CHAPTER ONE-INTRODUCTION

1.1 Internal Combustion Engines

The **internal combustion engine** is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber. In an internal combustion engine, the expansion of the high-temperature and high -pressure gases produced by combustion apply direct force to some component of the engine. This force is applied typically to pistons, turbine blades, or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy. The first internal combustion engine was created by Étienne Lenoir

The term internal combustion engine usually refers to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the six-stroke piston engine and the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle as previously described

1.2 Function of Internal Combustion Engine

Functions of I.C. Engine: Engine is that kind of prime mover which converts chemical energy of fuel into mechanical energy. The fuel on burning changes to gas which impinges upon the piston and pushes it to change into reciprocating motion. The reciprocating motion of piston is then converted to rotary motion of crank shaft with the help of slider mechanism involving connecting rod and crank shaft. Several types of

I.C. Engines are used on various automobiles i.e. marine, locomotive, air craft and other industrial applications.

1.3 Component of Internal Combustion Engine

1.3.1 Cylinder Block

Function- In the bore of cylinder the fresh charge of air-fuel mixture is ignited, compressed by piston and expanded to give power to piston.

1.3.2 Cylinder Head

Function-It carries inlet and valve. Fresh charge is admitted through inlet valve and burnt gases are exhausted from exhaust valve. In case of petrol engine, a spark plug and in case of diesel engine, an injector is also mounted on cylinder head.

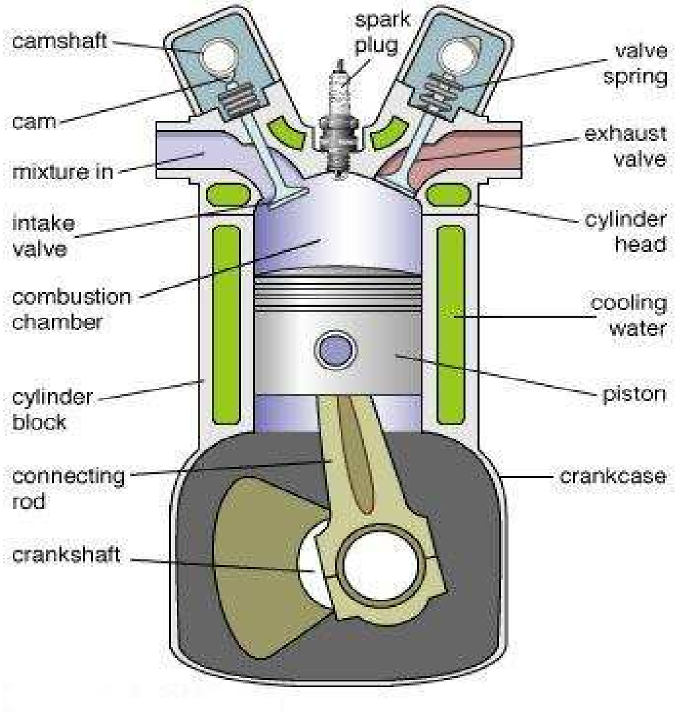

Figure 1.1 Parts of Internal combustion engine [97]

1.3.3 Piston

Function-During suction stroke, it sucks the fresh charge of air-fuel mixture through inlet valve and compresses during the compression stroke inside the cylinder. This way piston receives power from the expanding gases after ignition in cylinder. Also forces the burnt exhaust gases out of the cylinder through exhaust valve.

1.3.4 Piston Rings [60]

Piston Ring Functions and Operation

The functions of a piston ring are to seal off the combustion pressure, to distribute and control the oil, to transfer heat, and to stabilize the piston. The piston is designed for thermal expansion, with a desired gap between the piston surface and liner wall. The rings and the ring grooves form a labyrinth seal, which relatively well isolates the combustion chamber from the crankcase. The position and design of the ring pack is shown in Fig 1.2 The ring face conforms to the liner wall and moves in the groove, sealing off the route down to the crankcase. The sealing ability of the ring depends on a number of factors, like ring and liner conformability, pre-tension of the ring, and gas force distribution on the ring faces. Some of the combustion chamber heat energy is transferred through the piston to the piston boundaries, i.e. the piston skirt and rings, from which heat transfers to the liner wall. Furthermore, the piston rings prevent excess lubrication oil from moving into the combustion chamber by scraping the oil from the liner wall during the down stroke. The piston rings support the piston and thus reduce the slapping motion of the piston, especially during cold starts where the clearance is greater than in running conditions. The rings are generally open at one location, at the ring gap, hence easily assembled onto the piston; see Fig1. 2.

