2 Piston design guidelines

In view of the operational requirements of typical internal combustion engines (two-stroke, four-stroke, gasoline, and diesel engines) aluminum-silicon alloys are generally the most appropriate piston materials. Large-bore pistons and commercial vehicle pistons, or their crowns or upper parts, however, are often made of steel.

2.1 Terminology and major dimensions

Functional divisions of the piston are the piston crown, the ring belt with top land, the piston pin boss, and the piston skirt; **Figure 2.1**. Additional functional elements, cooling galleries, and ring carriers indicate the piston type. The piston rings, piston pin, and–depending on the design–the pin retaining system are all part of the piston assembly.

In order to keep the masses as low as possible, a careful design of the piston and good piston cooling are necessary. Important dimensions and typical values are shown in **Figure 2.2** and **Table 2.1**.

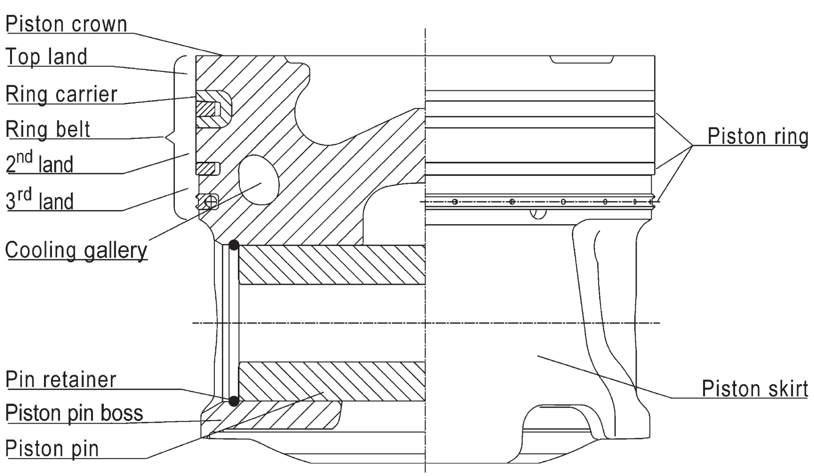

Figure 2.1: Important piston terminology

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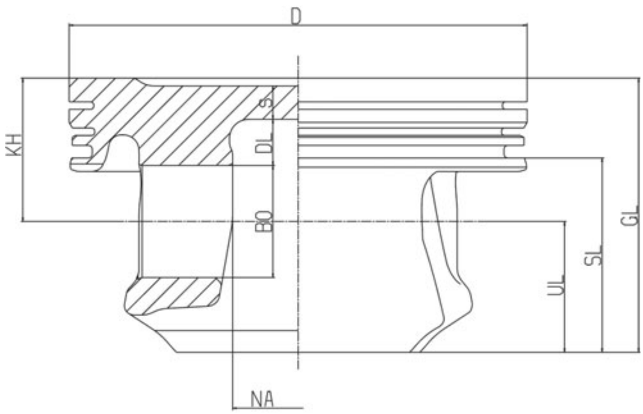


Figure 2.2:
Important piston dimensions
BO: Pin bore Ø (piston pin Ø)
KH: Compression height
NA: Pin boss spacing
D: Piston Ø
s: Crown thickness
DL: Elongation length
SL: Skirt length
GL: Total height
UL: Lower height

Table 2.1: Major dimensions of light-alloy pistons

	Gasoline engines		Diesel engines*
	Two-stroke	Four-stroke (passenger cars)	Four-stroke (passenger cars)
Diameter D [mm]	30–70	65–105	65–95
Total height GL/D	0.8–1.0	0.6–0.7	0.8–0.95
Compression height KH/D	0.4–0.55	0.30–0.45	0.5–0.6
Pin diameter BO/D	0.20–0.25	0.20–0.26	0.3–0.4
Top land height [mm]	2.5–3.5	2–8	6–12
1st ring land height St/D*	0.045–0.06	0.040–0.055	0.055–0.1
Groove height for 1st piston ring [mm]	1.2 and 1.5	1.0–1.75	1.75–3.5
Skirt length SL/D	0.55–0.7	0.4–0.5	0.5–0.65
Pin boss spacing NA/D	0.25–0.35	0.20–0.35	0.25–0.35
Crown thickness s/D or s/DMu, max**	0.055–0.07	0.06–0.10	0.14–0.23

