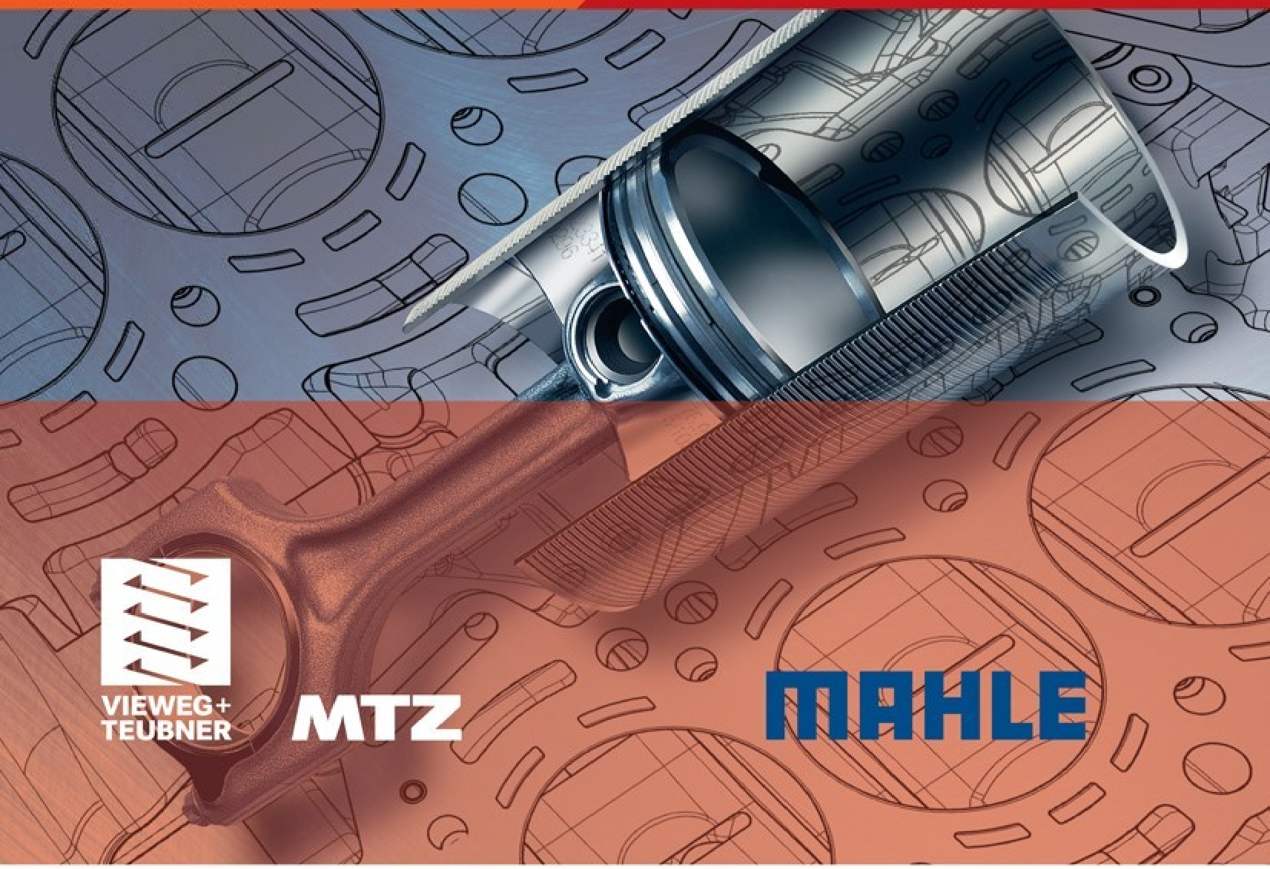
MAHLE GmbH (Ed.)

Pistons and engine testing



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With 269 illustrations and 20 tables

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Preface

Dear readers,

The second volume of the MAHLE Knowledge Base, a series of technical books, is both a broader and a more in-depth companion to the first volume, “Cylinder components.” In this volume, MAHLE specialists share their broad, extensive technical knowledge on the subject of the piston, its design, layout, and testing. The many illustrations, graphs, and tables provide a vivid visual overview of the subject, making your work in this area easier every day.

Never before have the requirements that international legislation and customers place on modern engines, and therefore on the piston, been so great, and sometimes so contradictory. That is why you will find so many details about the piston–its function, requirements, different types, design guidelines–as well as about simulating operational durability with finite element analysis, about piston materials, piston cooling, and component testing. Engine testing, however, is still the most important element in the component development program, as is the validation of new simulation programs and systematic development of design specifications. Learn more about it here–with the scientific depth and meticulousness you expect–in the extensive chapter on “Engine testing.”

This second volume of the technical books series is, once again primarily directed to the engineers and scientists in the areas of development, design, and maintenance of engines. However, professors and students in the subjects of mechanical engineering, engine technology, thermodynamics, and vehicle construction, as well as any readers with an interest in modern gasoline and diesel engines, will also find valuable information on the following pages.

