3.0 PISTON RING

The piston ring is essentially a seal with a spring-like property. Similar rings are also used in other piston and cylinder mechanisms, such as compressors or hydraulic devices. The piston ring of an internal combustion engine must be designed with sufficient heat resistance to withstand exposure to high temperature gas. The single-piece metallic piston ring with self tension, which is generally used in internal combustion engines, was first invented by J. Ramsbottom in 1854. Figure 3.1(a) shows typical rings used in a four-stroke engine. A piston generally uses three or more rings. Figure 3.2 shows a schematic representation of a piston, illustrating the relative positioning of the piston rings and the cylinder wall.

Figure 3.3 gives a summary of the various functions required of a piston ring. A running clearance of about 20–30 μm exists between the cylinder and piston. The piston rings seal in the combustion gas. The combustion gas exerts pressure on the rings through the gap between the piston and cylinder bore (Fig. 3.2). The rings also control the thickness of the oil film on the cylinder wall, providing hydrodynamic lubrication which sustains a high thrust load. In addition, the rings also play an important role in cooling the piston head. The combustion heat received by the piston head flows into the cylinder wall through the piston rings. About 70% of the heat received by the piston head is transmitted through the rings. A high rotational velocity is necessary to generate high power output, requiring light piston rings with low friction and high wear resistance. Cast iron rings were often used in the past. However, more demanding requirements have increased the use of steel piston rings coated with various surface treatments.

Generally, four-stroke petrol engines use three rings per cylinder, whilst two-stroke engines use only two. Figure 3.1(a) shows the three rings of a four-stroke petrol engine, these being the top or compression ring (left), second ring (middle) and oil control ring (right). The oil control ring consists of three individual pieces, two side rails and a spacer (the corrugated sheet, Fig. 3.1(c)). Figure 3.4 shows the two rings in a two-stroke petrol engine. The second ring is shown with the expander (located inside). The expander supports the second ring (described later in Fig. 3.9), adding tension without a significant increase in total weight. To obtain the same tension with a one piece ring, the thickness needs to be increased, which in turn makes the ring much heavier.

Some diesel engines use more than three rings. In order to obtain high revolutions and quick response by reducing the weight of moving parts, fewer rings are preferred. However, for more powerful engines with high cylinder pressures, such as diesels, a greater number of rings are required to obtain sufficient durability in sealing.

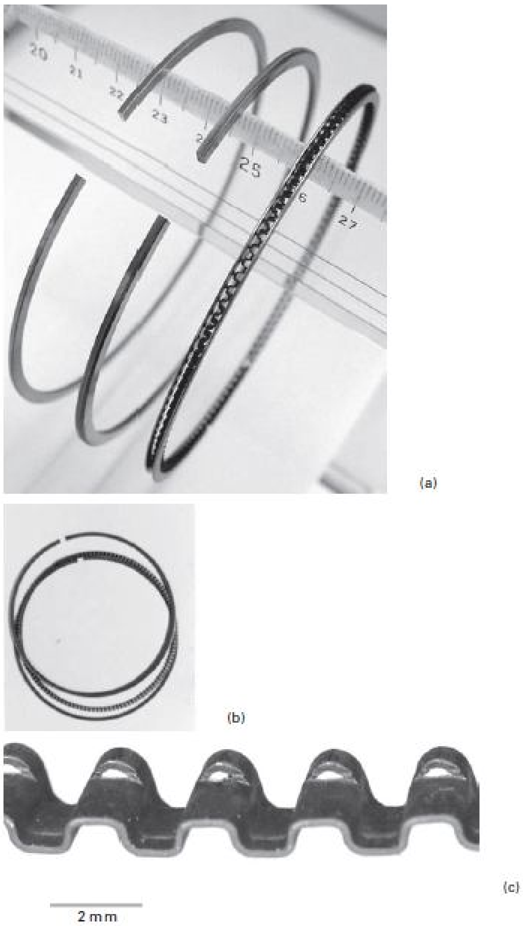

Figure 3.1: (a) Piston rings for a four-stroke engine. Top and second rings (two rings on the left) and assembled three-piece oil control ring (on the right). (b) Disassembled three-piece oil ring (c) Magnified view of the spacer.