* Values for diesel engines apply to ring carrier pistons, ** Diesel

2.1.1 Crown shapes and crown thickness

The piston crown forms part of the combustion chamber. Pistons for gasoline engines can be flat, raised, or sunken. For diesel engine pistons, the combustion chamber bowl is usually located in the piston crown. The geometry of the piston crown is also affected by the number and location of the valves; **Figure 2.3**. The maximum gas pressure and the quantity of heat to be dissipated determine the thickness of the piston crown (crown thickness). The piston crown, or the bowl rim for diesel engine pistons, is the part of the piston that is exposed to the greatest thermal stress.

The values listed in **Table 2.1** for the crown thickness s apply in general to pistons with flat, convex, or concave crowns.

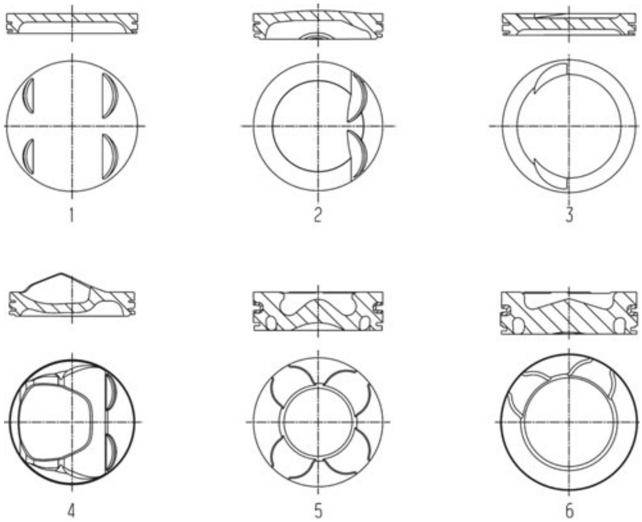


Figure 2.3: Examples of piston crown shapes of various pistons for gasoline and diesel engines (1 to 3 for four-stroke gasoline engines with port fuel injection, 4 for four-stroke gasoline engines with direct injection, 5 to 6 for four-stroke diesel engines with direct injection)

2.1.2 Compression height

The compression height is the distance between the center of the piston pin and the upper edge of the top land. The goal is to have as low a compression height as possible, in order to keep the piston mass and the height of the engine as low as possible. The number and height of piston rings, the required ring lands, the piston pin diameter, and the top land width, however, result in a minimum compression height; a lower height is not possible. For diesel engine pistons, in addition to the combustion chamber depth, the conrod bore radius and the required minimum crown thickness below the bowl generally determine the compression height.

Reducing the compression height also has disadvantages. For high power output and gas pressures, higher temperatures in the pin bore and higher stresses on the piston crown are the result of the low compression height. Cracks in the pin bore or the piston crown may then occur. Accordingly, for diesel engine pistons, a large expansion length is advantageous for the load carrying capacity of the bowl rim.

2.1.3 Top land

In the piston ring zone, the distance between the edge of the piston crown and the upper flank of the top ring groove is called the top land. Its dimensions are a compromise between the following requirements: low piston mass and minimal dead volume for reducing fuel consumption and exhaust gas emissions, on one side; on the other side, the first piston ring, which is a compression ring, requires a temperature range that is still compatible with its function. This, in turn, depends greatly on the combustion process, the material, and the geometry of the first piston ring and its piston ring groove, as well as the location of the water jacket on the cylinder.

For gasoline engines, the top land width is 4 to 10% of the piston diameter, tending to decrease in order to further reduce the hydrocarbon emissions caused by gaps.

For passenger car diesel engines with direct injection, this value is 8–15% of the piston diameter.

For commercial vehicle diesel engines with direct injection, it is 8 to 13% of the piston diameter for aluminum pistons, and 6 to 10% for steel pistons.