I wish you much enjoyment and many new insights from this reading.

Stuttgart, November 2011

Heinz K. Junker

Acknowledgment

We would like to thank all authors for contributing to this technical book.

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Contents

1 Piston function, requirements, and types

1.1 Function of the piston

1.1.1 The piston as an element of power transmission

In the cylinder of an engine, the energy bound up in the fuel is rapidly converted into heat and pressure during the combustion cycle. The heat and pressure values increase greatly within a very short period of time. The piston, as the moving part of the combustion chamber, has the task of converting this released energy into mechanical work.

The basic structure of the piston is a hollow cylinder, closed on one side, with the segments piston crown with ring belt, pin boss, and skirt; **Figure 1.1**. The piston crown transfers the gas forces resulting from the combustion of the fuel-air mixture via the pin boss, the piston pin, and the connecting rod, to the crankshaft.

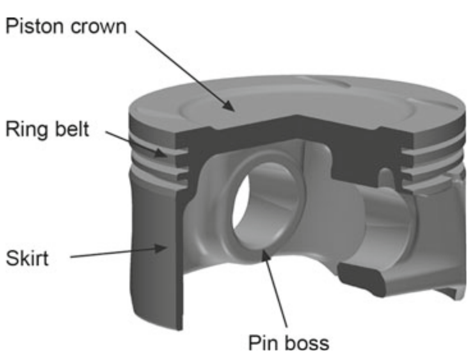

Figure 1.1: Gasoline engine pistons for passenger cars

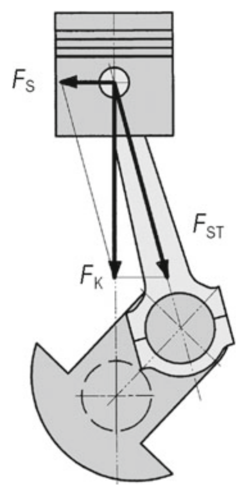

Figure 1.2: Forces on the piston

The gas pressure against the piston crown and the oscillating inertial forces, referred to in the following as the inertia force, of the piston and the connecting rod constitute the piston force F_K; **Figure 1.2**. Due to the redirection of the piston force in the direction of the connecting rod (rod force F_{ST}), an additional component arises–following the force parallelogram–, namely the lateral force F_S, also known as the normal force. This force presses the piston

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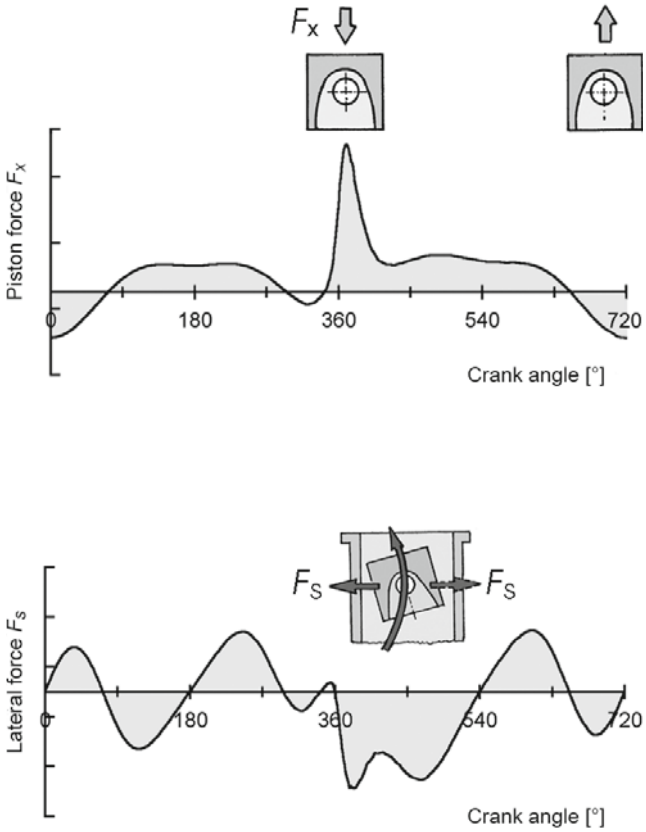

Figure 1.3:
Force curves

skirt against the cylinder bore. During a combustion cycle, the lateral force changes direction several times, which presses the piston from one side of the cylinder bore to the other, due to the existing piston clearance. **Figure 1.3** shows the piston force and lateral force curves as a function of the crank angle.

1.1.2 Sealing and heat dissipation

As a moving and force-transmitting component, the piston, together with the piston rings, must reliably seal the combustion chamber against gas passage and the penetration of lubricating oil under all load conditions. It can fulfill this task only if a hydrodynamic lubricating film is present between the piston rings or skirt and the cylinder bore. The stoppage of the piston at the two dead center points, where the lubricating film isn't fully functional, is particularly problematic. The piston rings must remain functional over very long running periods. Average sliding speeds are typically 10 to 12 m/s.