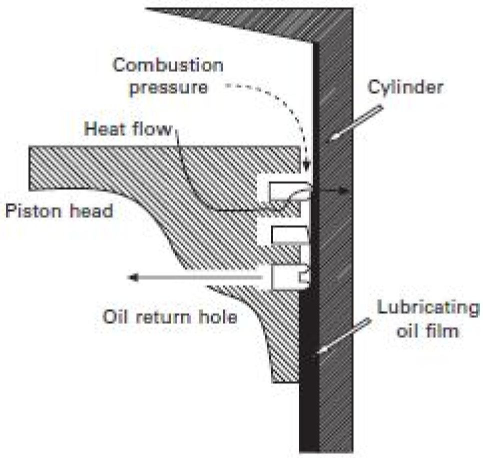

Figure 3.2: Phenomena taking place around piston rings

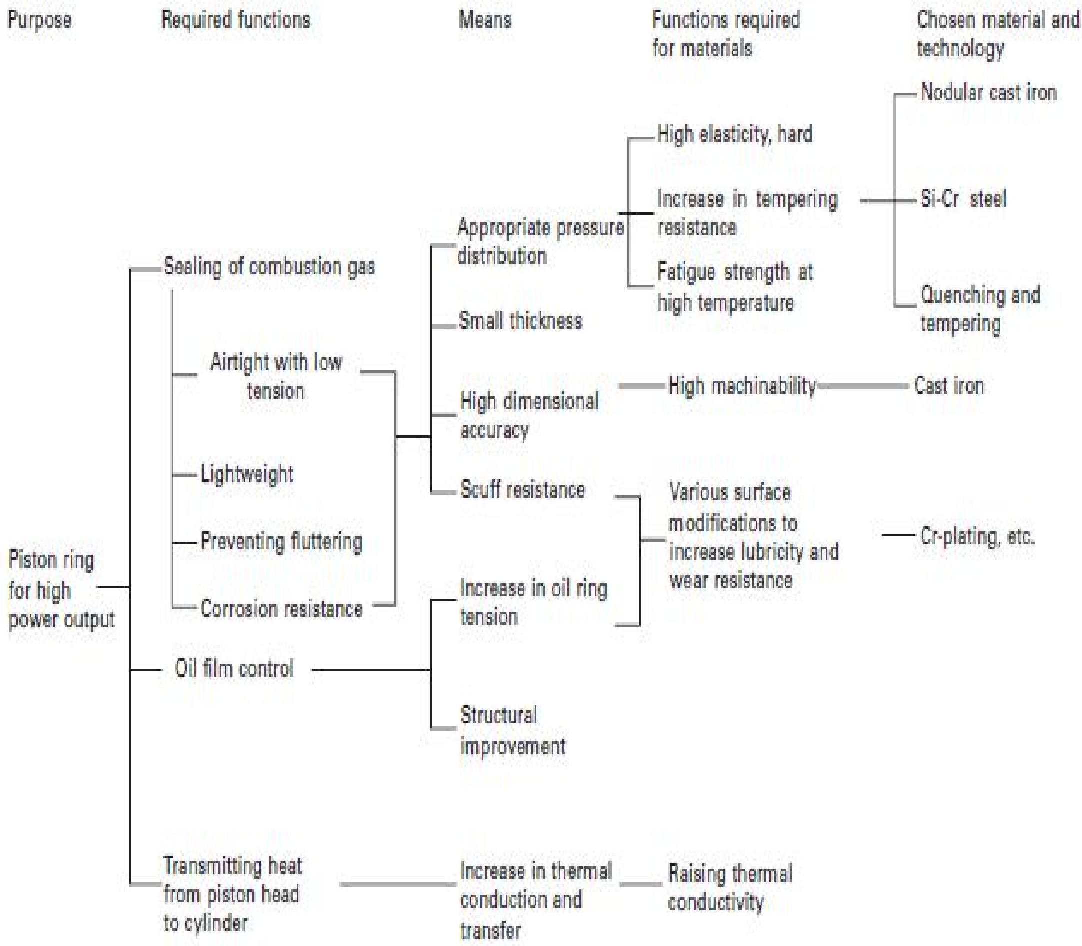

Figure 3.3: Functions of piston rings, particularly illustrated to generate high power output.

Figure 3.4: Piston rings for a two-stroke engine. The expander put at the center takes free state. When set into the piston ring groove, it spreads and gives additional force from the back of the second ring.

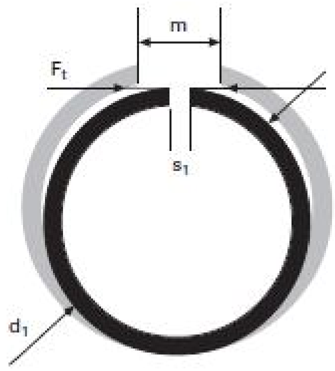

Figure 3.5: Nomenclature of a piston ring at open and close states. The gap contracts from m (free gap size) to s_1 (closed gap, end clearance) when installed in the cylinder bore. The spacing between two facing planes forms a gap. This small portion including the gap is called 'butt ends'.