2.1.4 Ring grooves and ring lands

The piston ring zone, in general, consists of three ring grooves that hold the piston rings. The piston rings seal off the combustion chamber and control lubricating oil consumption. Their surface must therefore be of the highest quality. Poor sealing leads to blow-by of combustion gases into the crankcase, to heating due to the contact of the hot gas flow on the surfaces, and to destruction of the critical oil film on the running surfaces of the sliding and sealing partners. The piston ring must not impact the groove root diameter of the piston when it is pressed into the groove so that it is flush with the outer diameter of the piston, that is, it requires radial clearance.

Current lubricating oils permit groove temperatures of over 200°C in gasoline engine pistons, and up to 280°C in diesel engine pistons, without the piston rings binding as a result of residue buildup in the top ring groove.

For diesel engine pistons, which develop significantly greater combustion pressures than gasoline engines, the top ring groove is made much more wear-resistant by casting in a ring carrier. Ring carriers are typically made of Ni-resist, an austenitic cast iron with a thermal expansion coefficient that is approximately the same as aluminum. The ring carrier forms a permanent metallic bond with the piston through the established process of Al-fin composite casting. This process also enables better heat transfer.

The ring land is the part of the ring belt of a piston that is located between two piston ring grooves. In particular, the first ring land, which is severely loaded by the gas pressure, must be sized sufficiently to prevent fracture of the ring land. Its height depends on the maximum gas pressure of the engine and the land temperature. For gasoline engine pistons, the ring land width is 4 to 6% of the piston diameter, for turbocharged passenger car diesel engines it is 5.5 to 10%, and for commercial vehicle pistons about 10%. The second or remaining ring lands can be smaller, on account of the lower pressures they are subjected to.

2.1.5 Total height

The total height GL of the piston, relative to the piston diameter, depends on the compression height and the guide length on the skirt. For small, high-speed engines in particular, the total height is kept as low as possible in order to obtain low piston mass.

2.1.6 Pin bore

2.1.6.1 Surface roughness

The pin bore/piston pin sliding system must be in perfect condition in order to ensure reliable engine operation. If the surface roughness is too low, particularly when starting, this can cause galling of the pin bore. Therefore, depending on the pin bore diameter, a surface roughness of R_a = 0.63–1.0 µm is desired for the pin bore. Pistons with piston pins that move only in the piston (shrink-fit connecting rods) generally have slightly greater surface roughness values, in order to increase oil retention, particularly under less than ideal running conditions.

Other detailed measures are often necessary in order to ensure lubrication under all operating conditions. These include oil pockets (slots) or circumferential oil grooves for improved lubrication in the pin bore.

2.1.6.2 Installation clearance

The clearance of the piston pin in the piston pin boss is important for smooth running and low wear of the bearing surfaces. As the materials of the piston and piston pin have different thermal expansion, the running clearances in a warm engine are greater than the installation clearances in a cold engine. This difference can be approximated as:

$$\text{increase in clearance} = 0.001 \times \text{pin diameter [mm]}$$

The increase in clearance for a 30 mm diameter piston pin is therefore approximately 30 µm.

Previously, very tight clearances were typical, so that the piston pin could be inserted only in a preheated piston. Today, the clearance is considerably greater, and the piston pin is inserted into the pin bore at room temperature. This prevents deformation of the skirt due to shrinkage stresses and potential galling of the piston pin in the piston when starting at low temperatures.

When designing the minimum clearance, **Table 2.2**, in gasoline engines, differentiation must be made between a floating piston pin or a piston pin with a shrink fit in the small end bore.

Table 2.2: Minimum pin clearance for gasoline engines [mm]–not suitable for motorsport engines

Piston pin with floating design	Shrink fit piston pin
0.002–0.005	0.006–0.012

The floating piston pin is the standard design and is the variant that can be specifically most highly loaded in the piston pin boss.

With shrink-fit connecting rods, the piston pin is seated in the small end bore with some interference. This makes the automatic assembly of the piston, piston pin, and connecting rod easier, because no special piston pin circlip is needed. The shrink-fit connecting rod design is not suitable for modern diesel engines and gasoline engines with turbocharging.