In four-stroke engines, the piston crown also supports the mixture formation. For this purpose, it has a partially jagged shape, with exposed surfaces (such as the bowl rim) that absorb heat and reduce the load capacity of the component. In two-stroke engines with outlet ports, the piston also acts as a sliding valve and is thermally highly loaded due to the combustion gases flowing out at high speed.

In order for the piston to be able to withstand the briefly occurring, extreme combustion temperatures, it must dissipate the heat sufficiently; Chapter 5.6. The heat in the cylinders is primarily dissipated by the piston rings, but also by the piston skirt. The inner contour transfers heat to the air in the housing and to the oil. Additional oil can be applied to the piston for improved cooling; Chapter 5.

1.1.3 Variety of tasks

The most important tasks that the piston must fulfill are:

- Transmission of force from and to the working gas
- Variable bounding of the working chamber (cylinder)
- Sealing off the working chamber
- Linear guiding of the conrod (trunk piston engines)
- Heat dissipation
- Support of charge exchange by drawing and discharging (four-stroke engines)
- Support of mixture formation (by means of suitable shape of the piston surface on the combustion chamber side)
- Controlling charge exchange (in two-stroke engines)
- Guiding the sealing elements (piston rings)
- Guiding the conrod (for top-guided conrods)

As the specific engine output increases, so do the requirements on the piston at the same time.

1.2 Requirements on the piston

Fulfilling different tasks such as

- structural strength,
- adaptability to operating conditions,
- low friction,
- low wear,
- seizure resistance and simultaneous running smoothness,
- low weight with sufficient shape stability,
- low oil consumption, and
- low pollutant emissions values

result in partly contradictory requirements, both in terms of design and material. These criteria must be carefully coordinated for each engine type. The optimal solution can therefore be quite different for each individual case.

Table 1.1: Operating conditions and solution approaches for piston design and materials

Operating conditions	Requirements on the piston	Design solution	Material solution
Mechanical load a) Piston crown/combustion bowl Max. gas pressure, two-stroke gasoline engine: 3.5–8.0 MPa Max. gas pressure, four-stroke gasoline engine: Naturally aspirated engine: 6.0–9.0 MPa Turbo: 9.0–12.0 MPa Max. gas pressure, diesel engine: Naturally aspirated engine: 8.0–10.0 MPa Turbo: 14.0–24.0 MPa b) Piston skirt Lateral force: approx. 10% of the max. gas force	High static and dynamic strength, even at high temperatures	Sufficient wall thickness, shape-stable design, consistent “force flow” and “heat flow”	Various AlSi casting alloys, warm-aged (T5) or age-hardened (T6), cast (partly with fiber reinforcement), or forged; Forged steel
c) Pin boss Permissible surface pressure temperature-dependent	High surface pressure in the pin bores; low plastic deformation	Bushing	Specialty brass or bronze bushings
Temperatures: Gas temperatures in the combustion chamber of up to 2,000°C, exhaust 600–900°C Piston crown/bowl rim, 200–400°C, for ferrous materials 350–500°C Pin boss: 150–260°C Piston skirt: 120–180°C	Strength must also be retained at high temperature. Identification mark: Strength at elevated temperatures, durability, high thermal conductivity, scaling resistance (steel)	Sufficient heat-flow cross sections, cooling channels	As above
Acceleration of piston and connecting rod at high rpm: partly much greater than 25,000 m/s^2	Low mass, resulting in small inertia forces and inertia torques	Lightweight construction with ultra-high material utilization	AlSi alloy, forged
Sliding friction in the ring grooves, on the skirt, in the pin bearings; at times poor lubrication conditions	Low frictional resistance, high wear resistance (affects service life), low seizing tendency	Sufficiently large sliding surfaces, even pressure distribution; hydrodynamic piston shapes in the skirt area; groove reinforcement	AlSi alloys, tin-plated, graphited, coated skirt, groove protection with cast-in ring carrier or hard anodizing
Contact alteration from one side of the cylinder to the other (primarily in the area of the top dead center)	Low noise level, moderate “piston tipping” in cold or warm engine, low impulse loading	Low running clearance, elastic skirt design with optimized piston shape, pin bore offset	Low thermal expansion. Eutectic or hypereutectic AlSi alloys

The operating conditions of the piston and the resulting design and material requirements are summarized in **Table 1.1**.

1.2.1 Gas pressure

The piston is subjected to an equilibrium of gas, inertia, and supporting forces. The supporting forces are the resultant of the conrod and lateral forces. The maximum gas pressure in the combustion cycle has critical significance for the mechanical loads. The maximum gas pressures that occur depending on the combustion process (gasoline, diesel, two-stroke, four-stroke) and charge intake (naturally aspirated/turbocharger) are shown in **Table 1.1**. At a speed of 6,000 rpm in a gasoline engine, for example, at a maximum gas pressure in the combustion cycle of 75 bar, each piston (D = 90 mm) is subjected to a load of about 5 metric tons, 50 times per second.