3.1 Suitable Shapes to obtain High Power Output

Figure 3.5 illustrates a piston ring both before and after it expands into the ring groove. Figure 3.6 shows a ring installed in the ring groove. The piston with rings is inserted into the cylinder bore. The ring then expands from its initial diameter (d_1) and is forced tightly against the cylinder bore wall (Fig.3.5). The ring width is called h_1 and the radial wall thickness a_1 (Fig. 3.6).

The distance m is defined as the gap when the ring is uncompressed. The gap s_1, also referred to as the closed gap or end clearance, is the minimum gap obtained when the ring is installed in the cylinder bore. The **load** necessary to close the gap from m to s_1 is called the **tangential closing force (F_t)**. The force increases by increasing the gap distance m. In the top ring of Fig. 3.1 these values are typically d_1 = 80, m = 10, a_1 = 3 and h_1 = 0.8 mm, the ring being very thin to minimize weight. It is the self-tension of the ring itself that presses the ring into the cylinder bore wall. During operation, the ring glides up and down, touching the bore wall. This puts stress on the ring. If the cylinder bore is not completely round and straight, the ring gap repeatedly opens and closes. The resulting stresses are likely to break the ring. A lack of lubrication also causes material failure.

The surface roughness of the ring groove and degree of groove and side clearances, are very important in controlling lubrication. Figures 3.7 and 3.8 show the cross-sectional diagrams of three rings in a four-stroke engine and two rings in a two-stroke engine, respectively. In four-stroke engines, the top (compression) ring is used mainly for sealing combustion gas. The second ring assists the top ring. The oil control ring is specifically used in four-stroke engines to scrape off lubrication oil from the bore wall. The second ring with a tapered cross-section also scrapes off the oil. The tapered face provides contact at the bottom edge to scrape oil during the downward stroke.

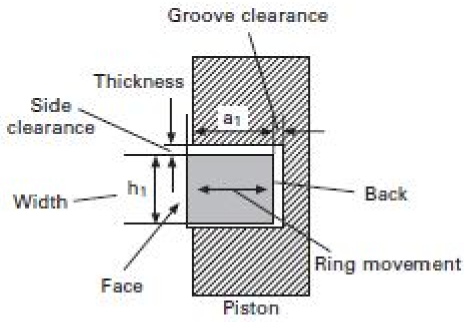

Figure 3.6: Cross cut view of a piston ring installed in the groove. The ring contacts the bore wall at the ring face. The inside surface against the ring surface is called ring back. The thickness is called a_1 and the width h_1.

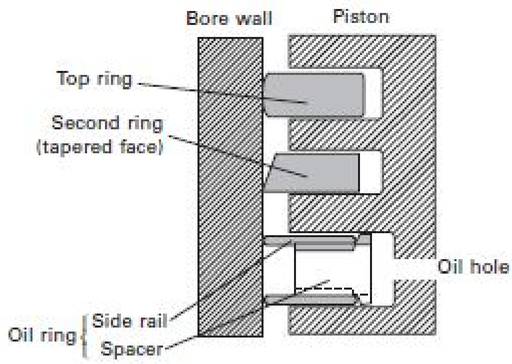

Figure 3.7: Three rings installed in piston-ring grooves for a four-stroke engine. The top ring has a barrel face shape. The oil control ring includes a sandwiched spacer between two side-rail sheets.

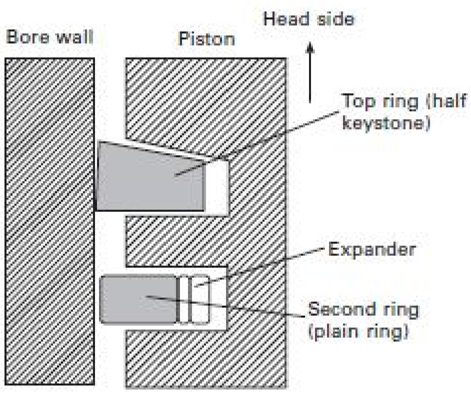

Figure 3.8: Two rings for a two-stroke engine. The top ring has a half keystone shape.

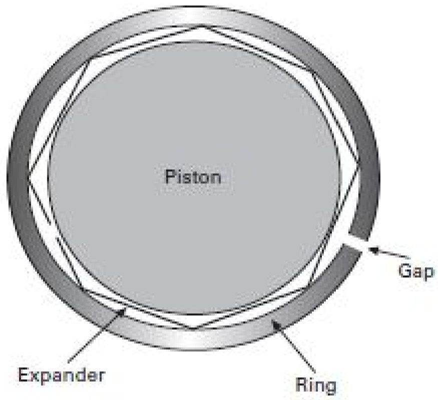

Figure 3.9: Expander installed at the back of the second ring of a two-stroke engine. Cross cut view at the second ring groove.

