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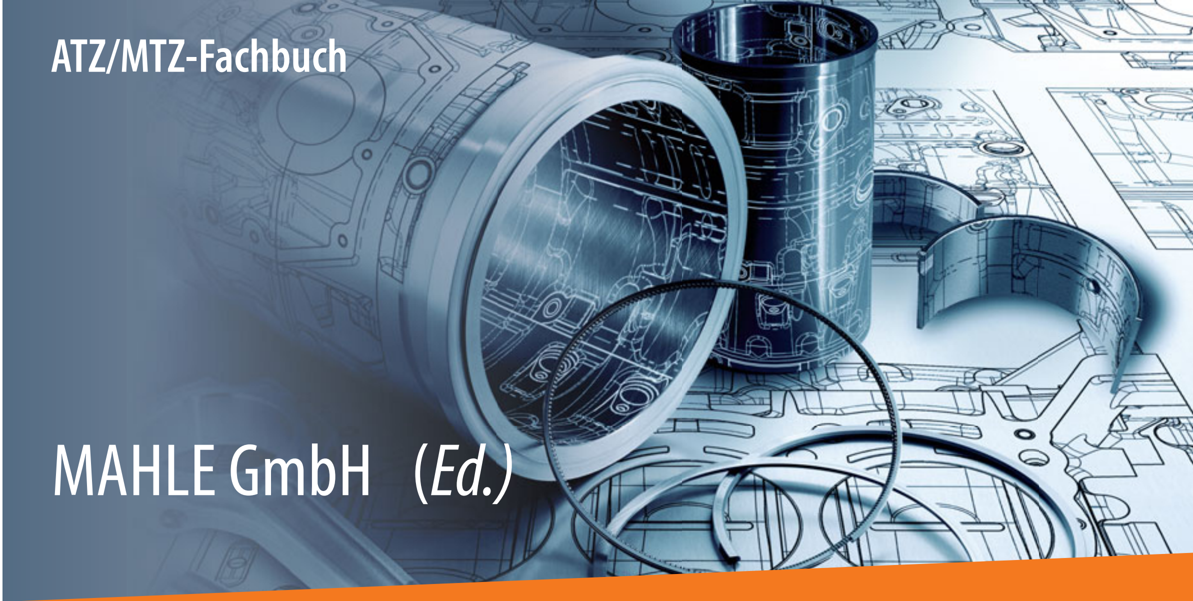

MAHLE GmbH (*Ed.*)

Cylinder components

Properties · applications · materials

2nd edition

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ATZ/MTZ-Fachbuch

MAHLE GmbH
Editor

Cylinder components

Properties, applications, materials

2nd Edition

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This book is based on the second, revised edition of the German book „Zylinderkomponenten" edited by MAHLE GmbH.

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Preface

Dear readers,

This is the second, revised edition of the first volume of the MAHLE Knowledge Base, a multivolume set of technical books. This first volume, like the second volume “Pistons and engine testing,” will make your daily work in this field of conflicting priorities somewhat easier and will be a good source of guidance for all the difficult questions, providing a good visual overview of the entire subject with many illustrations, charts, and tables. The MAHLE Knowledge Base is aimed at engineers and scientists in the areas of development, design, and maintenance of engines, at professors and students in the fields of mechanical engineering, engine technology, thermodynamics, and vehicle construction, and of course at any reader with an interest in modern gasoline and diesel engines.

The development and design of combustion engines is currently going through an extremely exciting phase. Never before have the demands of international lawmakers, customers, and consumer organizations been so contradictory, in part, in their effects on the design and development of engines. Environmental protection through clean exhaust gas, for instance, is not free of charge, neither in terms of costs, nor in terms of engine weight. Particulate filters, exhaust gas recirculation, SCR systems, and other solutions for exhaust gas treatment are also often in direct conflict with the goal of lower fuel consumption.

In this first volume, we present all the details of important cylinder components in meticulous scientific depth. Many questions concerning piston rings, piston pins and pin circlips, bearings, connecting rods, crankcases, and cylinder liners are answered. The contents reflect the experience, knowledge, and technical expertise of the engineers and scientists at MAHLE.

Many descriptive photos and graphics provide information on recent and future trends in cylinder components. Whether it is materials, types, coatings and surface treatments, numerical simulations and FE analyses, or casting processes; no relevant subject was left out. We wish you much enjoyment and many new insights from this reading.