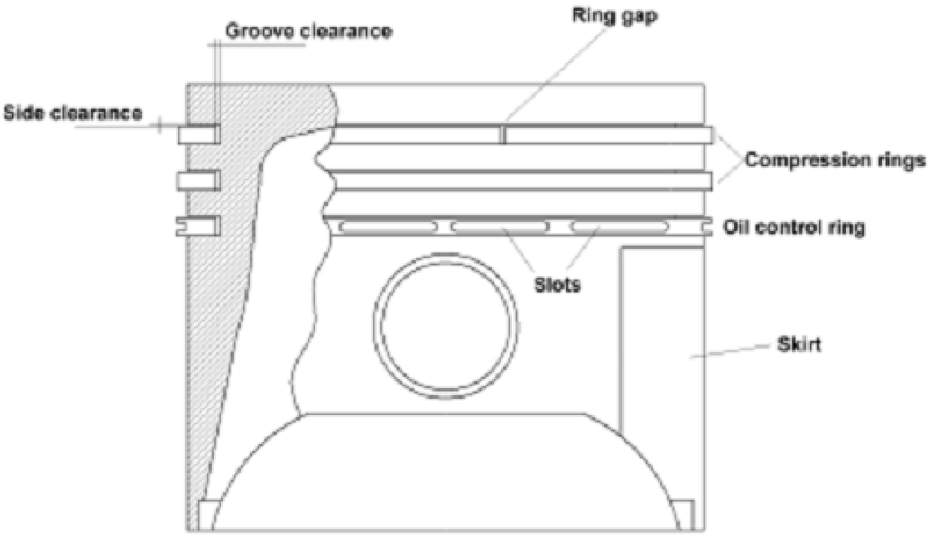

Fig 1.2 Position of different type of piston rings on piston [60]

Function-It prevents the compressed charge of fuel-air mixture from leaking to the other side of the piston. Oil rings, is used for removing lubricating oil from the cylinder after lubrication. This ring prevents the excess oil to mix with charge.

1.3.5 Connecting Rod

Function-It changes the reciprocating motion of piston into rotary motion at crankshaft. This way connecting rod transmits the power produced at piston to crankshaft.

1.3.6 Gudgeon Pin

Function- Connects the piston with small end of connecting rod.

1.3.7 Crank Pin

Function- Hand over the power and motion to the crank shaft which come from piston through connecting rod.

1.3.8 Crank Shaft

Function-Receives oscillating motion from connecting rod and gives a rotary motion to the main shaft. It also drives the camshaft which actuates the valves of the engine.

1.3.9 Cam Shaft

Function-It takes driving force from crankshaft through gear train or chain and operates the inlet valve as well as exhaust valve with the help of cam followers, push rod and rocker arms.

1.3.10 Inlet Valve & Exhaust Valve

Function-Inlet valve allow the fresh charge of air-fuel mixture to enter the cylinder bore. Exhaust valve permits the burnt gases to escape from the cylinder bore at proper timing.

1.3.11 Governor

Function-It controls the speed of engine at a different load by regulating fuel supply in diesel engine. In petrol engine, supplying the mixture of air-petrol and controlling the speed at various load condition.

1.3.12 Carburetor

Function-It converts petrol in fine spray and mixes with air in proper ratio as per requirement of the engine.

1.3.13 **Fuel Pump**

Function-This device supply the petrol to the carburetor sucking from the fuel tank.

1.3.14 **Spark Plug**

Function-This device is used in petrol engine only and ignites the charge of fuel for combustion.

1.3.15 Fuel Injector

Function-This device is used in diesel engine only and delivers fuel in fine spray under pressure.

