Applications – Power train – Pistons

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1 Pistons

1.1 Pistons for gasoline and diesel engines

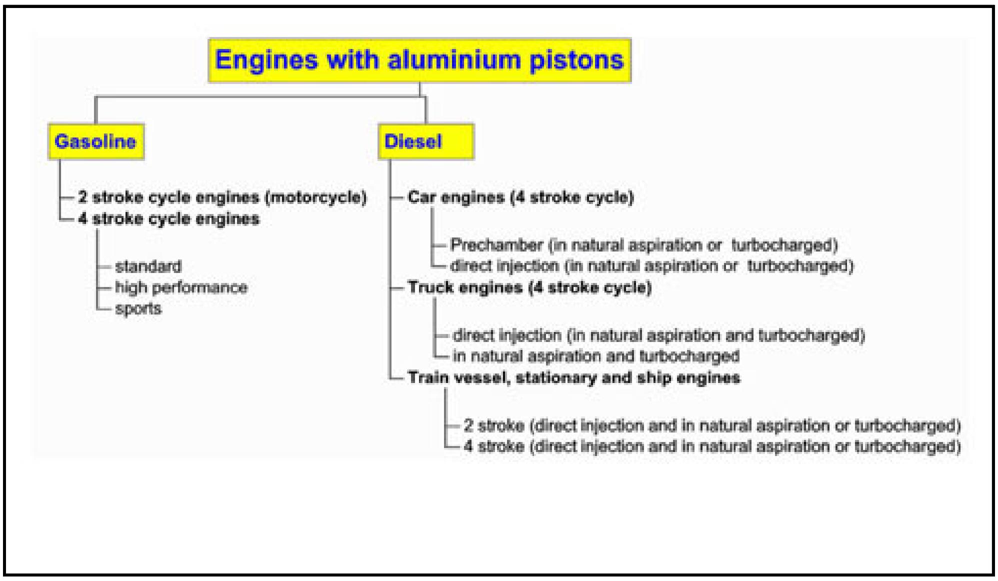
In an internal combustion engine, pistons convert the thermal into mechanical energy. The functions of the pistons are

- to transmit the gas forces via the connecting rod to the crank shaft,
- to seal - in conjunction with the piston rings - the combustion chamber against gas leakage to the crankcase and to prevent the infiltration of oil from the crankcase into the combustion chamber,
- to dissipate the absorbed combustion heat to the cylinder liner and the cooling oil.

Aluminium alloys are the preferred material for pistons both in gasoline and diesel engines due to their specific characteristics: low density, high thermal conductivity, simple net-shape fabrication techniques (casting and forging), easy machinability, high reliability and very good recycling characteristics. Proper control of the chemical composition, the processing conditions and the final heat treatment results in a microstructure which ensures the required mechanical and thermal performance, in particular the high thermal fatigue resistance.

The continuing development of modern gasoline and diesel engines leads to specific objectives for further piston development: reduction of piston weight, increase of mechanical and thermal load capacity, lower friction and thus improved scuffing resistance, etc. In addition, the basic requirements for durability, low noise level and minimum oil consumption have to be taken into account. These goals are achieved by a targeted combination of high performance aluminium piston materials, novel piston designs and the application of innovative coating technologies.

For future development, new aluminium materials using e.g. powder-metallurgical production methods or aluminium-based metal matrix composites produced by various methods as well as other lightweight materials such as magnesium alloys, carbon, etc., are being investigated. However, the ongoing improvements achieved with cast and forged aluminum alloys reveal that aluminium piston materials still offer great optimization potential and will continue to play a dominant role as piston material in the future.



Various combustion engines with aluminium pistons

Source: F. Rösch

1.2 Operating conditions

Literature:
- Röhrle, M. D.: Pistons for Internal Combustion Engines, Verlag Moderne Industrie, 1995
- Junker, H.and Ißler, W.J.: Kolben für hochbelastete Dieselmotoren mit Direkteinspritzung, Technische Information Mahle GmbH Stuttgart