Stuttgart, October 2015

Wolf-Henning Scheider
Chairman of the Management Board and CEO

Heinz K. Junker
Chairman of the Supervisory Board

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1 Piston rings

1.1 Purpose and function of piston rings

Piston rings fulfill the following important tasks for engine operation:

- Sealing off the combustion chamber, in order to maintain the pressure of the combustion gas. The combustion gas must not enter the crankcase (also known as blow-by) and lubricating oil must not enter the combustion chamber.
- Transfer of heat built up in the piston to the cylinder surface
- Controlling the oil balance, where a minimum oil quantity needed to form a hydrodynamic lubricating film must reach the cylinder surface, while oil consumption needs to be kept as low as possible

The piston ring pack usually consists of three piston rings: two compression rings (also known as the first and second piston rings) and an oil control ring (third piston ring).

The piston rings perform the following functions:

1st piston ring: compression of combustion air or gas mixture, and support of gas pressure in the operating cycle, dissipation of generated heat to the cylinder surface (see also Section 1.3), and, to a slight degree, scraping of the residual oil from the cylinder surface

2nd piston ring: support of the remaining gas pressure due to blow-by past the first piston ring, throttling piston land pressures and control of pressure ratios in the ring belt, scraping of oil from and dissipation of generated heat to the cylinder surface

3rd piston ring: homogeneous distribution of the oil for lubrication of the piston group/cylinder bore tribological system and scraping of excess oil

The following issues, however, must be considered in the design of piston rings:

- Scuffing: partial seizure process leading to severe wear, poor sealing, increased oil consumption, and increased blow-by value
- Ring flutter or radial collapse: incidence of radial or axial instabilities that lead to leakage and therefore to increased blow-by
- Ring sticking: at excessive piston temperatures, the oil in the ring grooves carbonizes, so that the piston rings get stuck in it.
- High oil consumption: determining factors are the ring conformability (see Section 1.5.1.4) of the piston rings, deformation and honing of the cylinder bore, and the gas pressure ratios in the piston land region.
- Friction: the piston rings have a large part in the friction of the piston group.

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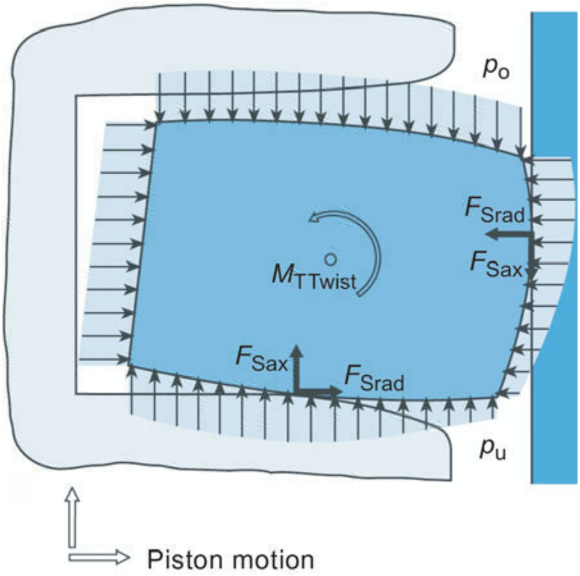

Figure 1.1:
Forces acting on a piston ring in the piston ring groove

Light blue: piston ring groove

Medium blue: piston ring

Dark blue: cylinder

Arrows encompassing the piston ring: forces acting on the piston ring

p_o: gas pressure above the piston ring

p_u: gas pressure below the piston ring

F_{Srad}: radial force and counterforce

F_{Sax}: axial force and counterforce caused by friction

$M_{T\ Twist}$: countermoment of the piston ring

The arrow shows the direction of positive twist.

Compression rings are mostly single-piece, with a spring force. Their basic shape is a thin-walled, axially short circular cylinder. To generate the necessary contact pressure against the cylinder wall, the piston rings are in the shape of an open circular spring. The spring force acting radially in the installed state is greatly amplified by the gas pressure behind the piston ring. Axial contact with the ring groove flank is substantially generated by the gas pressure applied to the piston ring side face (**Figure 1.1**).

When the piston is installed in the cylinder, the piston rings are compressed at their ends to their gap clearance. In the piston, they are guided in piston ring grooves corresponding to their dimensions and therefore follow the piston motion. This type, invented in 1854 by John Ramsbottom, is known as a self-tightening ring and has proved itself from the beginning in pistons for steam locomotives. It became a basic invention in engine technology, because reliable sealing of high gas pressures in the combustion chamber was first made possible by this type of ring–up to more than 260 bar today.