In addition to the maximum gas pressure, the rate of pressure increase also affects the stress on the piston. The values for diesel engines are about 6 to 12 bar/1 CAD (crank angle degree), but can be significantly higher in case of combustion faults. The rates of pressure increase in gasoline engines are in the range of 3 to 6 bar/1 CAD. Especially if unsuitable fuels are used (octane number too low), combustion faults can occur under high load, known as “knocking.” Pressure increase rates of up to 30 bar/1 CAD are possible. Depending on the knock intensity and period of operation, it can lead to significant damage to the piston and failure of the engine. As a prevention method, modern gasoline engines are equipped with knock control systems.

1.2.2 Temperatures

The temperature of the piston and cylinder is an important parameter for operational safety and service life. The peak temperatures of the exhaust gas, even if present only for a short time, can reach levels in excess of 2,200°C. The exhaust gas temperatures range between 600 to 850°C for diesel engines, and 800 to 1,050°C for gasoline engines.

The temperature of the fresh intake mixture (air or mixture) can be in excess of 200°C for turbocharged engines. Charge air cooling reduces this temperature level to 40–60°C, which in turn lowers the component temperatures and improves filling of the combustion chamber.

Due to their thermal inertia, the piston and the other parts in the combustion chamber do not exactly follow these temperature fluctuations. The amplitude of the temperature fluctuations is only a few °C at the piston surface, and drops off rapidly toward the interior. The piston crown, which is exposed to the hot combustion gases, absorbs different amounts of heat, depending on the operating point (rpm, torque). For non-oil-cooled pistons, the heat is primarily conducted to the cylinder wall by the compression ring, and to a much lesser degree, by the piston skirt. For cooled pistons, in contrast, the engine oil carries off a large portion of the accumulating heat; Chapter 7.2.

Heat flows that lead to characteristic temperature fields result from the material cross sections that are determined by the design. Typical temperature distributions for gasoline and diesel engine pistons are shown in **Figures 1.4** and **1.5**.

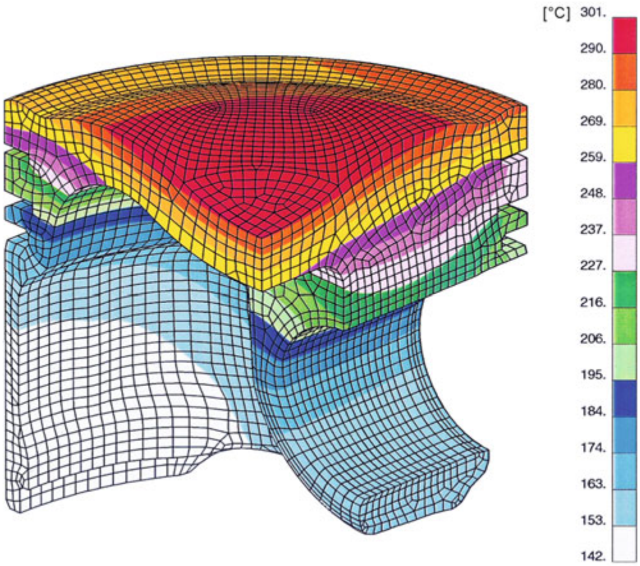

Figure 1.4:
Temperature distribution in a gasoline engine piston

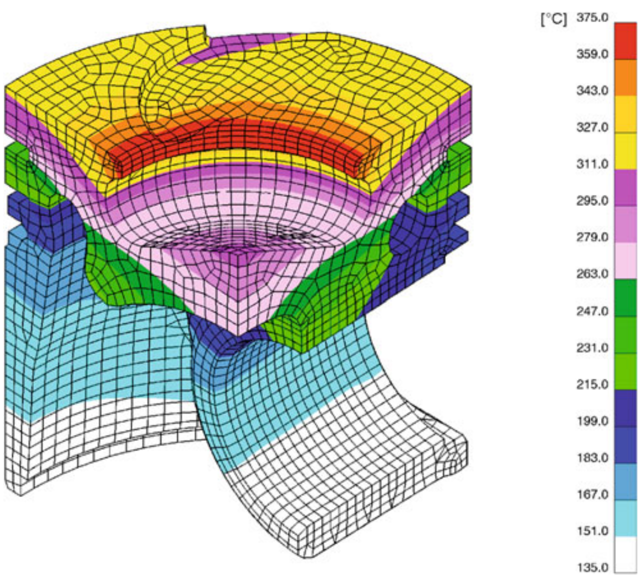

Figure 1.5:
Temperature distribution in a diesel engine piston with cooling channel

The temperature levels and distributions in the piston essentially depend on the following parameters:

- Operating process (gasoline/diesel)
- Operating principle (four-stroke/two-stroke)
- Combustion process (direct/indirect injection)
- Operating point of the engine (speed, torque)
- Engine cooling (water/air)
- Design of the piston and cylinder head (location and number of gas channels and valves, type of piston, piston material)
- Piston cooling (yes/no)
- Intensity of cooling (spray jet cooling, cooling channel, cooling channel location, etc.)