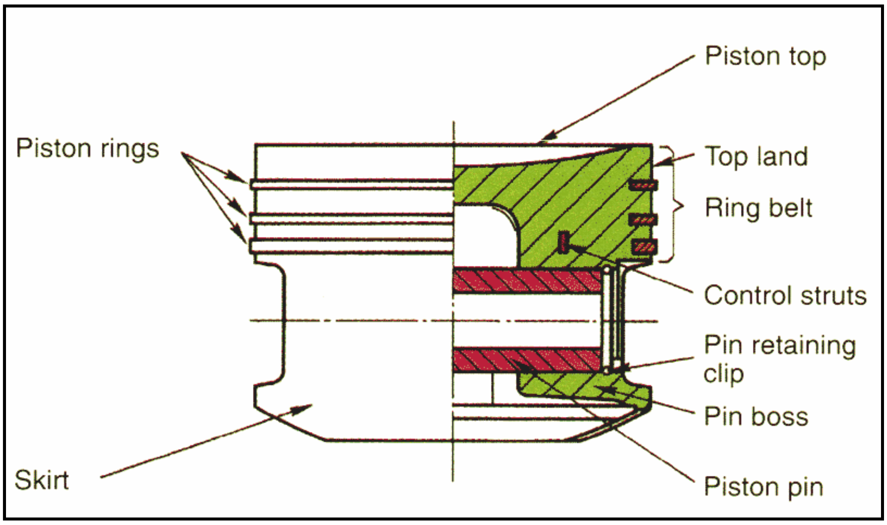
Pistons are subjected to high mechanical and thermal loads. The mechanical loads on the piston result from
- extreme pressure cycles with peak pressures up to 200 bar in the combustion chamber and
- huge forces of inertia caused the by extremely high acceleration during the reciprocating motion of pistons.

These mechanical loads are superimposed by thermal stresses which are primarily generated by the high temperature gradients prevalent on the piston top.

Ever rising demands regarding power density as well as the need for reduced emissions, low noise and more efficient fuel and oil consumption are the main engineering challenges for engines. For the pistons, these challenges translate into maximum strength requirements in the relevant temperature range combined with minimum weight.

In gasoline engines, the thermal loads have risen significantly during the last years as a result of higher power demands. Also the stresses at average ignition pressure have increased as a consequence of the introduction of knock control, direct fuel injection and turbocharging. Moreover, high speed concepts have led to an increase in inertia load. The requirements for pistons for diesel engines are even more demanding. Modern diesel engines for passenger cars (equipped either with direct injection or super-charging with charge cooling) operate with injection pressures up to 2,000 bar, mean effective pressures over 20 bar, peak pressures of 170 to 200 bar, and achieve specific powers of up to 80 kW per litre. But also the demand for ever lower exhaust gas emissions asks for significantly improved piston material characteristics.

The different elements of the piston system are indicated in the following schematic drawing:



Important piston terms

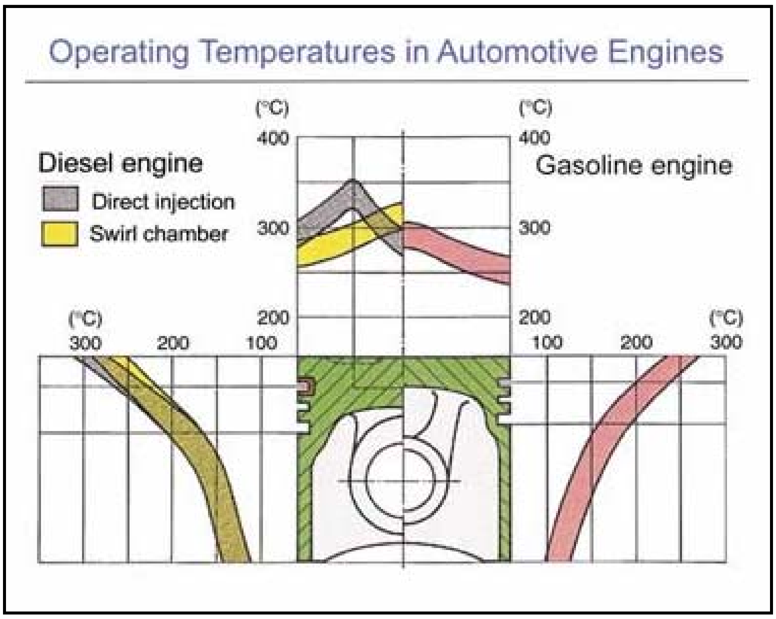
Source: M. Röhrle. Mahle, 1995

The thermal loads on the piston result from the combustion process with peak gas temperatures in the combustion chamber between 1800 and 2600°C depending on type of engine, fuel, gas exchange, compression, and fuel/gas ratio. Exhaust gases have temperatures between 500 and 800 °C.