2.1.6.3 Tolerances

Similar considerations apply to matching the piston pin and piston as for the piston and cylinder. In order to facilitate assembly–aided by lower production tolerances for the pin bore and piston pin–only one defining group is typically used. The tolerance for piston pins is 4 to 8 μm, depending on the pin diameter. The pin bore tolerance is about 1 μm greater in each case.

2.1.6.4 Piston pin offset

The kinematics of the crank mechanism of a reciprocating piston engine leads to multiple contact alteration of the piston on the cylinder wall during a working cycle. After the top dead center point, the gas pressure presses one side of the piston skirt against the cylinder wall. This zone is known as the thrust side, and the opposite side of the skirt is the antithrust side.

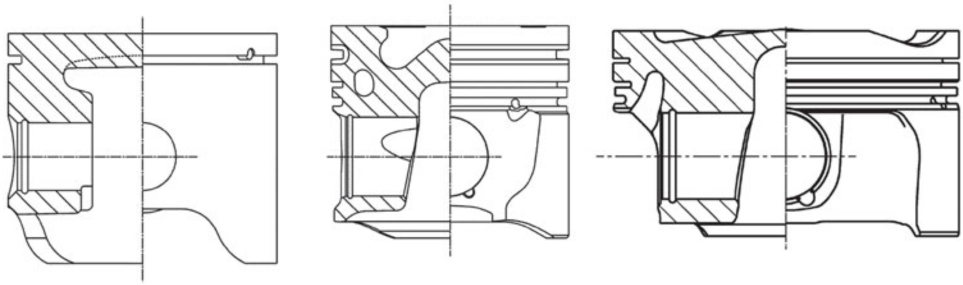
An offset of the piston pin axis relative to the piston axis (piston pin offset) causes a change in the contact behavior of the piston as the side changes, and decisively affects the lateral forces and impacts. By calculating the piston motion, the location and amount of offset from the piston axis can be optimized, thus drastically reducing piston running noise and the risk of cavitation on the cylinder liner.

2.1.7 Piston skirt

The piston skirt, as the lower part of the piston, guides the piston in the cylinder. It can fulfill this task only if it has suitable clearance to the cylinder. Sufficient skirt length and tight guidance keep the tipping of the piston low during contact alteration from one cylinder wall to the other.

For diesel engine pistons, the full-skirt piston was previously dominant, with its closed skirt, interrupted only in the area of the pin bore. This construction is still sometimes used for pistons in two-stroke gasoline engines. Aluminum diesel engine pistons for commercial vehicle engines still feature a full-skirt design at times, with only a slight setback in the area of the piston pin boss, but window-type pistons are used across the board in passenger cars.

Gasoline engine pistons have a wide range of designs for the piston skirt; **Figure 2.4**. In order to keep inertia forces low, they now have only relatively narrow skirt surfaces, which led to the box-type piston, sometimes with different running surface widths (asymmetrical duct pistons) and/or inclined box walls (including EVOTEC® pistons).



Full-skirt piston for two-stroke gasoline engine | Window-type piston for passenger car diesel engine | Box-type piston for passenger car gasoline engine

Figure 2.4: Skirt profiles

The piston skirt must meet a few requirements related to its strength. First, it must bear the lateral forces without major deformations, and second, it should elastically adapt to the deformations of the cylinder. The piston crown deflects under the temperature and peak cylinder pressure, and deforms the piston skirt to an oval in the thrust and antithrust direction. This increases the diameter in the direction of the piston pin, and reduces it along the thrust-antithrust axis. Residual skirt collapse due to plastic deformation, however, should be avoided. Remedial measures for at-risk pistons include greater wall thickness, oval interior piston profile, or small circumferential length of the piston skirt.

The lower end of the piston skirt should protrude out of the cylinder only a little or not at all (lower edge of pin bore). The protrusion must be considered appropriately when designing the piston profile.

2.2 Piston profile

2.2.1 Piston clearance

The piston is deformed under the effect of gas temperatures and forces, particularly the gas force. This change in shape must be taken into consideration when designing the shape of the piston in order to ensure that it runs without binding at the operating temperature. To this end, the piston is installed with some clearance in the cold state, which takes the expected deformation and the secondary piston motion into consideration. Its shape, known as the piston profile (or fine piston contour), also deviates from an ideal circular cylinder.

