2. service function;
3. structural function.

The engine block does its support function by supporting the follow components:

- support the cylinder liner;
- fix the cylinder head;
- fix the main bearing caps to support the crankshaft;
- support the oil pan.

The cylinder block does its service function by hosting the lubricant and cooling circuits.

Fig.57: engine lubricant circuit [10]

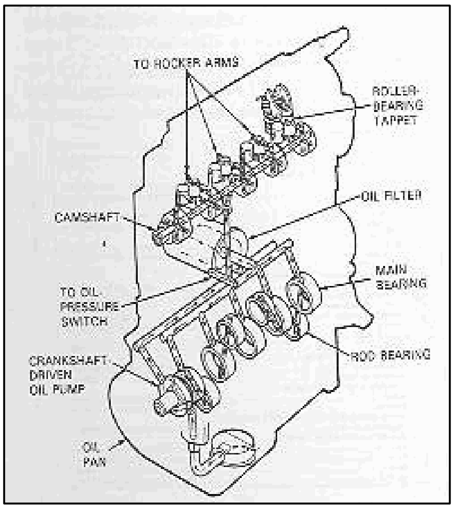
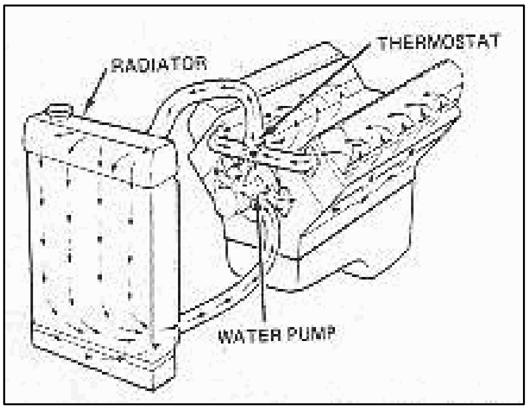


Fig.58: engine coolant circuit [10]



The last function of the cylinder block is the structural function. It means the engine block could be stiff enough to guarantee a good coupling with the piston rings, the main bearing and the gear box under thermal and mechanical loads.

Fig. 59: cylinder liner deformation [11]

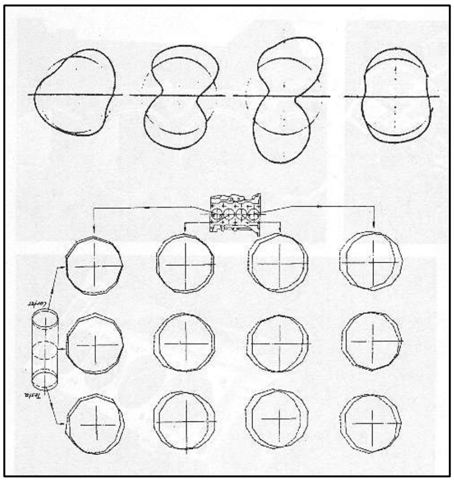
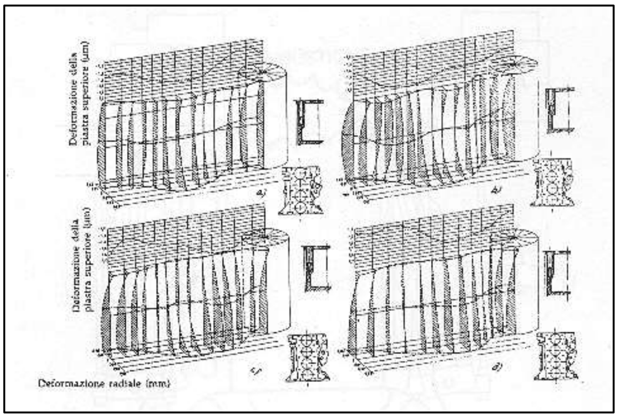


Fig.60: cylinder liner deformation [11]



The technology process to build a cylinder block is the casting owning to the complex geometry of this component. So the materials use to built the engine block beyond to have both adequate macroeconomics – raw material availability, accessible cost, stable geo-politic situations of extracting country – and mechanical characteristics, they have to have necessarily the property request from the technological process as high fluidity and low percentage shrinkage. The best materials have this property are: cast iron; aluminum alloys; for racing and niche motorcycle are using titanium alloys too.

The more used cast irons to produce the engine block are [12]:

- special P-Mn cast iron with much fine grain : it has high castability and good hardness;
- special Ni-Cr cast iron with much fine grain, white martensitic cast iron, hard Ni cast iron: good mechanical properties, high withstand at high temperature wear
- gray lamellar cast iron;
- vermicular cast iron.

In the last decade, with the increase of engine performance, the aluminum alloys are stated, particularly the Al-Si alloys and the Al-Cu alloys [13 - 14].

About the Al-Si alloys, the most used it is the G-AlSi9Mg that has the follow mechanical characteristics:

- very good castability behavior;
- excellent wear resistant;
- after artificial aging, it obtain very good mechanical property with no change until 220 °C;
- good workability at tool;
- for this kind of alloy it executes solution tempering at 500 °C with 3 – 6 hours pre-hating and artificial aging at 180 – 210 °C for 4 – 8 hours.

Normally, the casting of G-AlSi9Mg in sand, are modified with same alkaline salts – NaF, KF, NaCl, KCl – and clear it, in this way it obtains both an increase of the alloy tensile characteristics and an increase of alloy workability at machine tools. About the Al-Cu alloys, the most used for the engine block casting is the G-AlCu5NiCoSbZr knows as the acronym RR350. This Al-Cu alloy presents the follow characteristics:

- high resistance at thermal gradient – cycling thermal load -;
- very good mechanical properties until 350 °C;
- corrosion resistance by Cu and Ni.

The standard thermal treatment is:

- heating at 535 – 545 °C for 8 - 10 hours;
- cooling in the water at 80 °C;
- aging at 210 - 220 °C for 9 - 11 hours;

or execute only:

- stabilization at 340 – 360 °C for 4 – 8 hours;
- cooling in the air.

Takami and Fujine [15] have evaluated, to reduce both the weight and the geometry dimensions of the cylinder block, and consequently of the whole engine, to develop a complete aluminum alloy cylinder block with cylinder liner in MMC – Metal Matrix Composite -. With the introduction of the MMC liner, it is evaluated the possibility to re-design the engine block, where it is possible, to achieve the goal to design a “bridge” of 5 mm width.