Combustion heat is transferred to the chamber walls and piston top primarily by convection. The heat is then dissipated by the water cooling of the chamber walls and by the oil cooling of the piston.

A large share of the heat absorbed by the piston top is transferred by the piston ring belt area. The remainder is essentially removed by the oil lubricant impinging on the underside of the piston.

The resulting temperature profile within the piston is schematically outlined in the following figure:



Operating temperatures in automotive engines under full load

Source: M. Röhrle, Mahle GmbH, 1995

1.3 Piston materials

Literature:

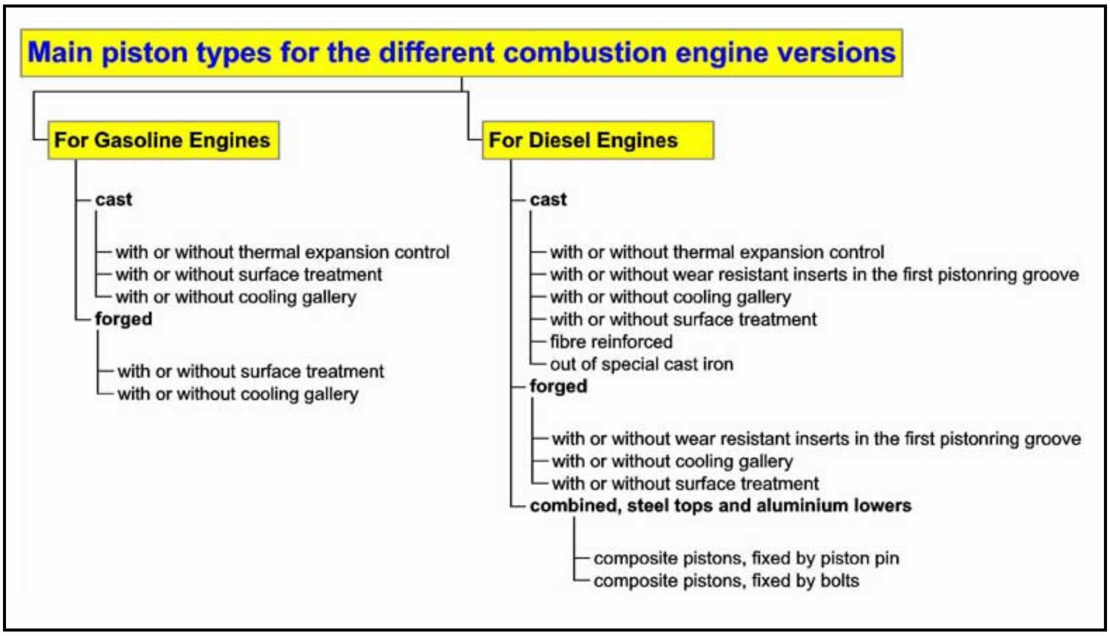
- Aluminium Taschenbuch, 15. Auflage, Dezember 1997, Band 3, Aluminium Verlag Düsseldorf (ISBN 3-87017-243-6)
- Röhrle, M. D.: Pistons for Internal Combustion Engines, Verlag Moderne Industrie, 1995

Pistons are produced from cast or forged, high-temperature resistant aluminum silicon alloys. There are three basic types of aluminium piston alloys. The standard piston alloy is a eutectic Al-12%Si alloy containing in addition approx. 1% each of Cu, Ni and Mg. Special eutectic alloys have been developed for improved strength at high temperatures. Hypereutectic alloys with 18 and 24% Si provide lower thermal expansion and wear, but have lower strength (see tabled property data on the following pages). In practice, the supplier of aluminium pistons use a wide range of further optimized alloy compositions, but generally based on these basic alloy types.

The majority of pistons are produced by gravity die casting. Optimized alloy compositions and a properly controlled solidification conditions allow the production of pistons with low weight and high structural strength.