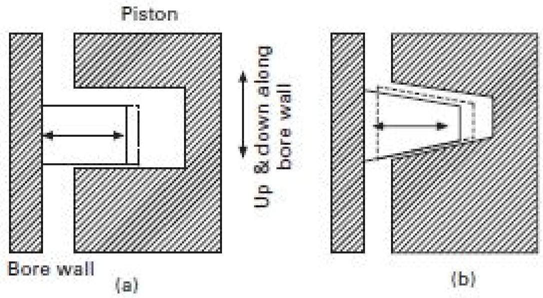

Figure 3.10: Section shapes of rings (a) rectangle and (b) keystone.

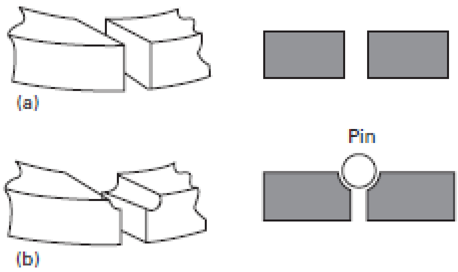

Figure 3.11: Gap shapes (a) straight gap (b) side notch gap. The piston ring should not rotate in the two-stroke petrol engine because the ports of the cylinder bore wall catch the gap (butt ends). Hence, a thin steel pin (locking pin) struck in the piston-ring groove, hooks the gap to stop the rotation.

In two-stroke engines, two rings are generally used without an oil control ring. (Fig.3.8). The expander frequently supports the second ring (Fig. 3.9). The tension created by the rings restricts the swing motion of the piston to suppress any abnormal stroke sound. Since increasing the a_1 size of a one piece ring can make it much heavier, this two-piece construction raises the tension with less increase in total weight.

The ring motion follows the uneven shape of the cylinder bore wall. Both the distorted cylinder and the swing motion of the piston make the ring gap open and close repeatedly. During this motion, the degree of side clearance does not change for the rectangular type of ring (Fig. 3.10(a)), but it does for the keystone (wedge form) type of ring. Figure 3.10(b) illustrates the motion of a keystone ring. The keystone ring has the added benefit that it can eliminate accumulated dust such as soot in the ring groove. This cleaning prevents gumming up or sticking of the ring in the groove, which in turn decreases ring groove wear. Diesel and two-stroke petrol engines frequently use this type of ring. Half keystone rings (the top ring in Fig. 3.8) are also used in two-stroke engines. The keystone form is, however, more costly to produce.

A top ring with a barrel-shaped face (the top ring in Fig. 3.7) is frequently used. In maximizing lubrication, the shape prevents abnormal wear during the running-in stage and decreases blow-by. Ring fluttering can sometimes take place during increased revolution speeds and this increases blow-by. This is due to ‘floating’ of the ring. Floating occurs when an inertial force lifts the ring in the piston ring groove, which in turn spoils the airtight seal between the lower face of the ring and the ring groove. This can be dealt with, by decreasing the ring weight by minimizing h_1. It is not feasible to decrease a_1 because it decreases contact pressure at the gap. Prevention of radial vibration can be achieved by either increasing a_1 or by using the pear type design which increases contact pressure.

Figure 3.11 illustrates typical Designs of Ring Gap. Figure 3.11(a) is straight gap, which is the most standard shape in four-stroke engines. The sealing of the gap is very important. However, a minimum gap of about 0.3 mm is required to accommodate thermal expansion. While the engine is operating, this gap produces a very slight gas pressure leakage that could lead to ring flutter. Balancing the s_1 values of the top and second rings (gap balancing) can achieve a balance of pressures, so that the pressure between the top and second rings is never sufficient to lift the top ring from its seat on the bottom flank of the piston groove at the highest cylinder pressure. This gap balancing is required to minimize top ring flutter and its negative effects on cylinder gas sealing. Figure 3.11(b) shows a side notch gap with a locking pin hooking the semicircle edges together. This is used generally in two-stroke engines. There are other types such as a stepped gap design. These are effective, but very rare because the intricate machining is costly.

3.2 Ring Materials

3.2.1 Flaky graphite cast iron

Table 3.1 lists the various materials used in pistons. Two-stroke air-cooled engines use nodular graphite cast iron (JIS-FCD) for both top and second rings. Water-cooled engines use Si-Cr spring steel (JIS-SWOSC) for the top ring. Four-stroke engines use FCD or flaky graphite cast iron (JIS-FC) for second rings. The top ring and the side rail part of the three-piece oil control ring use SWOSC. The spacer of the oil control ring, the undulate sheet sandwiched between the side rail parts (Fig. 3.1(c)), requires a far more intricate shape, so it uses stainless steel JIS-SUS304 because of its good formability. The percentage of steel rings is increasing year by year. However, up until 1970, most engines used cast iron rings.