The strength properties of the piston materials, particularly of light alloys, are very dependent on the temperature. They determine the level and distribution of the temperatures in the piston and the stresses that can be withstood. High thermal loads cause a drastic reduction in the fatigue resistance of the piston material. The critical locations for diesel engines with direct injection are the boss zenith and the bowl rim; and for gasoline engines, the transition area from the boss connection to the piston crown.

The temperatures in the first piston ring groove are also significant in terms of oil coking. If certain limit values are exceeded, the piston rings tend to “lock up” (coking) due to residue build-up in the piston ring groove, which leads to an impairment of their functionality. In addition to the maximum temperatures, the piston temperatures are significantly dependent on the engine operating conditions (such as speed, brake mean effective pressure, ignition angle, injection quantity). **Table 7.2.3** in Chapter 7.2 shows typical values for passenger car gasoline and diesel engines in the area of the first piston ring groove.

1.2.3 Piston mass

The piston, equipped with piston rings, piston pin, and circlips, together with the oscillating connecting rod portion, constitute the oscillating mass. Depending on the engine type, free inertia forces and/or inertia torques are thus generated that can no longer be compensated at times, or that require extreme efforts to do so. This characteristic gives rise to the desire to keep the oscillating masses as low as possible, particularly in high-speed engines. The piston and the piston pin account for the greatest proportion of the oscillating masses. Any weight reduction undertaking must therefore start with these components.

About 80% of the piston mass is located in the area from the center of the piston pin to the upper edge of the crown. The remaining 20% is in the area from the center of the piston pin to the end of the skirt. The determination of the compression height *KH* is therefore of great significance, because it predetermines about 80% of the piston mass.

For pistons of gasoline engines with direct injection, the piston crown can be used to support mixture formation and can thus be shaped accordingly. These pistons are taller and heavier. The center of gravity is thus shifted upward.

Piston mass m_K can best be compared (without piston rings and piston pin) when related to the comparative volume D^3, as shown in **Figure 1.6**. The compression height, however, must always be taken into consideration. Mass figures ("X factors") for proven piston designs m_K/D^3 are shown in **Table 1.2**.

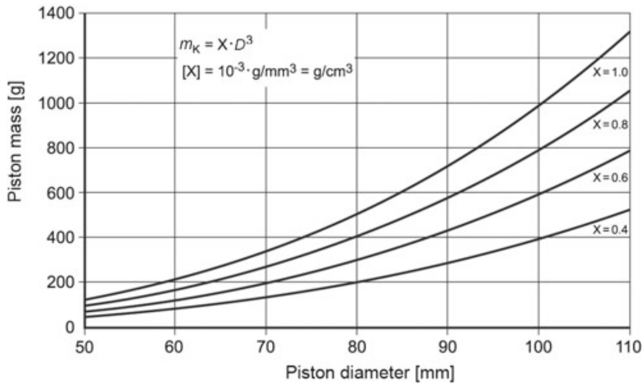

Figure 1.6: Piston mass m_K (without piston rings and piston pin) for passenger car engines, as a function of the piston diameter

Table 1.2: Mass figures for passenger car pistons <100 mm in diameter, made of aluminum base alloys

Operating principle	Mass figure m_K/D^3 [g/cm^3]
2-stroke gasoline engine with manifold injection	0.50–0.70
4-stroke gasoline engine with manifold injection	0.40–0.60
4-stroke gasoline engine with direct injection	0.45–0.65
4-stroke diesel engine	0.90–1.10

1.2.4 Friction and wear

The design, shape, and installation clearance are not the only factors that ensure flawless operation of the piston in the cylinder. The friction forces on the skirt and the skirt lubrication play a decisive role in smooth piston running behavior.

Certain roughness values must be maintained at the piston skirt and the honed cylinder surface. They

- enhance running-in characteristics,
- prevent abrasive wear,

- are a prerequisite for the formation of a hydrodynamic lubricating film between the piston skirt and the cylinder wall, and
- prevent the piston from seizing, i.e., local fusing between the piston and the cylinder due to lack of clearance or lubricating oil.

Roughness values of R_a = 2.5–5 μm are aimed for on the piston skirt.

Figure 1.7 shows the location and shape of the boundary lubrication gap between piston and cylinder. The hydrodynamic lubrication behavior is disturbed only at the reversal points (top and bottom dead center) of the piston, due to the change in direction of the piston motion.

Protective coatings on the running surfaces, such as MAHLE GRAFAL®, reduce friction and improve resistance to seizing.