Forged pistons from eutectic and hypereutectic alloys exhibit higher strength and are used in high performance engines where the pistons are subject to even high stresses. Forged pistons have a finer microstructure than cast pistons with the same alloy composition. The production process results in greater strength in the lower temperature range. A further advantage is the possibility to produce lower wall thicknesses - and hence reducing the piston weight.

Also aluminium metal matrix composite materials are used in special cases. Pistons with Al_2O_3 fibre reinforced bottoms are produced by squeeze casting and used mainly in direct injection diesel engines. The main advantage, apart from a general improvement of the mechanical properties, is an improvement of the thermal fatigue behaviour.



Source: F. Rösch

	Eutectic Alloy AlSi12 CUMgNi		Hypereutectic Alloy AlSi18CuMgNi		Special Eutectic Alloy AlSi12Cu4Ni2Mg
	cast	forged	cast	forged	cast
Yield Strength $R_{P0,2}$ (MPa) at Temperature					
20°	190 – 230	280 – 310	170 – 200	220 – 280	200 – 280
150°	170 – 220	230 – 280	150 – 190	200 – 250	–
200°	120 – 170	–	100 –150	–	150 – 200
250°	80 – 110	90 – 120	80 – 120	100 – 140	100 – 150
300°	50 – 80	–	60 – 80	–	85 – 100
Ultimate Tensile Strength R_m (MPa) at Temperature					
20°	200 – 250	300 – 370	180 – 230	230 – 300	210 – 290
150°	180 – 230	250 – 300	170 – 210	210 – 260	–
200°	160 – 200	–	160 – 190	–	170 – 210
250°	100 – 150	110 – 170	110 – 140	100 – 160	130 – 180
300°	80 – 100	–	90 – 130	–	100 – 120
Elongation to Fracture A_5(%)					
20°C	0,3 – 1,5	1 – 3	0,2 – 1,0	0,5 – 1,5	0,1 – 0,5
Hot Hardness after 200 hours at temperature: Hardness ($HB_{5/50/30}$)					
20°C	90 – 125	90 – 125	90 – 125	90 – 125	100 – 150
150°C	80 – 90	80 – 90	80 – 90	80 – 90	80 – 115
200°C	60 – 70	60 – 70	60 – 70	60 – 70	60 – 75
250°C	35 – 45	35 – 45	35 – 45	35 – 45	45 – 50
300°C	20 – 30	20 – 30	20 – 30	20 – 30	30 – 40
Fatigue Strength σ_w (N/mm^2)					
20°C	80 – 120	110 – 140	80 – 110	90 – 120	90 – 120
150°	70 – 110	90 – 120	60 – 90	70 – 100	90 – 120
250°	50 – 70	60 – 70	40 – 60	50 – 70	60 – 80
300°	–	–	–	–	45 – 60

Mechanical properties of piston alloys at various temperatures

Source: F. Rösch

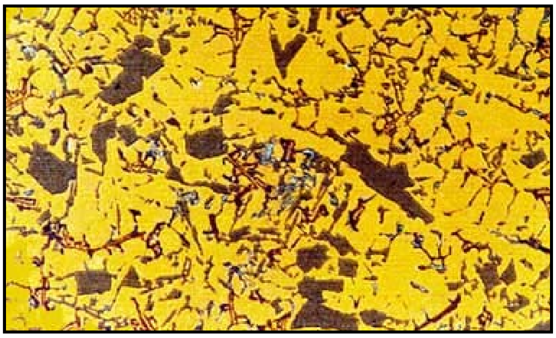
	Eutectic Alloy AlSi12 Cu MgNi		Hypereutectic Alloy AlSi18CuMgNi		Special Eutectic Alloy AlSi12Cu4Ni2Mg
	cast	**forged**	**cast**	**forged**	**cast**
Density (kg/dm^3)					
at 20°C	2.70	2.70	2.68	2.68	2.80
Linear thermal expansion coefficient (1/K)					
between 20° and 200°C	20.5 - 21.5	20.5 - 21.5	18.5 - 19.5	18.5 - 19.5	20.5 - 21.5
Thermal conductivity (W/cm · K)					
at 20°C	1.43 - 1.55	1.47 – 1.60	1.34 - 1.47	1.43 - 1.55	1.30 – 1.40
Specific heat (J/g · K)					
at 100°C	0.96	0.96	0.96	0.96	0.96
Youngs modulus (MPa)					
at 20°C	80.000 - 81.000	81.000	83.000 - 84.000	84.000	82.000
at 200°C	73.000 - 74.000	-	75.000 - 76.000	-	78.000
at 250°C	68.000 - 72.000	74.000	-	76.000	72.000
at 300°C	-	-	-	-	70.000