Piston rings are directly exposed to the very high temperatures of combustion gas, but they also receive heat from the piston head. The highest temperature appears in the top ring where temperatures reach about 250 ˚C. The material must maintain its elastic property at high temperatures for a long period of time. Cast iron is excellent in this regard. A pearlite or tempered martensite microstructure is generally used. The carbon crystallizes to generate flaky graphite during solidification of cast iron.

Table 3.1: Composition (%) and applications of ring materials

Ring material	JIS	C	Si	Mn	P	S	Cr	Applications
Flaky graphite cast iron	FC	4	3	0.6	<0.2	<0.02	<0.4	4- and 2-stroke second rings
Nodular cast iron	FCD	4	3	0.6	<0.2	<0.2	–	4- stroke second ring. 2-stroke top and second rings.
Spring steel	SWOSC	0.5	1.4	0.7	<0.03	<0.03	0.7	4- and 2-stroke top and oil rings
Stainless steel	SUS304	<0.08	<1.0	<2.0	<0.04	<0.03	18(8Ni)	Oil ring spacer

Cast iron has the following qualities that make it highly suitable for piston rings.

1. ***Heat resistance*:** Cast iron rings are heat-resistant even when exposed to high temperatures. The hard martensite or pearlite microstructure does not soften at high temperatures. The high quantity of alloying elements (especially a Si content of around 3%) gives excellent resistance against tempering. Only casting can shape such high alloy compositions. Plastic working cannot shape cast iron into rings due to its low deformability.
2. ***Self-lubrication*:** Graphite is self-lubricating, which helps to prevent scuffing. This is due to the layered crystal structure of graphite. Scuffing is a moderate form of adhesive wear characterized by macroscopic scratches or surface deformation aligned with the direction of motion. This is caused when the points on two sliding faces weld themselves together. Scuffing can occur between the cylinder bore wall and the ring or the piston outer surface.

3. ***Machinability*****:** Cast iron has good machinability. The dispersed graphite itself is soft and brittle, which works as a chip breaker during machining. A proper oil film must be produced between the ring face and cylinder bore wall. A residual burr at the ring corner is unfavourable, because it disrupts the oil film and obstructs hydrodynamic lubrication, thus all corners should be chamfered. Cast iron has high machinability compared to steel, which makes deburring much easier.

Sand casting is used to shape the flaky graphite cast iron ring. The distribution and shape of flaky graphite is very sensitive to solidification rate. Typically, a number of rings are cast together like a Christmas tree as illustrated in Fig. 3.12. This casting plan hangs several rings around the down sprue and runner, and ensures that all the rings of one tree will have a homogeneous graphite distribution.

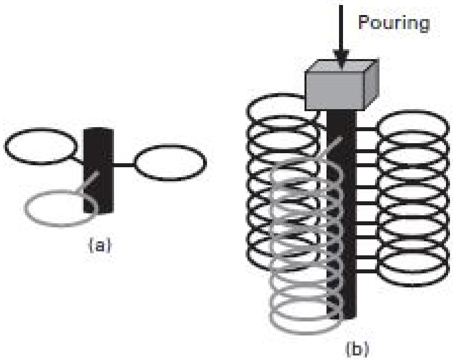

Figure 3.12: casting plan for flaky graphite cast iron rings (a) rings produced by one layer of the mold and (b) rings produced by the stacked mold.

An alternative method is to slice a cast iron tube into rings. It may be cheaper, but this method gives various solidification rates at different portions of the tube, which in turn disperses graphite unevenly. Hence, particularly for flaky graphite cast iron, each ring should be cast separately. High-alloy cast iron is used to give much higher wear resistance. It disperses Cr-carbide through increasing Cr content or hard steadite through an increased phosphorus quantity of around 0.3%.

3.2.2 Use of Spherodized Graphite Cast Iron to Improve Elastic Modulus and Toughness

Decreasing h_1 can make the cast iron ring lighter, but it also raises the stress. Cast iron has excellent properties as a ring material, but is not that tough. The microscopic stress concentration caused by flaky graphite is likely to initiate cracking, and the flaky graphite microstructure is too weak to resist such cracking. To increase the strength, nodular graphite cast iron (JISFCD), which includes spherical graphite, has become more widely used. It is also called **spheroidized graphite iron** or **ductile iron**. This microstructure is resistant to cracking.

Figure 3.13 is a magnified view showing tempered martensite surrounding spherical graphite in the second ring of a two-stroke engine. Figure 3.14 is a photograph of the ring in cross-section. This is a half keystone shape with hard chromium plating on its face. The hardness is around 40 HRC due to the increased concentrations of Cu, Cr and Mo.