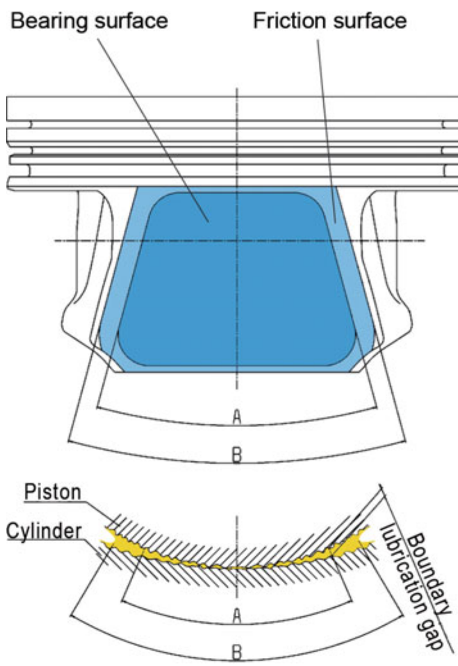

Figure 1.7:
Boundary lubrication gap between piston and cylinder

1.2.5 Blow-by

One of the primary functions of the piston and the piston rings is to seal off the pressurized combustion chamber from the crankcase. Due to the clearance between the piston and the cylinder, combustion gases (blow-by) can enter the crankcase during the kinematic motion sequence. In addition to the resulting energy loss, escaping leakage gas also poses a risk to the piston and piston ring lubrication due to contamination and displacement of the lubricating film, and due to oil coking as a result of overheated temperatures at the locations in contact with the combustion gases. Increased blow-by values also require greater crankcase ventilation.

Sealing against gas penetration is mainly accomplished by the first piston ring, which is a compression ring. For naturally aspirated engines, the quantity of blow-by is a maximum of 1%; for turbocharged engines, it is a maximum of 1.5% of the theoretical air intake volume.

1.3 Piston types

The various operating principles of combustion engines give rise to a wide variety of engine types. Each engine type requires its own piston variant, characterized by its construction, shape, dimensions, and material.

The most significant piston types in engine design are described in the following. There are also new development paths, such as pistons for very low-profile engines, or pistons made of composite materials with local reinforcement elements.

1.3.1 Pistons for four-stroke gasoline engines

Modern gasoline engines employ lightweight designs with symmetrical or asymmetrical skirt contours and potentially different wall thicknesses for the thrust and antithrust sides. These piston types are characterized by low weight and particular flexibility in the center and lower skirt areas.

1.3.1.1 Controlled-expansion pistons

Controlled-expansion pistons are pistons with insert strips that control thermal expansion. They are installed in gray cast iron crankcases. The main target of controlled-expansion piston designs, and many inventions in this field, was and still is to reduce the relatively large differences in thermal expansion between the gray cast iron crankcase and the aluminum piston. The known solutions range from Invar strip pistons to autothermic or Autothermatik pistons.

Due to various adverse properties–notch effects due to cast-in strips, increased piston mass, and higher cost–controlled-expansion pistons are fading more and more into the background. For completeness' sake, however, older piston types are addressed briefly.

Autothermic pistons

Autothermic pistons, **Figure 1.8**, are slotted at the transition from the piston crown to the skirt, at the height of the oil ring groove. They are characterized by their particularly quiet

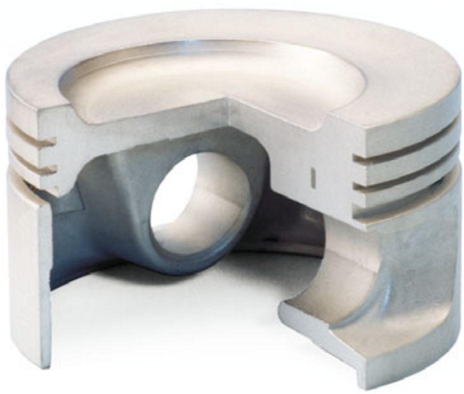

Figure 1.8: Autothermic piston

Figure 1.9: Autothermatik piston

running behavior. The unalloyed steel strips cast in between the skirt and the pin boss, together with the light alloy that surrounds them, form control elements. They reduce the thermal expansion of the skirt in the direction that is critical for the guiding of the piston in the cylinder. Due to their relatively low load capacity (slits), however, autothermic pistons are no longer up to date.

Autothermatik pistons

Autothermatik pistons, **Figure 1.9**, operate according to the same control principle as autothermic pistons. In the case of Autothermatik pistons, however, the transition from the crown to the skirt is not slotted. The transition cross sections are dimensioned such that they barely constrain the heat flow from the piston crown to the skirt and, on the other hand, do not significantly degrade the effectiveness of the steel strips through the connection of the skirt to the rigid crown. This piston design thus combines the high strength of the nonslotted piston with the advantages of the control strip design. Autothermatik pistons are still used to some extent in gasoline and naturally aspirated diesel engines.

1.3.1.2 Box-type pistons

This piston type, **Figure 1.10**, is characterized by its low mass, optimized support, and box-like, often slightly oval skirt design. The box-type piston was designed for use in modern passenger car gasoline engines and is compatible with both aluminum and gray cast iron crankcases. With a flexible skirt design, the difference in thermal expansion between the gray cast iron crankcase and the aluminum piston can be compensated very well in the elastic range. If the box width is different on the thrust and anti-thrust sides, the piston is referred to as an asymmetrical duct piston. Box-type pistons are cast or forged.