Local clearance in the cold state is made up of the difference of the cylinder diameter and the piston, imagined as a circular cylinder (the installation clearance), as well as the deviation of the piston from this circular cylinder shape. The piston profile deviates from the ideal circular cylinder in the axial direction (conicity, barrel shape) and in the circumferential direction (ovality).

2.2.2 Ovality

Pistons typically have a slightly smaller diameter in the piston pin axis than in the thrust-antithrust axis. The difference is the (diametric) ovality; **Figure 2.5**.

The oval shape of the crown and skirt provides many design opportunities. The skirt ovality creates space for thermal expansion in the piston pin axis direction. The ovality can be varied to generate an even wear pattern with sufficient width. It is typically (diametric) 0.3 to 0.8% of the piston diameter.

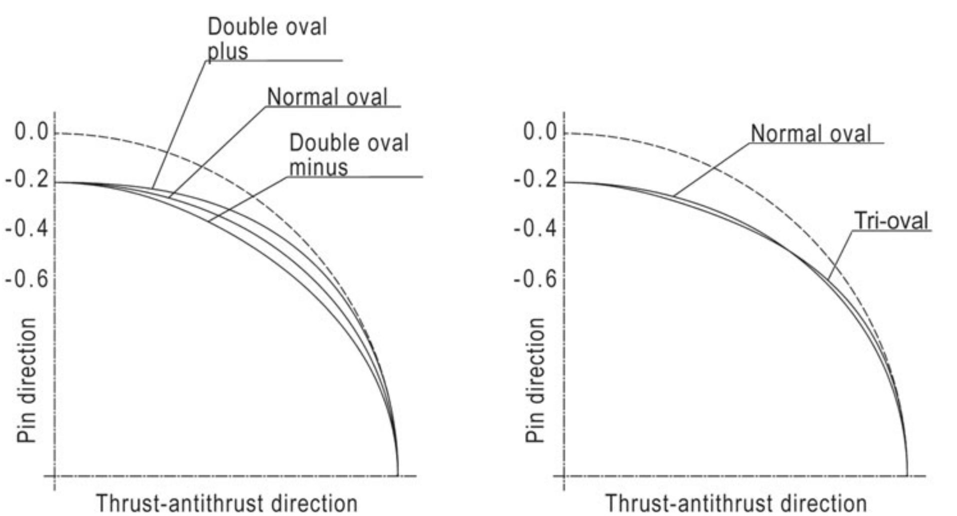


Figure 2.5: Ovality and superposition, double oval (left), tri-oval (right)

In addition to the normal ovality, ovalities with superposition are also possible, such as double or tri-ovality. For double ovality, in the form of a positive (double oval plus) or negative (double oval minus) superposition, the local piston diameter is greater or less than for normal ovality; **Figure 2.5, left**. The positive superposition widens the wear pattern relative to normal ovality, and the negative makes it narrower. Tri-ovality in the form of positive superposition widens the wear pattern, which is limited because of a significantly reduced local piston diameter starting at about 35° from the thrust-antithrust axis; **Figure 2.5, right**.

The resulting running surfaces in the thrust and antithrust direction should not be too narrow, so that the specific pressures between piston and cylinder remain low. In order to prevent hard contact and the risk of galling, the support area should not, however, extend out to the box walls. **Figure 1.7** in Chapter 1.2.4 shows the support area of an advantageous piston profile.

Further opportunities for optimizing the piston profile are provided by different ovalities in the thrust and antithrust direction, as well as ring belt offsets and so-called corrections.

2.2.3 Skirt and ring belt tapering

The piston is tapered slightly at the upper and lower skirt ends, in order to promote the formation of the wedge of lubricating oil that acts as a support element.

The greater taper in the area of the ring belt compensates for the great thermal expansion due to high temperatures in this area and for the deformation due to gas force. It also prevents the piston ring belt from impacting the cylinder owing to secondary piston motion.