The casting techniques used for the engine block production are the horizontal clamp casting and the vertical clamp casting [16]. The advantages and disadvantages of horizontal clamp casting are:

- cheaper than vertical one because it allow the contemporary casting of much more engine block;
- “green” lateral flank of engine block: modeling the casting sand of the bottom of both clamp and counter clamp;
- cost increasing owing to casting sand recycle.

On the other hand, the advantages and disadvantages of vertical clamp casting are:

- much precise so the engine block flank are realized with the casting cores and consequently the whole cast has the same thermal expansion;
- better control of both tolerances and widths;
- expensive than the horizontal one;
- cost increasing owing to casting sand recycle.

Thin casting techniques allows the production of any size engine block, in fact it is possible to realize components up 1000 kg with a dimensional tolerance between 1,5 – 3 %.

About the aluminum alloys, there are several casting technique that the company use to produce a wide dimension range cylinder block [17]. As follow there are the main techniques with their characteristics.

The first one is the high pressure die casting – HPDC -, it consist to push the pressurized melted metal between a matrix and a metal punch. This casting technique allows to made the open – deck engine block only and it is convenient for high series. The main parameters are:

- metal melted pressure: 375 – 850 bar;
- melted metal velocity: 20 – 65 m/s;
- dimension tolerance: 0,1 – 0,4 %
- suitable to produce casting less than 50 kg.

The lower pressure casting – LPC – consists to fill the shape through the spill of melted metal by the pressure of a gas on the crucible. The main parameters of the LPC technique are:

- minor investment costs;
- allow to made both open deck and closed deck cylinder block;
- no sprue;
- economical for middle volumes – some tens of thousands per year;
- technique advised to produce thin wall components and fins;
- allow to realize components up 70 kg;
- dimensions tolerances 0,3 – 0,6 %
- it is used by Ford in North America to produce cylinder blocks, Audi in the United Kingdom to produce cylinder heads and Powertrain Ltd., United Kingdom, a company that was previously part of BMW, to realize gear box houses [18].

The sand casting consists to pour in a sand shape that allows it to be open. The production costs are increased by the recycling cost of the casting sand. In theory, it is not a limit at size of the components but the dimensions tolerances are between 2,5 – 5 %.

The basket casting used by Honda with a mean pressure, is one of the most versatile casting technique and produce robust cast without porosity. It allows to realize components over 100 kg with dimensions tolerances between 0,3 – 0,6 %.

The squeeze casting [19] consists to fill the shape by a cylinder that squeeze the melted metal and it stands on the squeeze pressure until its complete solidification. It allows to produce both open deck and closed deck engine block. The main parameters of this technique are:

- squeeze pressure from 100 to 1000 bar;
- fill velocity: 0,5 – 2 m/s;
- cast without internal defects;
- cast with high elasticity, elongation and tensile strength;
- high quality and productivity.

The lost foam casting technique uses an expanded polystyrene model to realize components with high complex shape. The reason of the name of this technique derives from the fact that the polystyrene model sublimates when the melted metal pour in the casting box. The dimension tolerances are among 2 – 4 %. An example is in the GM Saturn engine plant in Tennessee, where the process is used for aluminum heads and blocks, and ductile cast iron differential cases and crankshafts [18].

The thixo-forming is a particular casting technique that counts to use a metal material in a semi-solid state. The developments of semi-solid state material – thixotropic - forming process are a little bit slow, at present, and not so showy, owing to go over the beginning difficulties of a new process. The main steps of thixo-forming process are:

- horizontal pour of AlSi alloy at controlled temperature;
- cutting of the billets;
- billets heating at controlled temperature;
- introduction of the billet in the casting chamber;
- thixotropy forming;
- finished components.

One of the difficulties of this process is the supply of the beginning material prepared in billets shape. These to be properly ready, have to show, after the cast and the cooling, a micro-structure so that after the next heating process, will be form the characteristic globular structure as to do, e.g., for the Althix® billets by Pechiney.
The last one is the vacuum suction casting process by Toyota that uses to realize its aluminum cylinder blocks.

CYLINDER LINER

The cylinder liner is the component located between the piston ring and the engine block and it has the follow main functions:

- heat transfer from the combustion chamber to the cooling system;
- drive the piston;
- have excellent heat anti-wear property;
- good tribological coupling among the liner, the piston mantle and the piston ring, to sum up, low friction coefficient;
- good sealing between liner and piston ring, to contain the oil consumption and limit the transit into the carter of the combustion gases – blow-by;
- limit the cylindrical surface deformation of the liner.

The main technological processes to realize the cylinder liner are:

- casting;
- sintering;
- micro-casting.

Conversely, the material uses to produce this component are:

- spheroidal cast iron;
- Ni cast iron;
- Al alloys;

- steel.

About the Ni cast iron property is possible, paid attention, to refer at Ni-Cr cast iron highlights for the cylinder block.

The spheroidal cast iron cylinder liners are produced directly in the cast of cylinder block through several operations at machine tools. Indeed, the Ni cast iron liners are used in aluminum alloys engine block and it needs the nitrating heat treatment. This kind of liner allows to achieve a very light engine block, and more he has the advantage to no need the grinder machine tool operation before it runs up.

The cylinder liner could add in two ways: the first one is a dry added as in the Figure 16 because the external surface of the liner is in contact with the cylinder block material; the second one is a wet added where the external surface of the liner is in contact with cooling water.

An evolution of the dry or wet cast iron cylinder liner is the Goedel one [20]. The peculiarity of this component is the material variation in the liner width, from the lamellar cat iron for the working surface – very good sliding and mechanical property – to aluminum alloy for the external surface – suitable for heat transfer and for the engine block anchorage -. The material change is gradually in the width liner between the two material that are chosen to show similar expansion coefficient and strong intermetallic bonding to issue excellent cohesion with the cylinder block material.

On the other hand, the AlSi alloy liner can make basically with two kind of alloys: hypereutectic AlSi alloy – with a Si percentage more than 11,7% - and hypoeutectic AlSi alloy – with a Si percentage less than 11,7% -.