1.4 Types of Piston Rings [60]

Piston rings form a ring pack, which usually consists of 2–5 rings, including at least one compression ring. The number of rings in the ring pack depends on the engine type, but usually comprises 2–4 compression rings and 0–3 oil control rings. For example, fast speed four-stroke diesel engines have 2 or 3 compression rings and a single oil control ring. The oil control rings used in diesel engines are two-piece assemblies and spark-ignited engine oil control rings may be three-piece assemblies as well. In addition to the general compression rings and oil control rings there are scraper rings, which have the tasks of both sealing and scraping off the oil from the liner wall. Scraper rings have a beak intended for scraping off the oil; see the Figs. 1.6a and 1.6b

1.4.1 Compression rings

The compression ring acts as a gas seal between the piston and the liner wall, preventing the combustion gases from trailing down to the crankcase. The rings have a certain pre-tension, i.e. they have a larger free diameter than the cylinder liner, which assists the ring in conforming to the liner. The cylinder gas pressure acts on the back-side of the ring, especially on the top ring, pressing it against the liner. The ring force distribution depends on the face form. With a rectangular face profile the force is higher than with a barrel-shaped face, as the compression pressure is able to act on the face-side of the barrel-shaped ring and thus counteract some of the force owing to ring pre-tension. Plain compression rings, with a rectangular cross-section, satisfactorily meet the sealing demands of ordinary running conditions and this type of compression ring is the most common one, see Fig. 1.3a. The use of rings with a barrel-shaped face profile (Fig. 1.3b) brings the benefit mentioned above. The ring may have a tapered face profile in order to shorten the running-in period, see Fig. 1.3c. The tapered face profile enables the compression gas pressure to act on the face-side as well and thus relieve the pressure against the liner wall, which reduces the wear rate during running-in. A tapered face profile has a good oil-scraping ability, and the ring can be used as an oil-scraping ring as well as a compression ring Beveled rings can be used as compression rings, see Fig. 1.4. The bevelled profile causes the ring to twist in the ring groove during engine operation. In running conditions the bevelled ring is pressed flat against the liner wall owing to the gas pressure, which causes an additional stress on the ring. The wedge-type profile or (half) keystone profile is used in order to prevent the ring from seizing in the groove, see Fig. 1.5. High temperature may cause the lubricant in the groove to carbonize. The wedge form makes the ring´s axial clearance greater at increasing radial groove clearance. Scraper rings, which are usually used as the second compression rings, can simultaneously be used as oil-scraper rings, see the Figs. 1.6a and 1.6b.

1.4.2 Oil control rings

In addition to the task of the compression rings to seal off the combustion chamber from the crankcase, there needs to be some mechanism to distribute the oil evenly onto the liner. The number of oil control rings in a ring pack is one or two. Normally a single oil control ring is sufficient but on occasions a second ring may be required. The appearance of the oil control ring differs from that of the compression ring; see the Figs. 1.6c and 1.6d.

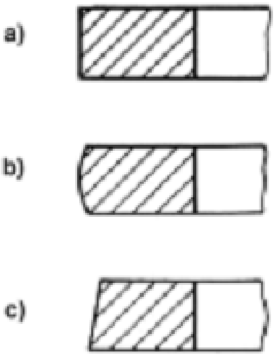

Figure 1.3 a- Most Common shape, b- barrel-shaped face profile, c- tapered face profile

Compression Ring cross-section (ISO 6621-1)

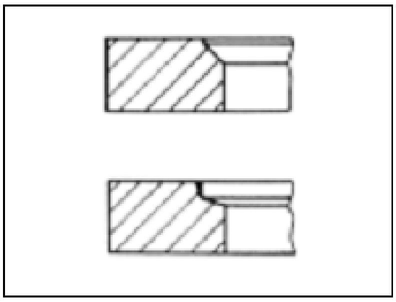

Figure 1.4

Bevelled ring edge configuration (ISO 6621-1)

