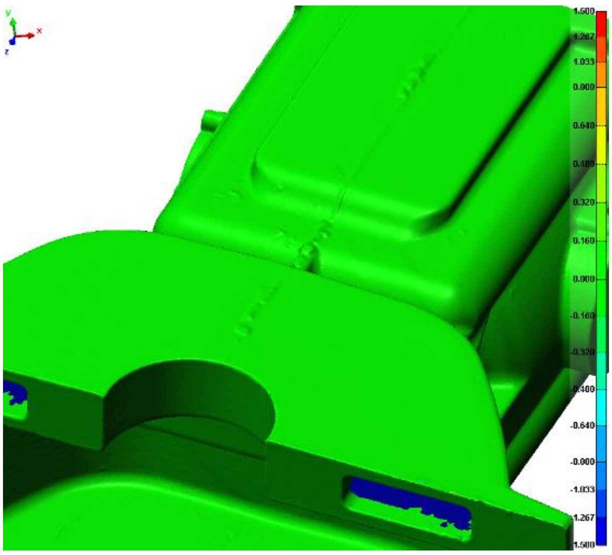


Fig. 23: Effects of solution Heat Treatment

a) HPDC casting shows blisters after solution treatment

b) SSR^{TM} casting with no evidence of significant blistering after solution treatment

TECHNICAL-ECONOMICAL ASPECTS

With present technologies, cylinder blocks in aluminum alloy for high performance Diesel engines, requiring Closed Deck configuration, can only be produced with GDC or LPDC processes.
Since the competition in terms of cost with the conventional cast-iron blocks is very tough and the market is not always ready to pay a premium price for the weight reduction, the possibility to consider HPDC, or one of its Semi-Solid variants, among the possible alternatives for serial production of this kind of aluminum blocks, opened by the development of suitable cores, becomes very interesting.

If, with no doubt, conventional HPDC is the most cost effective casting technology for high volume serial production of aluminum components, the question is now how much will its cost be affected by the introduction of cores in the cycle and, then, by the need to remove them from the casting?

To answer this question a comparative cost analysis for the production of a 4 cylinder block between GDC and HPDC+cores has been performed. The main considerations arising from the analysis are listed below:

- The raw material for ceramic cores is cheap and high volume production technologies for ceramic components are well known and available; as a result the estimated cost of a ceramic core is not substantially higher than a conventional sand core of the same size.
- The operation of core positioning into the die can reasonably be coupled with the robotized setting of the cast-iron liner inserts, without affecting significantly the cycle time.
- The HPDC die maintenance can be reduced, since the expensive steel water jacket inserts requiring frequent replacement are eliminated.

- The core removal process is surely the most impacting phase: to achieve adequate productivity on a multi-cylinder engine block, multiple nozzles have to be used in parallel, requiring fairly high investment for a high pressure pump with suitable flow rate. In addition energetic cost for water pressurization cannot be neglected.
- Other benefits usually associated with HPDC like further weight reduction due to thin wall capability, improvement of yield rate over GDC, reduction of machining due to near net shape, can be maintained.

Based on this analysis it can be concluded that, even if the introduction of ceramic cores results in an estimated cost increase in the range of 7-10% over conventional HPDC, this new technology should still be competitive with GDC, in particular if production volumes are high enough to compensate for high capital investment required and tooling cost and if only one core is used.

Of course in order to evaluate the application to other types of components a similar dedicated analysis would be required, nevertheless, it seems reasonable to say that in many cases, if the cores geometry is such to provide adequate strength and to allow an easy removal (accessibility, shape and volume), this technology could be considered as an economic alternative to conventional casting processes using sand cores.

SUMMARY AND CONCLUSIONS

The main objective of present work was to demonstrate the technical and economic feasibility of producing hollow components in HPDC through the use of ceramic lost cores.

The ceramic cores developed in the project have been tested in a single cylinder block casting and proved to be able to resist, without breakage or appreciable distortion, to injection and overpressure conditions typical (or even beyond) of those found in High Pressure Die Casting or Semi Solid Rheocasting processes.

A system, based on High Pressure Water Jet technology, to remove the cores, even the ones with the highest achieved strength, from the castings has been built and successfully tested.

Parts cast with the SSR process showed excellent soundness and were able to undergo a solution heat treatment without formation of blisters on the surface.

Sand cores, produced by shell molding process for optimized strength and tested in parallel to ceramic ones, showed resistance capabilities beyond expectations, in particular in combination with SSR, even if they were penalized by excessive deformation during the casting process.

HPDC with ceramic cores may become competitive, from a cost point of view, with conventional casting process for the production of hollow parts, provided that they are properly designed.

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