About the hypereutectic AlSi alloy cylinder liner, it has inherently the mechanical property suitable to withstand at running stresses of the component. So the only treatment that needs to be done for this kind of liner consists in an alkaline salts attack of internal surface of the liner to highlights the silicon crystals that support the piston mantle.

Indeed, the hypoeutectic AlSi alloys cylinder liner does not have inherently the mechanical property to withstand the running stresses of the component and so it needs suitable treatment before the launching. The main surface treatments used are:

- nickering or rather the application of a galvanic layer constitutes of a co-deposition of nickel matrix in which silicon crystal are englobed; this layer is knew as Nikasil;
- to use a double deposition where the first application is a layer of short ceramic fibers and than a layer of Nikasil;
- surfacing heat treatment by laser;
- co-deposition to find out at very low friction coefficient:
    - matrix: nickel, copper, galvanic bronze;
    - englobed material with a lamellar structure: graphite particles, molybdenum sulfide, boron nitride.

The cylinder liner could realize in sintering aluminum alloy too through the spray compacting process [20-21].

Now, it will be analyzed different solution for all aluminum alloy cylinder block with unabridged cylinder liner. There are two types of this kind of engine block: the first one provides for adoption of thin galvanic layer on the working surface; while the second one provides to use an high silicon content material without no other kind of layer.

In the second category there are the Silumal by Mahale and the Alusis by KS; the aluminum alloy used is the AlSi17Cu4Mg and the casting technique is the low pressure one. After the machine tool operation, the working surface of the cylinder liner is subjected to a light chemical attack to allow of expose the crystal of primary silicon taking away a small amount of matrix to achieve a surface with excellent tribologic, oil retention and anti-wear property. The dimensions of silicon crystal are 20 – 70 micron and their Vickers hardness is 1400 HV. With this kind of solution, the mantle piston needs to be coated with FeZn or Cr galvanic layer.

The coated liner used in the series engine has a galvanic Ni matrix in which a myriad of silicon carbide particles are cleaned. This coat is known as Nikasil by Mahale. The matrix width is 50 – 80 micron and the silicon carbide particles are 3 – 4 % in weight with an average diameter of 2 micron. But the same technology is possible find in top engine as Ferrari V12 which have the stand edge on the top and the centering at the bottom. With this kind of solution the piston mantle can have no coating.

A system proposed by KS is the Lokasil that provide the adoption of sintering liner constitutes of an aluminum base and silicon grain but it can present short alumina fiber too. This kind of liner is merged by a downright impregnation of the fused aluminum alloy of the engine block during the casting process through the squeezing casting technique. This happen because the liner makes by sintering is porous and the melted metal of the engine block can go into the pores of the liner. In this case, the KS uses a liner material with excellent composition and structure and a cheap and easy working alloy for the engine block. Porsche use this system to make the engine block of its Boxster model. About the piston mantle is enough that it is graphitate – lower cost solution -.

The Mercedes Benz proposal for a lightweight engine is the Silitec system used on light alloy casting engine block in which sintering liners realize with the complex technique of spray compacting are merged. The materials of the liner are aluminum and silicon in a percentage of more than 25 %. In this system, the liners are not impregnate from the fused metal during the casting process but the more external surface of the liner melt down that issue after solidification, a perfect metallic bond that means in high heat transfer and a strong anchorage. The casting technique used for this application is a conventional high pressure die casting with a closed force of 4400 tonne. Mercedes Benz use this system to realize its V6 and V8 engine. After a two steps of smoothing, the liners are subjected to a light attack with a alkaline water solution. This attack is 30 seconds long and it is necessary to remove a small amount of matrix to highlight the silicon grain. This grains are beveled and they have a diameter of 2 – 15 micron. With this system the piston mantle is coated with a FeZn or FeSn base galvanic layer.

Several high performance engines, used in top level cars, have wet liner with the edge stand in the middle, in which the wet part has a height of one third of the whole height. The application of wet liner generally entails a slightly increase of engine dimension in comparison to the dry liner or the full material engine.

About the cylinder liners, a proposal solution to reduce their mass and to increase their mechanical, physical and tribological properties are the plasma coating. Akalin and Newaz [25] have investigated the low cost and solid lubricant contained in the plasma spray coated cylinder liners for their frictional performance. While Kamo and Saad [26] have developed a low cost, durable ceramic composite cylinder bore coating for diesel engine operating under severe conditions. The fundamental components of the coating are iron oxide, iron titanate and partially stabilized zirconia.

The machine tool operations that a engine block cast, more or less finished off, has to do before its running up are:

- possibly internal tuning of the cylinder liner or the liner location to lodge the liner;
- smoothing of the coupled plane between cylinder head – engine block, oil pan – block and all the lodge to stand pumps, covers, etc…;
- drilling and tapping to lodge the prisoners;
- drilling of lubrication ducts, unless they create by casting;
- boring of the main bearing lodge;
- eventually verification of cylinder liner internal surface.

CYLINDER HEAD

The cylinder head is one of the most important engine components and it has three main functions:

- allow air and combustion feed;
- withstand at mechanical load due to the cylinder pressure;
- allow with a suitable cooling distribution the thermal gradient control.

The cylinder head, usually made with cast iron or aluminum alloy, has two fundamental development fields: materials & mechanical property and design & methodology.

About the simulation methodology, its contribution is the boundary conditions of traditional simulation. In facts in the integrated simulation methodology by Cupitò and Trabucco [27] are taken account all phenomena that could effects the mechanical property and so the durability of the cylinder head. First of all, this methodology take account of no-homogeneous mechanical properties that it uses in the numerical analysis. In fact, all cast properties change respected to the micro-structure produced by the several thermal gradients generate during the cooling process; and from defects as porosity or oxides that strongly influence the component performance. But all this conditions do not lead at great results, they only highlight with a bit more details the critical areas that the traditional simulation has marked yet.

About the design, it has been investigated new features and so parameters to evaluate them. An important aspect analyzed by Hamm and Rebbert [28] are the design features of cylinder head concepts which have the capability for increasing thermal and mechanical loads in modern diesel engines due to increase of the peak firing pressure that is approaching 200 bar and even higher in heavy duty diesel engines. In the end the solution with the best rate, mechanical performance on cost, is the classical intermediate deck cylinder head. But with this work, a methodology to evaluate an cylinder head design in a very early stage has been defined.