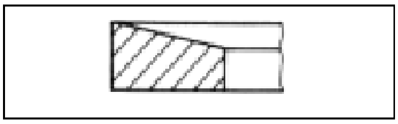

Figure 1.5

Half keystone ring (ISO 6621-1)

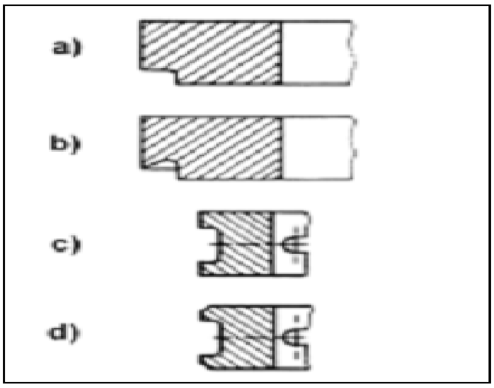

Figure 1.6 a, b, c, d

Compression & Oil Control Rings

The oil control ring is perforated by slots in the peripheral direction; see Fig. 2.1, which provides a way for the excess oil to leave the ring pack area. The scraped oil is collected in the oil control ring groove and transported through the piston back to the crankcase. The scraped oil may run through the possible gap between the liner wall and the piston skirt. With the latter alternative, the oil is forced in front of the oil control ring. The oil control rings may have a coil spring inserted, as the pre-tension of the ring is not sufficient in all instances. The additional force on the oil control rings causes them to have the most extreme lubrication conditions, even though these are the rings that control the oil film. Oil control rings are not always necessary, contrary to the compression rings. Two-stroke spark-ignited engines, for example, have the lubrication oil mixed in the fuel, and therefore need no oil control rings.

1.5 Types of Piston Rings Material

A piston ring material is chosen to meet the demands set by the running conditions. Furthermore, the material should be resistant against damage even in emergency conditions. Elasticity and corrosion resistance of the ring material is required. The ring coating, if applied, needs to work well together with both the ring and the liner materials, as well as with the lubricant. As one task of the rings is to conduct heat to the liner wall, good thermal conductivity is required. Grey cast iron is used as the main material for piston rings [61].

From a tribological point of view, the grey cast iron is beneficial, as a dry lubrication effect of the graphite phase of the material can occur under conditions of oil starvation. Furthermore, the graphite phase can act as an oil reservoir that supplies oil at dry starts or similar conditions of oil starvation [62]

Alloyed grey cast irons is used in a heat-treated condition used for 2nd groove. Besides having a high bending strength and modulus of elasticity, an increased hardness of 320 to 470 HB is produced in order to obtain the required wear resistance in the uncoated condition.

The demand for high wear strength is also met by the use of a tempered, alloyed cast iron . This has the benefit of a high bending strength of min. 800 MPa and high modulus of elasticity. The good wear resistance results from the combination of a fine-pearlitic matrix structure and finely dispersed, precipitated secondary carbides [63].

Unalloyed grey cast iron is used for 2-piece oil rings in the 3rd groove. These ring materials are characterized by a fine-lamellar graphite structure in a pearlitic matrix and have good conformability due to a relatively low modulus of elasticity.

Reduced width piston rings in gasoline engines to match reductions in the overall height of pistons, and increasing combustion pressures in diesel engines call for materials with increased strength characteristics.
These challenges are met by the use of high-chromium alloyed steels and spring steels. The greater durability under increased stresses is demonstrated by the improved fatigue strength manifested as form stability.

The wear resistance derives from finely distributed chromium carbides of the type $M_{23}C_6$ and M_7C_3 embedded in the tempered martensite matrix. For improved wear resistance these steelsare mainly used in a nitrided condition or with a peripheral coating.

The steels mentioned are used chiefly as compression ring materials for gasoline engines and truck diesel engines as well as for the steel rails and expander-spacers of oil control rings and for 2-piece profiled steel oil rings.