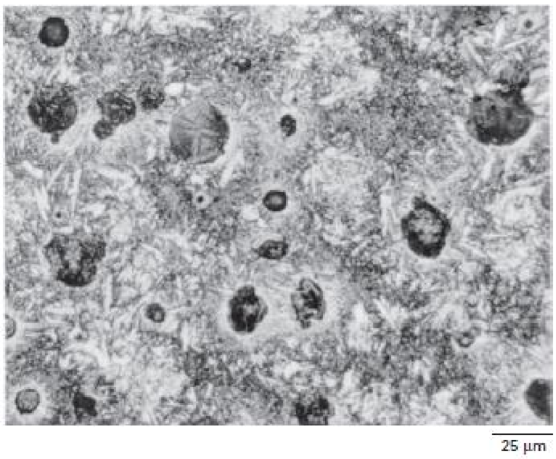

Figure 3.13: Nodular graphite cast iron with martensite matrix.

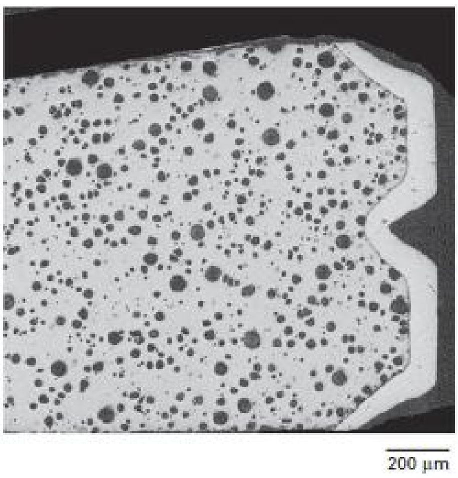

Figure 3.14: The ring section of a two-stroke second ring. The magnified view is shown in Figure 3.13.

3.2.3 Using steel to generate lightweight rings

Up until 1970, all piston rings were made using cast iron. However, the low fatigue strength and toughness of cast iron mean that it is not possible to reduce the weight of the rings by lowering h_1. Steel rings using spring steel have been developed to address this problem. Steel does not have the self lubricating property of cast iron, but it does have excellent elastic properties.

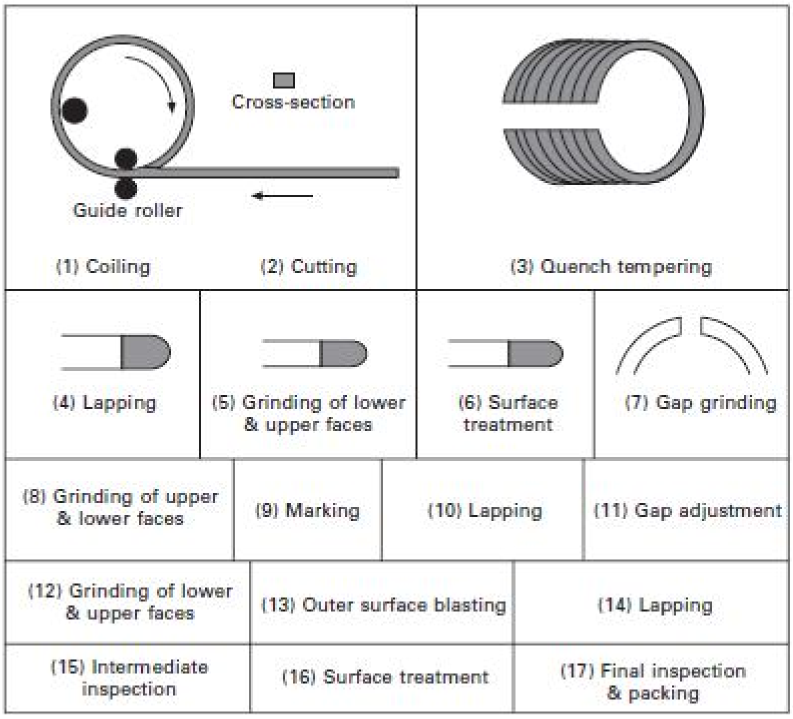

Figure 3.15: Manufacturing process of a steel ring.

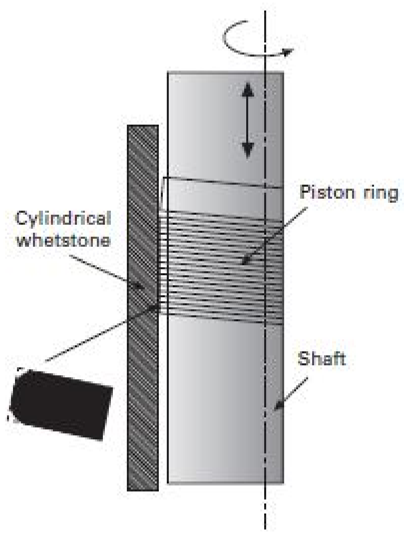

Figure 3.16: Shaping of the barrel face.