About the mechanical properties of the aluminum alloys there are a constant trend to increase tensile properties as ultimate tensile stress, yield stress and elongation by: move the eutectic point of the alloy with metal addiction as Na and Sr; evaluate the effects of several iron contents, as shown by Zhang and Albertinazzi [29]. And even more reduce the residual stress by optimize the heat parameters and its process as well as presented by Zhang and Albertinazzi [29]. On this last point, Garro and Zhang [30] have focused many efforts to understand and reduce the residual stress considering: the micro-structure alloy, the ageing temperature, the waiting time, the solution temperature and the position of how the cylinder head meets the water of the quench bath. How the waiting time is the main parameter to control the residual stresses in the casting process, the thermal gradient is the main parameter in the quenching phase. For this reason, Su and Lasecki [31] have analyzed a air-quench cylinder head study focused on the physical motivation that produce residual stress and a visco-plastic material model to describe and evaluate it.

Many machining operations are required to convert the rough casting into a finished cylinder head, including:

1. drilling tapped holes for the spark plugs, for bolts and studs to attach the manifolds, and for other parts;
2. finishing coolant and oil-passage holes;
3. finishing mounting surfaces;
4. drilling valve-guide holes;
5. finishing valve seats.

OIL PAN

The oil pan is the bottom engine component and it usually makes of iron steel, lightweight alloy, plastic material. The oil pan has the follow main function:

- lubricant oil tank;
- reduction engine noise;
- allow engine lubrication in severe dynamic conditions.

The research areas about oil pan are: solutions to reduce the engine noise; materials; and passive optimization that means both NVH – Noise, Vibration and Harshness – and structural one.

About the solutions to reduce oil pan noise, the more interesting one are: the use the oil viscosity as damper made by Uraki and Kondo [32]; and the use of piezo-electric actuator to change the stiffness of the softer oil pan surface made by Wolff and Wimmel [33]. Passive optimization measures, such as structural optimization and acoustic shielding, can be limited by e.g. light-weight design, package and thermal constraints. Therefore, the potential of the Active Structure Acoustic Control – ASAC – method based on piezo-ceramic foil technology for noise reduction was investigated. The method has proven to have significant noise reduction potential with respect to oil pan vibration induced noise. The piezo-electric solution highlights the challenges, in terms of costs, benefits, reliability, robustness and so on, that a new technology has to win to arrive in mass production.

In term of materials Vert and Niu [35] have compared the magnesium alloy for oil pan and the aluminium one. About the magnesium alloy is presented the properties of the classical magnesium alloys as presented by Koike and Washizu [34] and an innovation one based on the metallic systems Mg – Zn – Al – Ca [35]. This kind of alloys have better mechanical properties, lighter, better creep, corrosion and high temperature behavior then that one with rare earths that are very expensive. In the end, a comparison between the A380 aluminum alloy and the MRI 153M magnesium alloy has been conducted to highlight the advantages and disadvantages. The main advantages of this new magnesium alloys are weight saving and a better NVH behavior even if the joint filters the major part of the vibration and harshness. This last point, due to a higher damping ratio and a lower Young module than the aluminum one, forces to design again the component in term of stiffness, if it is not enough with the material changing. So, the magnesium alloys have great potential but it cannot move directly from aluminum or iron steel to magnesium.

A methodology to passively optimize the oil pan as shown by Duran and Sever [36] foresees 3 steps: topography optimization, frequency response analysis and surface velocity integration. The methodology steps have the aims of increase the stiffness with constant mass, improve the frequency behavior and reduce the transmission of the noise to external environment, respectively. The findings of this methodology are validated by experimental tests.

Another methodology to optimize the oil pan respect to oil suction point of view is focused on a multi-phase CFD – Computational Fluid Dynamic – analysis where the behavior of the oil and air contained in the oil pan is studied. Furthermore, this kind of methodology defined by Kolekar and Anderson [37] is applied to both steel and plastic oil pan assembly, highlight the advantages and disadvantages to change material from steel to plastic alloy. The fundamentals objectives that lead this methodology are: reduction in the weight of components, affordability in terms of cost, use of recyclable / renewable materials, performance comparable to metal oil pan. At the end, the plastic oil pan assembly has a lot of advantages but the performance respect to oil suction point of view are pretty the same. The plastic alloys as the magnesium one, have many advantages but it cannot directly move towards it. The plastic oil pan assembly has required a properly FSI – Fluid Structural Interface – optimization.

CONNECTING ROD

The connecting rod is the component that changes the reciprocating motion of the piston in the rotating motion of the crankshaft. This component, usually calls con-rod has four main parts: the small end, the shank, the big end and the cap that is bolted at the big end.

The most important and interesting aspects related to this component are the lubrication, the manufacturing process, the materials, the fracture splitting process, the structural analysis and the influence on the thermal efficiency of the engine.

The lubrication aspect on the connecting rod is focused, in particular, on the big-end bearing. The most important requirement is the good lubrication between the big-end con-rod and the crankshaft journal and it is mandatory too. The bearing performance is influenced by several parameters as the oil supply rate analyzed by Suzuki and Osaka [38], the lubrication groove location shown by XU and Wang [39] and the big-end stiffness presented by Sato and Makino [40]. But the bearing performance influences different aspects of the engine as the weight and dimension of the crankshaft, the oil pump displacement, the friction, the quality of the shell bearing, the fuel consumption and the efficiency of the engine.

The knowledge about the right oil supply rate to have a sufficient lubrication condition lead a technical advantage on the proper oil pump displacement. The optimization of the oil pump displacement could obtain several advantages on engine as decrease the engine measure, the engine weight and so have an easier engine layout and increase the number of vehicle that can mount that engine. On the other hands, a decrease of oil pump supply rate decreases the BSFC – Break Specific Fuel Consumption – and increase the organic efficiency of the engine.