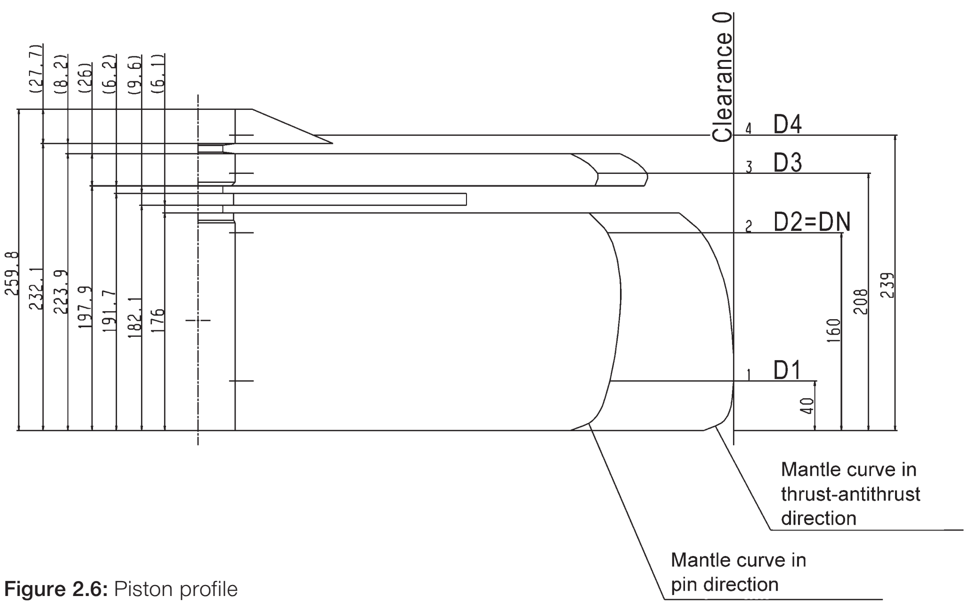


Figure 2.6: Piston profile

For noise-sensitive gasoline engines, in particular, there should be no contact between the ring belt and the cylinder.

All of these aspects require optimized machining forms of the outer surface for the various piston types. The final piston profile can only be verified through extensive simulation and engine testing. **Figure 2.6** shows a detail from a piston profile drawing.

2.2.4 Dimensional and form tolerances

The piston diameter is typically determined absolutely at one of at least three measuring planes. This reference measuring plane is designated as DN. It is preferably located at the point with the tightest clearance between the piston and cylinder (DN = D1) or in an area with a stable shape (DN = D2). The dimensional tolerance (diametric) is 8 to 18 µm, depending on the piston diameter.

The outer contour of the piston is manufactured by NC-controlled precision turning. A funnel-shaped tolerance band results from the elasticity of the piston, as shown schematically in **Figure 2.7**. Deviations from the nominal form are called form tolerances. The form tolerances of the diameters D1, D2, D3, and D4 for passenger car and commercial vehicle pistons are