1.6 Piston Rings Coatings

Most piston rings and metallic sealing rings for today's modern application will require one of the following types of coating:

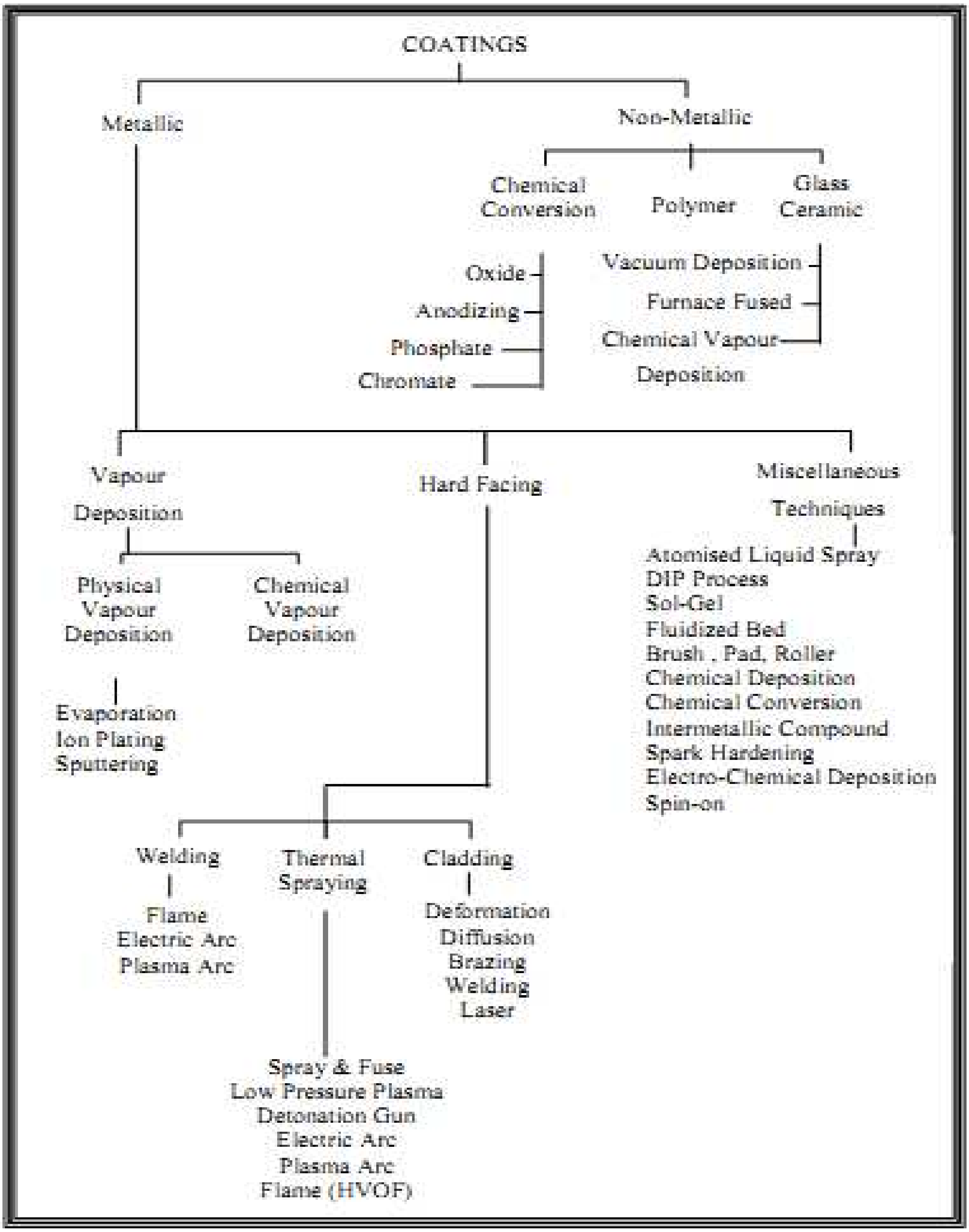

Figure 1.7 Coating deposition technologies [64]

Coatings for rings are widely used. One example of such a coating is chromium, which is used in abrasive and corrosive conditions where running conditions are severe. Hard chrome plating is particularly relevant for the compression ring.

Piston ring surfaces are, in addition to chromium plating, thermally (plasma) sprayed with molybdenum, metal composites, metal-ceramic composites or ceramic composites, as a uniform coating or an inlay coating material [65].