Physical properties of piston alloys

Source: F. Rösch

Microstructure of a eutectic piston alloy

Source: M. Röhrle, Mahle GmbH



Microstructure of a hypereutectic piston alloy

Source: M. Röhrle, Mahle GmbH

1.4 Design considerations for automotive pistons

Literature:

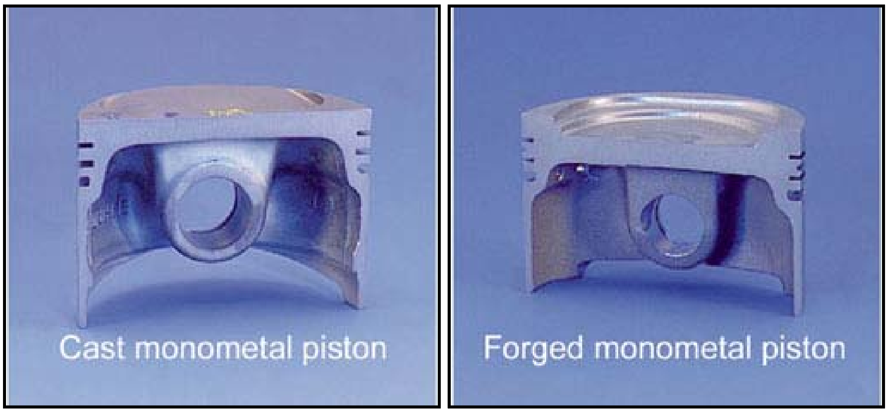
- Röhrle, M. D.: Pistons for Internal Combustion Engines, Verlag Moderne Industrie, 1995

In engines for passenger cars, the diameter of the aluminum pistons for both gasoline and diesel engines ranges typically between 65 and 110 mm. There are two basic types:

- mono-metal aluminium pistons
- aluminium pistons with cast-in elements.

Steel or ceramic cast-in elements are used as local reinforcements to improve the high temperature mechanical properties and/or to control thermal expansion (i.e. reduce the effects of different thermal expansion coefficients in contact areas with other materials).

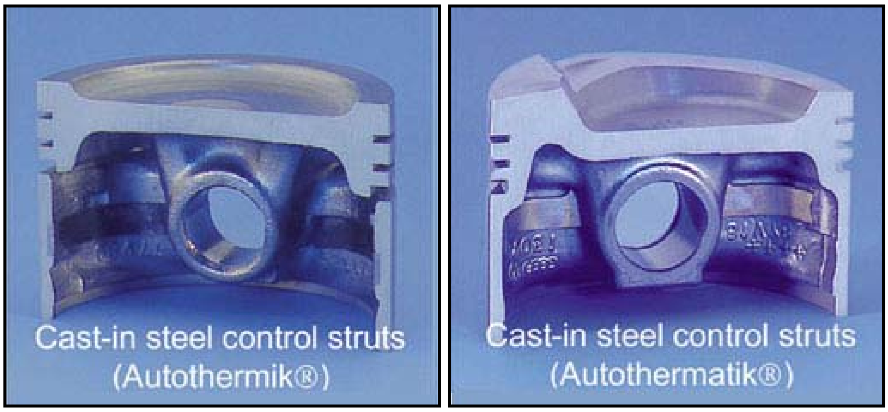
Mono-metal pistons can be used in combination with cast iron engine blocks, but only in low-performance engines due to the larger clearance needed on account of the difference in thermal expansion between cast iron and aluminium. In engines with an aluminium engine block, this effect causes no problem, but special care must be taken to properly control friction and wear in the tribological system "cylinder-piston-piston ring".