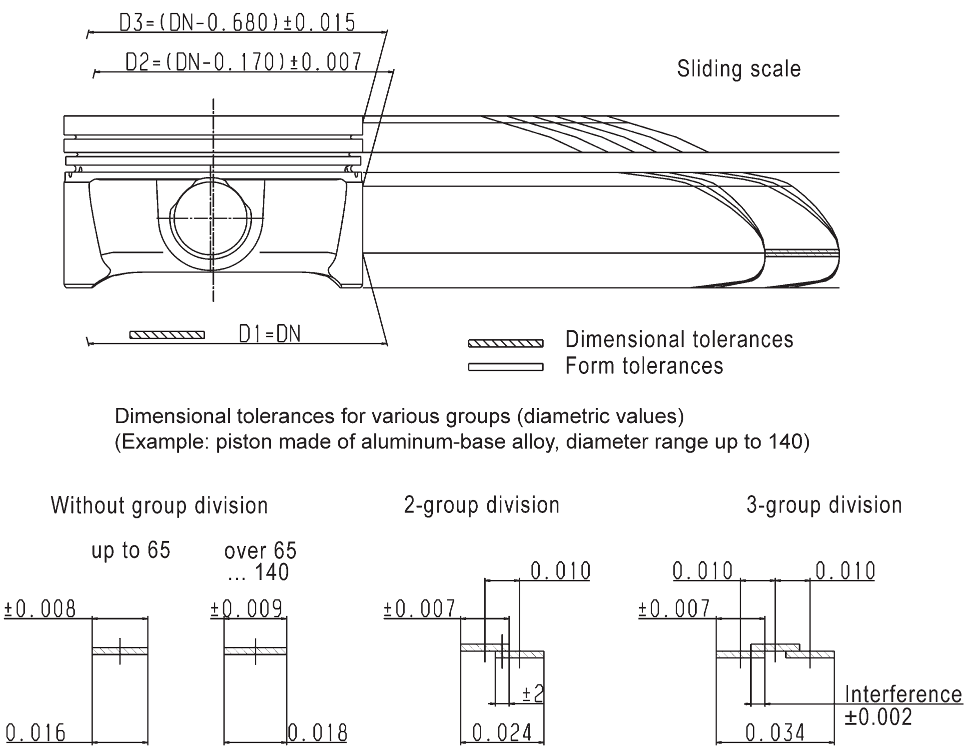


Figure 2.7: Piston profile, dimensional and form tolerances

about 7 µm in the skirt area (diametric) relative to DN, and 10 to 15 µm in the ring belt area (diametric). The principle of the sliding scale applies. The tolerance band for the form tolerances shifts according to the actual diameter in the classification plane.

2.2.5 Installation clearance

The installation clearance is the difference between the cylinder diameter and the largest piston diameter D1. For low friction power loss, the installation clearance must not be too small. However, it also must not be too large, so that consistently smooth running is achieved under all operating conditions. Because of the difference in thermal expansion, these goals are most difficult to achieve for the combination of an aluminum piston and gray cast iron cylinder. Previously, cast-in steel struts were often used to reduce thermal expansion. Table 2.3 gives an overview of the (diametric) clearances at the skirt for various piston types.

The installation clearance decreases with increasing operating temperature, which is caused by the greater heating of the piston relative to the cylinder, and possibly the different thermal expansion of the piston and cylinder materials. At operating temperature, the piston runs in the cylinder with interference. Because of the ovality, the interference is limited to the elastically adaptable area of the skirt.

Table 2.3: Typical installation clearances for light-alloy pistons [‰ of nominal diameter]

	Gasoline engines			Diesel engines
	Two-stroke	Four-stroke (passenger cars)		Four-stroke (passenger cars)
Engine block material	Aluminum-base alloy	Aluminum-base alloy	Gray cast iron	Gray cast iron
installation clearance	0.6–1.3	0.2–0.6	0.4–0.8	0.6–0.9
Clearance at upper skirt end	1.4–4.0*	1.2–1.8	1.7–2.4	1.9–2.4

* Only for single-ring designs and high-performance engines (skirt end close to top land)

2.2.6 Defining group

One defining group for the piston and cylinder makes logistics easier in large-scale production. If the highest priority is the economic efficiency of production, then slightly wider bands must be used for the dimensional tolerances than for division into several groups, e.g., (diametric) 18 µm compared to (diametric) 14 µm for a two-group division; **Figure 2.7**.

When pistons up to 140 mm in diameter are divided into several classes, overlap zones of 2 µm are required at the group boundaries. The pistons in the overlap zones can be assigned to the larger or smaller defining group, as desired. This ensures that the desired quantity can be supplied for each defining group.

2.2.7 Skirt surface

Besides the skirt profile, the surface of the skirt running surface also has a great influence on the sliding behavior of the piston. Too little surface roughness means the piston will not run in properly, while too much increases the friction power losses. Skirt roughness profiles with roughness values of R_a = 1.5–5 µm (R_z = 6–20 µm), generated precisely by diamond turning, provide good results (cf.: Chapter 1.2.4).

Thin metal layers of tin (0.8 to 1.3 µm) or synthetic resin graphite coatings (10 to 40 µm) further improve the boundary lubrication properties, particularly in the critical run-in process or when starting the engine under less than ideal conditions, such as during cold start.