The con-rod is usually made with iron steel by forging but in the last decade with the towards of the powder metallurgy, several carmakers and metallurgy company have developed new processes and materials to achieve a powder forged item with the same performance of the forged metal con-rod but with the advantages of lighter, cheaper and more flexible design. The more interesting processes are the warm compaction process presented by Kosaka [41] and Skoglund [42] and the precision powder forged presented by Geiman and Christopherson [43]. The warm compaction process is based on the usual uni-axial sintering process but it adds a pre-heat step of both the die and the punches where the temperature arrives around 140 degrees Celsius. The process to work with this high temperature needs specific lubricant. The specific lubricant and the high temperature give to the components make with the warm compaction process a metal structure that increase the fatigue and the tensile strength without increase the component weight. The warm compaction process increases the green strength as well as allow to machining the connecting rod before the sintering step. This aspect leads to conspicuous cost saving on the manufacturing process. On the other hand, the precision powder process is not clearly identified because it is not easy find reliable information on it. But it is focused on the follow tree key parameters: performance, precision and consistency. This method allows to control, in a narrow range, the dimensions and the weight of the connecting rod produced by this system. The three key parameters allow cutting several machining operation and having more design flexibility. The result is a higher performance and cheaper connecting rod in comparison with the forged one.

However, the performance engine trend that guides the worldwide market until a couple of years ago, leads to increase the performance reducing the displacement, in particular for the diesel engine. The consequence of this trend is a huge increase of the combustion pressure that means a huge increase of the stress and thermal level around the combustion chamber. The powder metal connecting rods are suitable, at present for the gasoline engine or in other words for combustion pressure up 80 bar. In the last couple of years, under a more sever environmental regulation, as the limit of 99 grams of CO_2 per 100 kilometers, push the carmakers towards the de-rating trend that means a reduction of the specific engine performance. A lower specific engine performance surely leads to a decrease of combustion pressure and of consequence a lower thermal and stress level around the combustion chamber. In this scenario it will be possible, with a proper materials development, to design and manufacture a powder metal connecting rod for diesel engine passenger car applications.

The basic components of a powder bland are iron, carbon and copper and every day the company from all over the world related to the powder metallurgy try to improve the tensile and fatigue mechanical properties of the sintered materials. The material properties can be improved following two directions: work on the process and work on the bland components.

The main effects related to the process as shown by Ilia and Chernenkoff [44] are the decarburization of the outer layer of the sintered components and the porosity as shown by Takada and Sato [45]; both this two characteristics decrease the cyclic properties of the components. The phenomenon of decarburization strongly affects all the aspects related with the surface of the sintered components as scuffing, oxidation, local variation of the component properties but the study analyzes here, highlight that only layer deep over 0.4 mm badly affect the cyclic properties. On the other hand, the study reported here, start with analyze of a cross section of a sintered connecting rod. The core of the shank section in particular, do not present any porosity, while the external layer present porosity due to the drop of temperature between the component and the die. This study highlights the link between the carbon content, the re-pressing temperature, the flow stress, the hardness, the shape of pore, the size of pore and the fatigue properties of material.

The efforts of the bland components are focused on increase the fatigue strength and increase the workability. Usually, the material is optimized on a bi-dimensional environment in according with Ilia [46-47]: a C – Cu plane where are analyzed some define range of C and Cu. Furthermore, it is possible add other components in the bland or substitute someone with such an innovative or powerful one. For example, as shown by Suzuki and Sawayama [48], the MnS improves the workability of the material but decrease the fatigue properties. It is possible substitute the MnS with a pre-alloyed MnS which increase the fatigue strength and the workability as well. At the end, it is possible substitute the MnS with an innovative addiction the KSX that is a calcium oxide complex. The KSX improves the workability, slightly improves the cyclic properties and reduce of two thirds the quantity of MnS used in a bland with the same properties. An optimized powder material could have high density, tensile and fatigue properties better than the 36MnVS4 iron steel. About the powder metal materials, the comparison between two connecting rods from two similar engines has been reported by Afzal and Fatemi [49]. In this study, the properties of hot-forged connecting rod are higher than the powder one that means there is no one uniform opinion and especially on the market, there are different pressure pro or against powder metallurgy. To sum up, at present the limit of powder materials are lower than the iron steels but this general statement does not have any sense. In other words, a powder bland is a complex system which needs to be optimized towards mechanical performance request for the specific applications.

Another important and sparkly research area is the fracture splitting materials and methods. The international university and industrial community work on this topic follow three big chapters: fracture splitting technology parameters; materials; and methods. First of all, the fundamentals of the fracture mechanics has analyzed to both understand the main aspects of the brittle fracture formation / growing, and characterize it as highlighted by Hoffmann and Geiman [50]. In Hoffmann's work, a verified fracture mechanics model has proposed and with this model, several powder forged steel has analyzed and compared. One of the question marks still open is how produce the V-notch on the con rod big end [51] and which method [52] – static or dynamic – should be use to have a better con rod rejoin. As follow there are several methods to produce the V-notch as well as advantages and disadvantages of both statically and dynamic splitting method [53]. The development material processes of a new fracture split steel has analyzed by Park and Ko [54]. The starting point is the microalloyed steel where the high carbon content has reduced to a medium one. The change in carbon content allow to introduce more addition elements as manganese and vanadium to increase both the mechanical - fatigue strength and increase the machinablity due to the reduced carbon content. The last step of the steel development highlights the need to accurately control the cooling parameters to enchant the cyclic performance of the medium carbon microalloyed steel. An interesting case is the Japan where until about ten years ago the fracture splittable connecting rod is not used in the automotive market. The advantages of fracture splittable con rod has led the Japanese car maker to move from hot forged microalloyed steel, which has very good mechanical properties and machinability but high ductility, to sinter forged materials or pearlitic steel, which have low ductility. This is the background to develop a new medium carbon content steel for the Japanese market. The advantages of a medium carbon microalloyed steel has led to investigate the behavior of low carbon content microalloyed steel through both the fracture strain rate characterization and specific tools to realize the fracture. The use of new steel lead to study the con rod big end from the fracture mechanics point of view to investigate the possibility of multiple fracture surface that produce gaps in the item. At the end, the fracture splitting technology parameters optimization has shown. In particular, the optimization involves the cooling rate and cyclic properties of several materials.