Source: M. Röhrle, Mahle GmbH

Pistons with cast-in control elements:

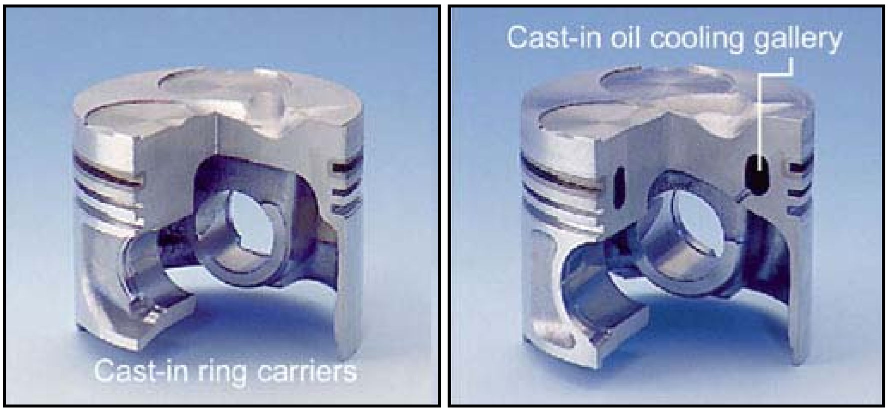
When used in cast iron engine blocks, the thermal expansion of aluminium pistons is usually controlled by cast-in steel struts in the pin boss area. During engine operation, undesired thermal expansions are thereby avoided and the advantages of small clearances can be fully utilized.



Source: M. Röhrle, Mahle GmbH

Diesel engines with pre-chamber, swirl chamber or direct injection operate under higher gas pressures and temperatures compared to gasoline engines. This increases the loads on the first ring groove, which is consequently strengthened by a cast-in stainless steel ring carrier in standard piston designs.

The even higher thermal loads in supercharged diesel engines are reduced by efficient cooling through a cooling gallery, a hollow annular cooling channel filled with oil through a nozzle installed in the crankcase. The cooling channel is usually produced using a salt core technology, but other methods are also possible, in particular for squeeze cast pistons where the cooling gallery is used in combination with ceramic fibre reinforcements.



Source: M. Röhrle, Mahle GmbH

For improved running properties, the piston skirt is generally protected by a wear resistant coating to reduce friction and hence to increase the scuffing resistance. Different coating methods are used (chromium plating, chemical nickel deposition, etc.).

During the last two decades, different measures allowed a reduction of the oscillating masses by 20 - 25 % in the system piston – connecting rod. The suitable choice of piston material proved to be just as crucial as an optimum production process and an appropriate design to achieve the ideal combination of low weight and high stability/reliability. A critical factor is also the application of the proper piston rings. Piston rings are produced from cast iron and steel and optimized in their performance with electroplated, thermal-sprayed or vapour-deposited coatings whether for reducing the flank wear, longer service intervals, better conformity to the cylinder, reducing oil consumption, or reducing friction.

1.5 Current examples of aluminium pistons

Modern cast aluminium pistons for gasoline engines such as the ECOFORM® piston concept developed by MAHLE are designed for minimum weight while increasing the load-bearing capacity. The inclination of the box walls enables relatively large skirt widths in the lower region and improves the stress distribution in the support area. For the next generation of lightweight pistons - the EVOTEC® piston - additional changes relating to the skirt connection, enlarged recesses behind the ring belt on the pin axis, an asymmetrical skirt width as well as supporting ribs on the pin axis result in further weight reductions of up to 10%.

Cast ECOFORM® piston

Source: MAHLE

The piston skirt for gasoline engines with cast iron or steel cylinder surfaces is usually coated with GRAFAL®. GRAFAL® helps to reduce friction and hence increases the scuffing resistance. For the application in aluminum cylinder surfaces, MAHLE uses the iron particle reinforced synthetic resin coating FERROPRINT®. MAHLE's new FerroTec® galvanic iron layer is another ongoing development available on the market. These coatings are necessary to enable the combination of aluminum pistons with pure aluminum engine blocks and hence represent an essential contribution to an overall reduction in engine weight.

Another piston system optimized for fuel economy and CO_2 emissions is offered by KS Kolbenschmidt:

Source: KS Kolbenschmidt

The totally harmonized piston-cylinder system consists of the LITEKS® 2 “advanced” piston generation, the NANOFRIKS® coating, the high duty alloy KS 309™, a low friction ring pack, a lightweight bushless sinter-forged conrod, and a DLC-coated piston pin. As a result, the system friction could be reduced by 32% and the system weight by 10%. At the same time, the fatigue strength was improved and an excellent balance between noise excitation and scuff resistance was achieved.