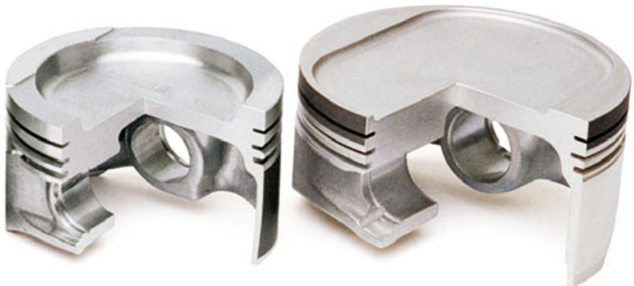

Figure 1.10:
Asymmetrical duct pistons

In addition to the classical box-type piston with vertical box walls, new shapes have recently been established, with box walls that are tapered toward the top. One example is the EVOTEC® piston; Chapter 1.3.1.3.

Pistons for engines with very high specific power output (greater than 100 kW/l) may have a cooling channel; **Figure 1.11**.

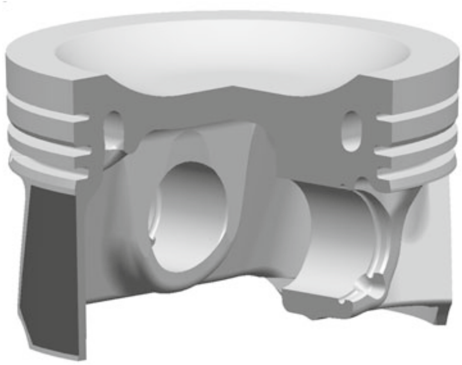

Figure 1.11:
Piston with cooling channel for gasoline engines

1.3.1.3 EVOTEC® pistons

The greatest current potential for reducing the piston mass in four-stroke gasoline engines is the EVOTEC® design, which is primarily used in conjunction with trapezoidal supports; **Figure 1.12**.

Box walls set at a steep angle allow particularly deep cast protrusions behind the ring grooves in the boss area, with good elasticity in the lower skirt area. The connection of the box walls far inside the piston crown–combined with supporting ribs in the piston window between the ring area and the box wall–provides excellent structural stiffness with very small cross sections.

Another significant feature of this piston concept is the asymmetric design of the box walls. In order to accommodate the higher lateral force load on the thrust side, the spacing of the box walls is smaller on the thrust side. The shorter lever arm between the box wall and the

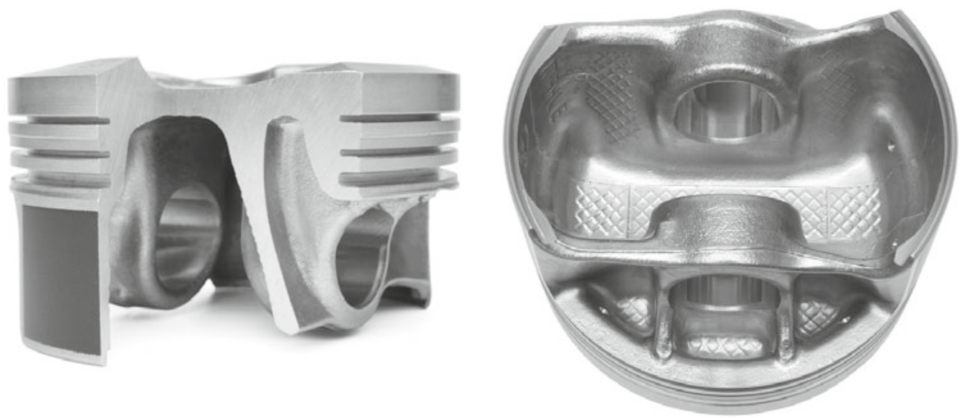

Figure 1.12: EVOTEC® piston

contact area between the piston and the cylinder reduces the bending moment load. This allows smaller cross sections, even with extremely high lateral forces, which are preferred for turbocharged gasoline engines with direct injection. In order to provide the required elasticity and good guiding properties, the anti-thrust side, which experiences significantly lower loads, features greater spacing between the box walls.

1.3.1.4 Forged aluminum pistons

In engines with very high power densities–such as highly loaded turbocharged gasoline engines–cast pistons reach their limits. MAHLE forged pistons are a particularly good fit for this area of application; **Figure 1.13**. Their strength advantage in the temperature range of up to about 250°C improves the load capacity for lateral forces, and increases the load capacity of the boss and the fracture toughness. Forged pistons are therefore especially

Figure 1.13:
Forged aluminum piston

well suited for high-speed concepts and turbocharged engines. Due to the high ductility of the forged material, they also react more tolerantly to peak pressures that can arise if an engine is operated very close to the knock limit. This allows lower ring land widths, among other things, and therefore lower compression heights. Since the manufacturing process is very stable, the forged pistons can be designed to the limit in order to minimize component weight.

One disadvantage, compared to cast counterparts, is the higher product cost of the forged piston. Limited design flexibility is another. Undercuts, in particular, cannot be incorporated in the design.

Motorsport pistons are all special designs; **Figure 1.14**. The compression height *KH* is very low, and the overall piston is extremely weight-optimized. Only forged pistons are employed in this field. Weight optimization and piston cooling are critical design criteria. In Formula 1, specific power outputs of greater than 200 kW/l and speeds of more than 19,000 rpm are common. The service life of the pistons matches the extreme conditions.