The pre-last topic is the structural analysis of the connecting rod. The three main fold are: structural and fatigue numerical analysis; topological analysis on connecting rod geometry; and the study of the fretting. The key points on the structural and fatigue analysis of con rod are, as presented by Londhe and Yadav [55] how built up a correct model, how the clearance has to take account, the structural behavior of bushing and bearing. In the end, the structural analysis is point out to estimate the fatigue life of con rod as shown by Chacon [56] and then the validation with experimental activities. Another example in this folder points out to development an accurate methodology through FEM analysis using p-method, several convergence methods and the feedback of stand-alone thermal-structural analysis for bushing. About the topological analysis, the effects of geometry parameters on big end structure stiffness are presented by Lee and Chang [57]. The results of topological analysis are evaluated by Taguchi method and describe the effects of geometric features on structure stiffness with advantages or disadvantages on bearing operation.

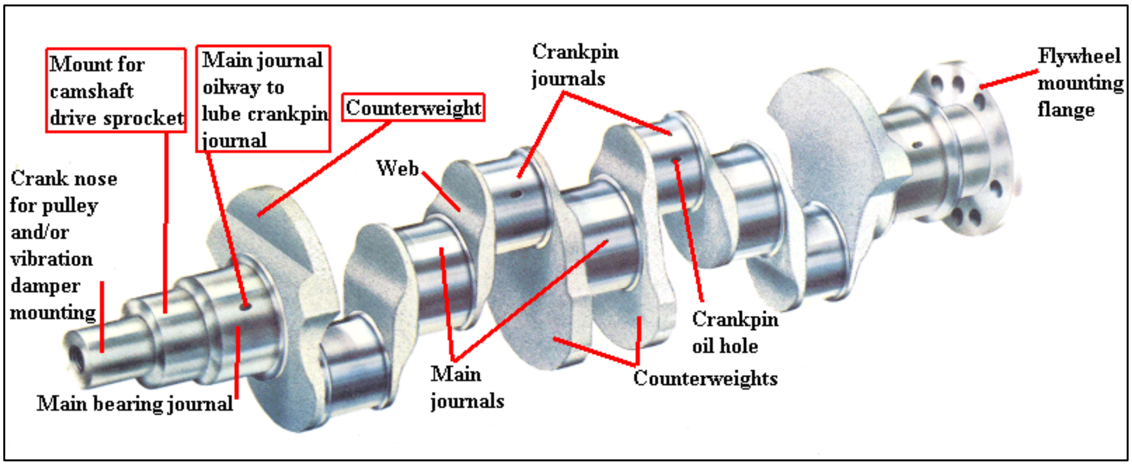
The last fold is the study of fretting and its effect of fatigue fracture. Merritt and Zhu [58] have conducted a study about the prediction of connecting rod fretting and fretting initiated fatigue fracture. The influence of big-end bore fretting on connecting rod fatigue fracture is investigated. A finite element model, including rod-bearing contact interaction, is developed to simulate a fatigue test rig where the connecting rod is subjected to an alternating uniaxial load.

Suzuki and Iijima [59] have conducted a study about the effect of the ratio between connecting-rod length and crank radius on thermal efficiency. An ICVC – Ideal Constant Volume Combustion – engine was produced and tested to improve thermal efficiency by enhancing the degree of constant volume; this was accomplished by allowing moderate change of the piston displacement around TDC. Although the degree of constant volume was improved, no improvement of thermal efficiency was attained.

CRANKSHAFT & ENGINE BALANCING

Crankshaft is component that transfers the energy from combustion chamber to transmission and then wheels. The parts that form this component are shown in Figure 61.

Fig. 61: crankshaft description

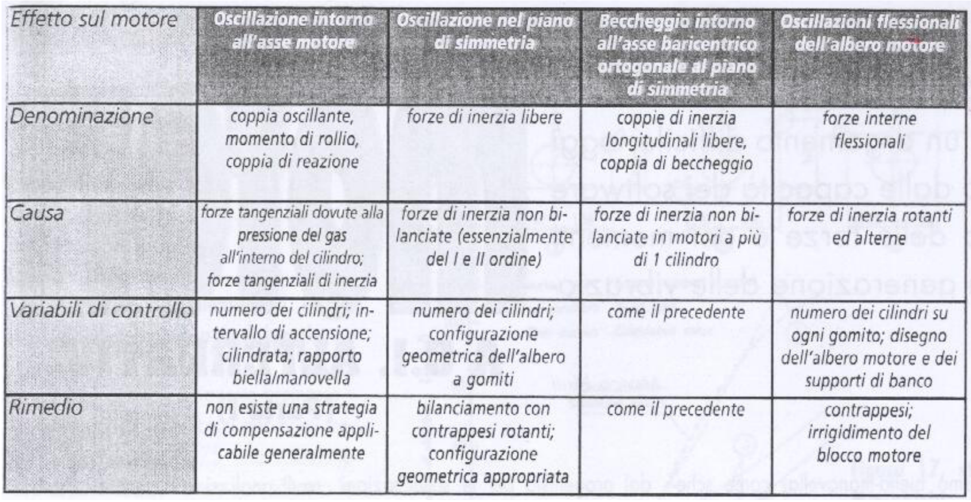


As shown in Figure 61, crankshaft transfers mechanical energy through pulley and sprocket, and through flywheel to gear box. Main journals are crankshaft supports and link this part to engine block. In main journals are channel which lead lubrication oil to crankpin journals. Main journals and crankpin journals are linked by webs or throws. Eventually, in the bottom of web could present counterweight to balance purpose.

The most important and interesting topics about crankshaft are: classification and balancing, optimization, vibration analysis, deep roller technique, fatigue analysis, and materials.

Durante [60–61] has developed the engine balancing topic and in particular, the kinematic and dynamic analysis of the crank mechanism, reciprocating and rotating force calculation, resultant load evaluation acting on engine block, rotating – first order inertial - second order inertial forces system balancing for both mono-cylinder and bi-cylinder engine.While Nuti [62–63] has discussed about the study of forces and moments that participate to engine vibration generation. Table 1 indicates the main reciprocating stresses acting on engine.