Forged piston

Source: MAHLE

Forged pistons are common in motor racing, but they are increasingly used also in series-produced engines subject to high stresses. Forged pistons have a finer microstructure than cast pistons with the same alloys. The production process results in greater strength in the lower temperature range. A further advantage is the opportunity for producing lower wall thicknesses-and hence reducing the weight.

Aluminium pistons for diesel engines require improved material properties with respect to the high temperature loads, especially a greater fatigue resistance over a wide temperature range. Standard features include ring carriers made from high-strength, austenitic cast iron (Niresist) for increasing the wear resistance of the first ring groove, salt core cooling channels or cooled ring carriers. For engines with especially high loads, bushings are used in the piston pin bores.

Aluminium pistons for diesel engines

Source: MAHLE

In piston production for diesel engines, MAHLE utilizes the extremely heat-resistant aluminium alloy "M174+". In addition, MAHLE improved the casting process with its newly developed ADC (Advanced Diesel Casting) method. With ADC, a fine microstructure can be achieved in the high-stress zone of the bowl rim, which improves fatigue resistance and the resistance to temperature fluctuations. To improve the piston properties at critical points beyond the limit of this base material and the casting process, additional parts are cast-in in the piston structure or inserted subsequently.

In addition to the measures described earlier, such as casting-in a ring carrier and inserting bushings, fibres made from aluminum oxides are infiltrated for strengthening the combustion bowl subject to high thermal stresses. The fibre reinforcement enables an increased fatigue resistance, improved rigidity as well as increased thermal shock resistance.

With its cooled ring carrier, MAHLE has developed a solution for high volume production which achieves a significant improvement in piston cooling in the critical areas of the bowl rim and first ring groove. The cooled ring carrier consists of a Niresist ring carrier onto which a thin austenitic steel sheet is welded with inlet and outlet openings. Cast-in in the piston, the combined insert brings the cooling oil even closer to the combustion chamber and the first ring groove.

A critical area of high-loaded state-of-the-art diesel pistons is the combustion chamber bowl. Specific engine performance outputs of 70 kW/l and more result in bowl edge temperature exceeding 400 °C. The combination of thermal-mechanical fatigue and high frequency fatigue resulting from the gas forces may lead to cracking at the bowl edge or other areas of the bowl. In diesel pistons from KS Kolbenschmidt, the required improvement of the material characteristics is achieved by the newly developed alloy V4 and a process-controlled microstructure adapted to the specific thermal and mechanical piston loads.

Source: KS Kolbenschmidt

For especially high thermal and mechanical loads at the bowl edge, KS Kolbenschmidt has developed a laser re-melting technology where the zone subjected to high loads is re-melted under controlled conditions to produce an optimized, fine and homogeneous microstructure. This process improves the thermal fatigue properties of the critical zone by up to 60%.

Fig. 5: Passenger car diesel piston with remelted bowl edge

Source: KS Kolbenschmidt

1.6 Outlook

Modern engines with variable valve train or different direct injection concepts require pistons with complex crown shapes which would often lead to a higher piston weight. Therefore in every new piston development, the piston geometry is optimized in particular in the ring belt/piston skirt area. Intensive application of numerical simulation methods enables significant weight reductions while increasing at the same time the load-bearing capacity. Newly developed alloys with better castability, but also higher fatigue resistance in the critical temperature and stress region, allow the realization of thinner wall structures. Improved casting methods enable large recesses for the ring belt and hence a considerable reduction in the piston weight. Boring or milling the internal areas of the pistons also helps reduce the weight. Improved piston cooling and the reduction of piston friction are other features which have to be considered. Local reinforcements with cast-in metallic or ceramic inserts offer further development potential. Thus the aluminium piston has not yet reached its limits.

But also the use of steel pistons in diesel engines for passenger cars is discussed again and again. The advantages of steel pistons such as reduced installation clearances, low fuel consumption figures and long service life would have to be evaluated against customer demands such as low emission levels, lightweight, efficient cooling and a competitive price. But up to now, there are no definite indications that steel pistons would be a viable concept for mass production.