Figure 1.14:
Forged piston for Formula 1

1.3.2 Pistons for two-stroke engines

For pistons of two-stroke engines, **Figure 1.15**, the thermal load is particularly high due to the more frequent heat incidence–one expansion stroke for every revolution of the crankshaft. It also needs to close off and expose the intake, exhaust, and scavenging ports in the cylinder during its up-and-down motion, thus controlling the gas exchange. This leads to high thermal and mechanical loads.

Two-stroke pistons are equipped with one or two piston rings, and their external design varies from open window-type pistons to full-skirt piston models. This depends on the shape of the scavenging ports (long channels or short loop-shaped scavenging passage). The pistons are typically made of the hypereutectic AlSi alloy MAHLE138.

Figure 1.15:
Piston and cylinder for a two-stroke engine

1.3.3 Pistons for diesel engines

1.3.3.1 Ring carrier pistons

Ring carrier pistons, **Figure 1.16**, have been in use since 1931. The first, and at times even the second piston ring are guided in a ring carrier that is securely joined to the piston material by metallic bonding.

The ring carrier is made of an austenitic cast iron with a similar coefficient of thermal expansion to that of the piston material. The material is particularly resistant to frictional and impact wear. The first piston ring groove, which is the most vulnerable, and the piston ring inserted in it are thereby effectively protected against excessive wear. This is particularly advantageous at high operating temperatures and pressures, which are particularly prevalent in diesel engines.

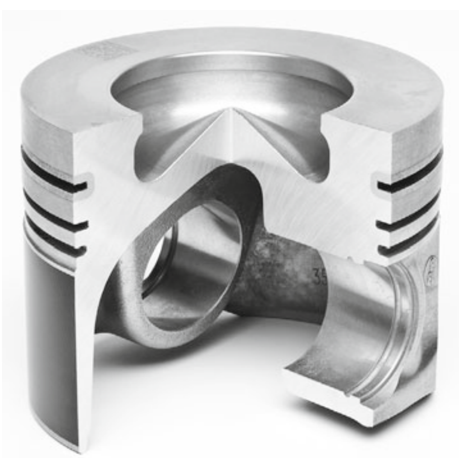

Figure 1.16:
Ring carrier piston

1.3.3.2 Cooling channel pistons

In order to cool the area around the combustion chamber most effectively, and thereby address the increased temperatures that result from higher power outputs, there are various types of cooling channels. The cooling oil is generally fed through fixed ports in the crankcase. Chapter 5 gives an overview of possible cooling variants.

Figure 1.17 shows a cooling channel piston with ring carrier for a passenger car diesel engine. The annular hollow spaces are formed by casting around salt cores, which are then dissolved and washed away with water.

1.3.3.3 Pistons with cooled ring carrier

The piston with "cooled ring carrier," **Figure 1.18**, is a new cooled piston variant for diesel engines. The cooled ring carrier significantly improves the cooling of the first piston ring groove and the thermally highly loaded combustion bowl rim. The intensive cooling of this ring groove makes it possible to replace the usual double keystone ring with a rectangular ring.

1.3.3.4 Pistons with bushings in the pin bore

One of the most highly stressed areas of the piston is the piston pin bearing. Temperatures of up to 240°C can occur in this area, a range at which the strength of the aluminum alloy starts to drop off considerably.

For extremely stressed diesel pistons, measures such as form bores, pin bore relief, or oval pin bores are no longer sufficient to increase the load capacity of the boss. For this reason,

Figure 1.17: Salt-core cooling channel piston with ring carrier for a passenger car diesel engine

Figure 1.18: Piston for passenger cars with cooled ring carrier

Figure 1.19: Ring carrier piston for a commercial vehicle diesel engine with piston pin bore bushings

Figure 1.20: FERROTHERM® piston

MAHLE has developed a reinforcement of the pin bore, using shrink-fit bushings made of a material with higher strength (e.g., CuZn31Si1); **Figure 1.19**.

1.3.3.5 FERROTHERM® pistons

In FERROTHERM® pistons, **Figure 1.20**, the guiding and sealing functions are implemented separately. The two parts, piston crown and piston skirt, are movably connected to each other through the piston pin. The piston crown, made of forged steel, transfers the gas pressure to the crankshaft via the piston pin and connecting rod.

The light aluminum skirt only bears the lateral forces that arise due to the angle of the connecting rod, and can therefore support the piston head with an appropriate design. In addition to this "shaker cooling" via the skirt, closed cooling channels can also be incorporated in the piston crown. The outer cooling gallery of the steel piston crown is closed by split cover plates.

Due to its design, the FERROTHERM® piston exhibits good wear values in addition to high strength and temperature resistance. Its consistently low oil consumption, small dead space, and relatively high surface temperature provide good conditions for maintaining low exhaust emissions limits. FERROTHERM® pistons are used in highly loaded commercial vehicle engines.