Tab. 1: forces and couples apply to the piston and to con rod / web system



Effetto sul motore	Oscillazione intorno all'asse motore	Oscillazione nel piano di simmetria	Beccheggio intorno all'asse baricentrico ortogonale al piano di simmetria	Oscillazioni flessionali dell'albero motore
Denominazione	coppia oscillante, momento di rollio, coppia di reazione	forze di inerzia libere	coppie di inerzia longitudinali libere, coppia di beccheggio	forze interne flessionali
Causa	forze tangenziali dovute alla pressione del gas all'interno del cilindro; forze tangenziali di inerzia	forze di inerzia non bilanciate (essenzialmente del I e II ordine)	forze di inerzia non bilanciate in motori a più di 1 cilindro	forze di inerzia rotanti ed alterne
Variabili di controllo	numero dei cilindri; intervallo di accensione; cilindrata; rapporto biella/manovella	numero dei cilindri; configurazione geometrica dell'albero a gomiti	come il precedente	numero dei cilindri su ogni gomito; disegno dell'albero motore e dei supporti di banco
Rimedio	non esiste una strategia di compensazione applicabile generalmente	bilanciamento con contrappesi rotanti; configurazione geometrica appropriata	come il precedente	contrappesi; irrigidimento del blocco motore

Clarke [64] has developed topic of dynamic balancers as devices, used in the past in others fields as agricultural, industrial and subsequently motorcycles engines, that nowadays has increased their diffusion as well as in automotive field. Vibration source are inertial forces and not balanced momentii through the counter-weightier of crankshaft. It is evident rotating mass could balance through others rotating mass, but is important do not generate disturbing monentii. Different discussion needs for reciprocating masses as piston, pin and part of con rod; inertial forces is generated by previous reciprocating parts, in several kind of engines, are balanced only used auxiliary devices as shafts with eccentric masses. First order inertial forces, proportional to piston stroke and to square of rotational velocity, are due to all masses with reciprocating motion. Suh and Lee [65] have conducted a study on the balancing of the three-cylinder engine with balance shaft. For the three-cylinder engine whose crankshaft has a phase of 120 degrees, the total sum of unbalanced inertia forces occurring in each cylinder will be counterbalanced among the three cylinders. However, parts of inertia forces generated at the No.1 and No.3 cylinders will cause a primary moment about the No.2 cylinder. In order to eliminate this out-of-balance moment, a single balance shaft has been attached to the cylinder block so that engine durability and ride comfort may be further improved. Accordingly, the forced vibration analysis of the three-cylinder engine must be implemented to meet the required targets at an early design stage. In this paper, a method to reduce noise and vibration in the 800cc, three-cylinder LPG engine is suggested using the multi-body dynamics simulation. The static and dynamic balances of the three-cylinder engine are investigated analytically. The vibration velocities at the three engine mounts with and without the balance shaft are evaluated through the real-time vibration analysis. Obviously, it is shown that the vibrations of the three-cylinder engine with the balance shaft are reduced to an acceptable level. On the other hand, Liu and Orzechowski [66] have conducted a study about the theoretical and practical aspects of balancing a V-8 engine crankshaft.

McLanahan and Srinivasan [67] have presented a study on compact multi-cylinder Z-crank axial engine. This paper focuses on a new design that shows promise of compactness, low internal friction and vibration levels (leading, respectively, to further efficiency gains and noise reduction), and higher power to weight ratios. The proposed design is based upon an axial piston configuration known as a Z-crank engine, in which cylinders of the engine are arranged around the shaft. This type of engine is also known as a “Barrel Engine” because the cylinders are similar to the staves around the outside of a barrel. The output shaft is at the center of the cylinder block, and is linked to the pistons by a wobble plate or a swash plate.

Montazersadgh and Fatemi [68] have conducted a study about an optimization of a forged steel crankshaft subject to dynamic loading. The optimization carried out in this work was not based on only the typical geometrical optimization techniques. This is because variables such as manufacturing and material parameters could not be organized in a mathematical function according to the set of constraints such that the maximum or minimum could be defined. Instead, each optimization step was approximated based on improving fatigue resistance while considering manufacturing feasibility and maintaining dynamic balance with an aim of reducing the weight and the final cost of the component. Zuhdi and Aziz [69] have conducted a study about an analytical comparison between 4 versus 8 conterweights for an I4 gasoline engine crankshaft. This paper presents results of an analytical comparison between two alternative versions of a crankshaft for a 2.2L gasoline engine. The first version had 8 counterweights and a bay balance factor of 80.3%. The second had 4 (larger) counterweights giving a bay balance factor of 56.6% and a crankshaft mass reduction of 1.42 kg. The results presented in this paper relate to the main bearings in terms of specific loads, oil film thickness and shaft tilt angle under full load and no load conditions across the speed range. The differences in bearing force and oil film thickness were very small and the only major difference in terms of shaft tilt angle occurred at Mains 2 and 4 (increase of ~20% compared with 8 counterweight version). This increase could result in extra edge wear of the bearing shells but the crankshaft mass reduction achieved by using the 4 counterweight version was significant. Londhe and Yadav [70] have conducted a study about a design and optimization of crankshaft torsional vibration damper for a 4-cylinder 4-stroke engine. The study refers to design of optimum torsional vibration damper in size and weight. The parametric study is carried out to study the effects of damper ring inertia, damper stiffness and damping on attenuation of torsional vibration amplitudes. Also revealed here is the use of Damper Characterization Curve (DCC) and Normalized DCC to select optimum damper. Based on numerical prediction of the crankshaft torsional vibrations and safety factors, optimised parameters for the ring inertia, hub inertia and elastomer properties are arrived at. Controlling the temperature and vibratory torques is critical aspect in designing the TVD (Torsional vibration damper). Jiang and Festag [71] have conducted a study about crankshaft axial vibration analysis and design sensitivity study. The influence of the pin/main bearing journal diameters and the counter weight orientation to crankshaft axial vibration were examined using a fully flexible finite element engine model.