Various spring steels have been tried for piston rings. At present, Si-Cr steel, which is also used for valve springs, is widely used because of its high resistance to tempering. The typical chemical composition as shown in Table 3.1. It is generally used with a tempered martensite microstructure. The high Si content maintains the hardness of the martensite in the middle to high temperature range, which in turn maintains ring tension.

Presently, nearly half of all piston rings manufactured use steel, and this is likely to increase further still in the near future. The use of a steel second ring is also becoming more common, despite difficulties in machining the taper face. Figure 3.15 illustrates the manufacturing process of a steel ring.

First, rolling produces a wire with a rectangular section (upper left). This wire is then coiled into an oval shape (1) so that the final shape after installation is round. Quench-tempering (3) generates the required elastic property. The tensile strength after quench-tempering is typically 1.5 GPa, and the elastic modulus 206 GPa. After heat treatment, a lapping machine (illustrated in Fig. 3.16) generates a barrel shape (4) from the rectangular cross-section. A cylindrical whetstone laps the outer surface of the stacked rings. The shaft revolves and moves up and down with the rings.

The top ring for diesel engines is exposed to a much higher temperature and pressure than that of petrol engines. In addition to the Si-Cr steel, the diesel engine frequently uses high-chromium martensitic stainless steel (17% Cr steel containing Mo, V, etc.) with additional nitriding, which shows superior anti-softening properties at high temperatures.

The steel ring with its high elastic modulus is also beneficial in terms of weight reduction, but it is not always the best solution. For example, compared to cast iron, the a_1 of the steel ring should be lowered to adjust the ring tension, but then the contact area between the ring and ring groove decreases, reducing heat transfer. A cast iron ring with a lower elastic modulus is much more favourable in such a case.

3.3 Designing the Self-Tension of Rings

3.3.1 The distribution of contact pressure and tension

Higher contact pressure for the rings is essential at higher-speed revolutions. This is because the hydrodynamic force that occurs in the oil film and tends to lift the ring away from the cylinder wall increases with sliding velocity. The self-tension of the ring forces it against the bore wall, which in turn generates a contact pressure. The combustion gas pressure transmitted through the groove clearance also forces the rings towards the bore wall, helping to increase the contact pressure. However, at high piston speeds, the time required for the formation of an effective gas pressure behind the rings becomes much shorter.

Figure 3.17 shows an example of the radial pressure pattern of piston rings. The black line has a peak contact pressure at the gap. This distribution is unacceptable, because such a localized high pressure is likely to disrupt the oil film. For four-stroke engines, a pear-shaped distribution with a fairly high value at the gap is ideal (shown by the gray line on Fig. 3.17). The most suitable shape for contact pressure distribution is determined by the engine type and material properties.

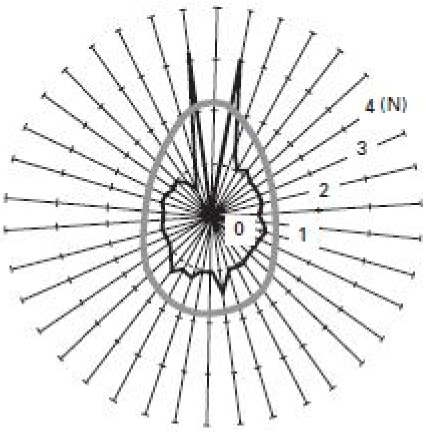

Figure 3.17: Radial pressure pattern of piston rings measured by a pressure sensor, contact pressures indicated by load (N). The gap locates at the top position. The gray line illustrates a favourable shape.

Designing a piston ring begins with calculating the contact pressure distribution. The following factors should also be taken into consideration: preventing blow-by, minimizing oil consumption, and decreasing friction loss and wear. These factors all determine the dimensions of the ring.

The combustion gas forces the top and second rings towards the bore wall, but does not push the oil ring against the bore wall because combustion gas leakage is sealed almost perfectly by the top and second rings. Hence, tension in the oil ring is generally high. Rings with higher contact pressure remain more effective over longer running periods. The stress loss from wear reduces contact pressure, whilst a high initial value of contact pressure tends to result in greater residual stress than the low initial value found in low-tension rings.

Lack of oil causes severe wear of the ring and bore wall, while excess oil generates too much soot. Soot accumulates in the combustion chamber and causes combustion conditions to deteriorate, which can result in a number of problems, including a tendency for the ring to stick to the ring groove. This is partially eliminated by using a keystone ring, but optimum oil control is still necessary. The quantity of oil is adjusted mainly by the oil control ring, although the combined effects of all rings, including the compression ring, should be taken into consideration. Operating conditions also influence oil consumption. The number of revolutions has a significant influence, as does the negative pressure inside the inlet pipe during engine braking. Increased tension in the oil ring rapidly leads to lower oil consumption, but flexibility is also important. Constant oil consumption appears above a certain tension value, and the correct tension value is determined empirically.