The force with which a piston ring presses against the cylinder wall depends mainly on the difference in diameters of the prestressed piston ring and the cylinder. This prestressing is designed in such a way that the piston ring meets the particular requirements arising from the working process and operating conditions. When the piston ring is installed in the cylinder, a tangential force is created that in turn generates the contact pressure.

- The radial distribution of the contact pressure is achieved by the shape of the piston ring–for example, by CNC turning or coiling.
- The radial distribution of the contact pressure depends on the shape of the running surface–cylindrical or conical–and the profile geometry of the piston ring (barrel shape).
- The contact pressure is determined by the working process.

The radial pressure applied by the piston ring to the cylinder bore is small in comparison to the gas pressure applied by the ring groove in the piston to the inner side of the piston ring (**Figure 1.1**). In diesel engines, with their high gas pressures, the piston ring is, in many cases, shaped against the running surface such that the gas pressure acts from here against the one on the inner side, which reduces the contact pressure on the cylinder surface. Owing to the ring gap dictated by the assembly process, the piston ring cannot provide complete sealing, which leads to leakage at this point.

Piston ring materials require
- good running and boundary lubrication capability;
- elastic behavior;
- mechanical strength;
- high strength at elevated temperatures;
- high heat conductivity; and
- good machinability.

Materials used include untempered and heat-treated gray cast iron, cast iron with nodular graphite (heat-treated), and tempered steel or nitrided stainless steel.

To improve running-in characteristics, reduce wear, and prevent scuffing, special measures are taken in coating and reinforcing (protecting) the running surfaces.

Operating behavior depends on many influence variables, which often makes the optimization of piston rings complex:
- Type and design of the engine
- Combustion process, combustion sequence, pressures, pressure gradients, aftertreatment technology, etc.
- Engine block and cylinder design, cylinder material and finishing (e.g., honing)
- Fuel and lubricant
- Piston technology
- Piston ring type, material, and running surface
- Operating conditions

1.2 Functional principles

As part of the moving boundary of the engine operating space, the piston ring fulfills various tasks. For the course of the thermodynamic process, it must ensure that the gas pressure in the cylinder is maintained and does not drop off. This is the task, in particular, of the first piston ring. One premise is that lubrication, acting as a “gas-sealing oil pressure barrier,” is present. Tests by Felix Wankel had demonstrated that without such a fluid layer, higher gas pressures cannot be sealed against moving parts. The motion of the piston ring develops a hydrodynamic pressure that is greater than the gas pressure. This is why it is so important for the function of the piston ring that the cylinder surface is sufficiently wetted with lubricating oil. The main distribution of this oil quantity is performed by the oil control ring, while fine control is achieved by the first piston ring through oil control.

The arrangement of several piston rings in series forms a system of throttle chambers, in which the pressure of leaking gases is further decreased by throttling and swirling. It is unavoidable, however, that a small portion of combustion gases, compressed mixture, or air will pass by the piston rings and enter the crankcase (blow-by gas). The width and tolerance of the ring gap has a significant effect on the blow-by value. The piston ring seals against the side faces like a valve. Leakage points are most noticeable at the running surface, because the blow-by gas breaks through the oil film. In general, the blow-by value should be as low as possible, because the combustion gases cause increased oil aging and component wear. A certain blow-by value is desirable, however, in order to prevent oil transport into the combustion chamber.

1.3 Forces and stresses

Forces and temperatures on piston rings

Piston rings are highly stressed mechanically, thermally, tribologically, and corrosively.

Piston rings must fulfill their task at high combustion gas temperatures and combustion pressures of up to 260 bar.

Depending on the design, up to 20% of the heat absorbed by the piston can be transferred to the cylinder wall by the piston rings.

The limit of the temperature load on the first piston ring is reached when the oil in the top ring groove starts to carbonize as a result of excessive temperature. The motion of the first piston ring, which is a requirement for its reliable function, is thereby limited. It can no longer maintain its proper contact with the cylinder surface, resulting in ring sticking. One ring-based solution is the keystone ring (**Figure 1.2**), developed in the early 1930s by the English engine manufacturer Napier.

Effective piston cooling is critical, as it significantly reduces the thermal load on the piston rings. Depending on the type of piston cooling, the heat flowing into the piston rings can be reduced.

During one revolution of the crankshaft, the piston moves from the top to the bottom (BDC) and back to the top dead center (TDC). It travels twice the stroke distance. During this