Ko and Park [72] have conducted a study about fatigue strength and residual stress analysis of deep rolled crankshafts. The endurance life of an engine crankshaft is closely related to its fatigue strength, in addition to other material properties and shape parameters. Deep rolling, moreover, enhances the fatigue limit by applying compressive residual stress within the fillet radius area as a major surface hardening technique. The objective of this research is to maximize engine fatigue life through crankshaft design optimization by quantifying fatigue strength for micro-alloyed steels versus a Cr-Mo alloy steel, and to examine the effects of deep rolling load and rolled fillet geometry. Choi and Pan [73] by have conducted a study about the effects of roller geometry on contact pressure and residual stress in crankshaft fillet rolling. Computations have been conducted for three different contact geometries between the primary roller and the crankshaft fillet to investigate the geometry effect on the residual stress distribution near the crankshaft fillet. The results suggest that the contact geometry between the two rollers has significant influence on the contact pressure distribution and the maximum contact pressure along the edge of the primary roller and, consequently, the fatigue lives of the primary rollers. The results also suggest that the contact geometry between the primary roller and the crankshaft fillet does not have significant influence on the overall residual stress distribution and, consequently, may not have significant influence on the fatigue performance of crankshaft sections under bending loads. Therefore, an appropriate adjustment of the contact geometry between the two rollers can significantly improve the fatigue lives of the primary rollers without a significant change of the overall residual stress distributions near the crankshaft fillet and, in turn, the fatigue performance of crankshaft sections under bending loads.

Feng and Li [74] have conducted a study on the duplex surface treatment of pearlitic ductile iron for diesel crankshaft. In comparison with forged steel, the Pearlitic Ductile

Iron (PDI) for diesel engine crankshaft is limited by its low bending fatigue strength. Nitriding followed by fillet deep rolling introduced in this paper is proved to be an effective way to improve the fatigue properties. Williams and Fatemi [75] have conducted a fatigue performance comparison among forged steel and ductile cast iron crankshafts. The two materials used in this study were forged steel (AISI 1045) and ductile cast iron. Spiteri and Lee [76] have conducted an exploration of failure modes in rolled, ductile, cast-iron crankshafts using a resonant bending testing rig. This report explores the relationship of different failure criteria – specifically, surface cracks, stiffness changes, and two-piece failures – on rolled, ductile, cast-iron crankshafts. Druschitz and Fitzgerald [77] have conducted a study about lightweight crankshafts. Cast crankshafts have the potential to produce significant weight savings (3-18 kg) with little or no cost penalty. With the advent of new, high strength, cast ductile iron materials, such as MADI (machinable austempered ductile iron), which has the highly desirable combination of good strength, good toughness, good machinability and low cost, lightweight crankshafts are posed to become a high volume production reality. This paper provides examples of lightweight crankshaft designs and a comparison of machinability, fatigue performance and vehicle performance of regular cast ductile iron, regular cast austempered ductile iron, cast MADI and forged steel. Asai and Takitani [78] have conducted a study on strength enhancement of nitrocarburized crankshaft material. Generally, an automobile crankshaft will undergo a normalizing thermal treatment, surface rolling, induction hardening and nitrocarburizing in order to enhance the mechanical properties. A nitrocarburizing treatment can be applied to complex shapes and, since it is performed at a relatively low temperature, the distortion is minimal. For these reasons, it is widely used as a heat treatment for enhancing wear resistance and fatigue strength.

PISTON

The last component evaluated in this section is piston. About this engine component, Several Authors [79] have presented fundamentals of piston operation. They have studied in details the lubrication of piston skirt – cylinder liner, through advanced numerical methodologies and they figure out the piston design optimization, minimize friction and so, increase organic efficiency of crank mechanism. The piston, main consists of a portion of combustion chamber, a cylindrical part with anti-friction coating and wrist pin location, accomplish to much severe mission. During its reciprocating movement, it is the main component that allows to move forces generate from combustion to crankshaft. This mission is only apparently easy, but need to consider piston works both at very high temperature when engine is at regime and at cold start, when due to thermal expansion, the operation clearance is not fitted. The piston, over its normal movement, has minimal radial clearance. This allows to have both minimum transversal movement and rotational movement around wrist pin. This last movement is the most damage one.

The main forces act on piston mass are forces due to combustion and resultant forces produce of lateral thrust on skirt. These pressures, counted as one resultant, normal to contact surface, blow up friction forces parallel to surface that produce momentum around wrist pin. Moreover, it is considered both forces and momentum owing to piston inertia around wrist pin. These are proportional to component mass and seriously they change sign continuously cycle after cycle. Not negligible are con rod inertia forces that acting on wrist pin, could also highlight both rotational piston movement around pin and piston centre of mass is far way from wrist pin. Friction forces of piston bush and piston rings against cylinder liner are not taken in account.

A deep focus on the effects of piston design parameters on secondary motion and friction for both big and medium engine are carried on by Mansuori [80] and Tsujiuchi [81]. Optimization of piston profile for piston slap reduction through polynomial function in small engine have been made by previous Authors. The “X” piston architecture will be taken as new concept to understand all constrain that lead and push the present piston architecture. For the “X” architecture piston, mono-material version in stainless steel was evaluated by Bruni and Casellato [82]. The skirt reduction to two bands suitably connected to bosses and crown has allowed the reduction of the reciprocating masses and the friction losses by 10 / 25% and 3% respectively. As shown by Brooks and Nito [83], lightweight piston design could lead and achieve trough DFMA and PFMA that means respectively Design Failure Mode Analysis and Process Failure Mode Analysis. These two quality methodology could highlight item functions and main manufacturing steps around those the piston could be designed. This way to approach the piston design leads to weight saving and increase piston reliability. Vettor [84] has faced short journey around specials pistons world.

I-IV From vehicle to propulsion system performance

Starting from worldwide hybrid vehicles market, it is analyzed every segments where hybrids are present and then is focused on thermal engine architecture. The best kind of vehicle to obtain best fuel economy is sedan one and, in particular, cars used small engine displacement in range of 1 – 3 liter. And in the last, it is pointed out how different car manufacturers approach thermal engine application strategy. Next step has understood which are electrical traction system components that are able to hybridize thermal engine and which are their scopes and functions. Moreover, main thermal engine components has been described and analyzed. To sum up, one knows segment and IC engine characteristics to achieve the best fuel economy, features that support hybridization, main engine components, how link vehicle performance to engine performance is point left.
How define vehicle performances is out of topic at moment but they are related to engine performances through vehicle power request to travel at certain speed and in certain conditions. Summarizing, thermal engine has to be able to win motion resistances of vehicle.
These resistances are: aerodynamic, slope, slope rolling and flat rolling. The first step to evaluate aerodynamic resistance is calculate aerodynamic force at wheel F_{aer}:

(1) $$F_{aer} = \frac{1}{2}\rho C_x A_f v_r^2$$