More recently, reducing fuel consumption has become important. To accomplish this, friction must be reduced and moving parts must be lighter. It has been said that the friction loss arising from the piston, piston rings and cylinder bore amounts to 40–50%9 of total friction loss in engines. For piston rings, friction on the cylinder bore is reduced by lowering the contact pressure and by using a narrower ring width. But if the contact pressure is reduced, sealability and oil consumption cannot be maintained, and the roundness and straightness of the bore must also be taken into account.

3.3.2 Tensioning

The most common designs of piston rings have a non-circular shape in the free state, so that when they are installed, they will conform tightly to the cylinder wall at every point and the desired contact pressure distribution will be obtained. This favourable shape, characteristic of the ring in its free state, can be produced by several different processes.

In the case of cast iron rings, the shape of the casting gives the desired contact pressure distribution. The flaky graphite iron is shaped into an oval without a gap (Fig. 3.12). In nodular iron rings, the tube cast for slicing is oval in cross-section, and the circular shape is obtained by cutting the gap.

During processing, the gap is subjected to several repeated cycles of opening and closing. This load cycle on the ring removes micro-yielding (an elasticity) to increase elastic properties. Micro-yielding is the phenomenon where small plastic deformation takes place before the macroscopic elastic limit is reached. The repeated load cycle on the ring removes it. This effect is very important and is called accommodation.

In steel rings, the shape generated in the coiling process (Fig. 3.15) determines contact pressure distribution geometrically. It is also possible to grind a non-circular shape out of a circular ring, but this raises the cost quite considerably. An alternative method of generating an oval shape involves first coiling the wire onto a circular form. The coil is then pressed around a core bar with an oval section. Heat treatment causes the coil to deform thermally and conform to the oval shape of the bar. This process is called thermal tensioning and is also applied to cast iron rings.

3.3.3 Surface Modification to Improve Friction and Wear

3.3.3.1 Surface modifications during running-in

Ring wear usually appears at the outer, top and bottom faces. However, the rings are not all subjected to the same conditions. The conditions are most severe for the top ring since it is directly subjected to the high pressure, high temperature and considerable chemical corrosive effects of combustion gas. Furthermore, the top ring also receives the lowest supply of lubricating oil. On the cylinder bore, the upper reversal point of the top ring (top dead center) is likely to suffer the greatest amount of wear. It is important to improve the tribological properties of rings. Table 3.2 summarizes typical surface treatments used on ring materials. The surface treatments can be classified into:

(i) improving initial wear during running-in, and

(ii) improving durability where very long running distances are required (for instance, for commercial vehicles, which are expected to run for several hundred thousand kilometers).

Table 3.2: Ring materials with surface treatments.

Specifications			Base material	Outer surface modification	Side surface modification
Top ring			Nodular cast iron	Cr plating	Phosphate conversion
			Si-Cr steel	Cr plating	Fe_3O_4 coating, Solid lubricant coating
			Martensitic stainless steel	Gas nitriding, Composite plating, Physical vapor deposition	Phosphate conversion Solid lubricant coating
Second ring			Nodular cast iron	Cr plating	Phosphate conversion
			Gray cast iron	Phosphate conversion	Phosphate conversion
Oil control ring	3-piece	Side rail	Carbon steel	Cr plating	Fe_3O_4 coating, Phosphate conversion
			Martensitic stainless steel	Gas nitriding Ion nitriding	Phosphate conversion
		Space expander	Austenitic stainless steel	Salt bath nitriding	
	2-piece	Oil ring surface piece	Carbon steel	Cr plating	Fe_3O_4 coating
			Martensitic stainless steel	Gas nitriding	Phosphate conversion
		Coil expander	Carbon steel	Cr plating	
			Austenitic stainless steel	Salt bath nitriding	

The running-in period is important, but unfortunately, drivers cannot always be relied on to conform to running-in requirements. To counteract this, surface treatments have been developed specifically for the running-in period. Typically, phosphate conversion coating, as listed in the table, is used. This is a chemical conversion treatment that generates a phosphate film, for instance manganese phosphate, through dissolving the iron substrate. The coated layer is porous, soft and insoluble, and retains oil to improve the initial accommodation between the parts. The treatment also removes burrs by dissolving the substrate, and prevents rust.

3.3.3.2 Surface modifications to improve durability

Combustion products generated inside the engine cause abrasive wear, as can the dust contained in the intake air or wear debris from the various parts. Without a hard surface coating, steel rings have poor resistance to scuffing. To improve durability, various materials are used to coat not only steel rings but also cast iron rings. Hard chromium plating is widely used to increase the wear resistance of the ring face.