Experimental work with new powder compositions for thermal spraying has included molybdenum-nickel-chromium alloys, chromium oxide ($Cr2O3$) with metallic chromium binder, alumina-titania ($Al2O3$-$TiO2$), tungsten carbide (WC) with metallic cobalt binder, $MoSi2$, CrC-NiCr [66].

Hard chromium layers can be improved by plasma spraying chromium ceramic on the ring face, thus increasing the thermal load capacity. A dense chromium carbide coating, produced by HVOF coating was found promising for piston ring applications in the work by Rastegar and Richardson [67].

Thin, hard coatings produced by PVD or CVD include coating compositions like titanium nitride (TiN), chromium nitride (CrN); however coatings of this type are currently used exclusively for small series production for competition engines and selected production engines[68].

Multilayer Ti-TiN coatings have been experimentally deposited onto cast-iron piston rings, and the coating is claimed to be more wear resistant than a chromium plated or phosphate surface, particularly when the number of layers is high [69].

Haselkorn and Kelley have investigated coatings for use in low-heat rejection engines. They conclude that high carbon iron-molybdenum blend and chrome-silica composite applied by plasma spray, and further chrome nitride applied by low-temperature arc vapour are coatings with properties that meet the demands in low-heat rejection engines [70]

Surface coatings/treatments for the entire piston ring surface are based on phosphorus, nitrides, and ferro-oxides, copper and tin, as some examples [65].

The possibility of using ceramic piston rings as a complement to metallic rings in advanced engine applications has been investigated. Miniature tribo tests with ceramic materials have included monolithic zirconia, sintered silicon carbide, silicon nitride [71], and silicon nitride with a gradient of titanium nitride on the sliding surface [72]. Unlubricated sliding turned out to be detrimental to the ceramics. Silicon nitride and silicon carbide performed satisfactorily under oil-lubricated sliding conditions, while zirconia suffered from thermal shock cracking.

1.7 New Development in Piston Rings Coatings

Federal-Mogul Corporation has developed a new piston ring coating that supports vehicle manufacturers’ efforts to make petrol engines more fuel-efficient.

The patented 'CarboGlide' coating delivers a claimed direct improvement in fuel economy and CO_2 emissions by reducing ring friction by up to 20% as compared to nitride or other commonly used coatings. Its high wear resistance will withstand an engine’s full operational life - even in the latest generation of high-output petrol engines with turbocharging or direct injection. CarboGlide additionally protects the cylinder surface from scuffing and scoring, especially under the most critical lubrication conditions, because of its high chemical and physical stability, the supplier said.

The superior coating properties are achieved due to a multi-layer microstructure and a special coating composition that contains carbon, deposited in diamond-like form, as well as hydrogen and tungsten. The unique structure can be produced for a coating thickness of 10 microns, more than three times that of the industry’s latest DLC coating. A specialised advanced process based on the combination of physical vapour deposition and plasma-assisted chemical vapour deposition, specifically developed for piston ring application, is used in applying CarboGlide. The coating’s multi-layer architecture, together with the company’s surface machining and finishing expertise, ensure the integrity of the coating structure, optimal adhesion of the coating and high coating stability on both steel and cast iron rings.

CarboGlide is Federal-Mogul's third and most advanced generation of the company's DLC coated ring technology. The coating was developed in Burscheid, Germany [73]

New Cr-based multilayer nitride hard coatings were developed by Teer Coatings Ltd., England, using a Teer UDP450/4 unbalanced DC magnetron sputter ion plating system. The coatings were incorporated with Ti, Al, V, Y, Mo and Cr metal target On the basis of the results of these tribological tests, the most promising coatings were determined according to an evaluation matrix and the further development was concentrated on these coatings [74].

1.8 Manufacturing

Grey cast iron and steel piston rings are manufactured in different processes. At some industry grey iron piston rings are cast as individual rings in a noncircular shape; there are other ring manufacturers who cut the individual rings from pots or cuffs. The rings are generally machined to the required shape by means of double cam turning, a process in which the ring blank, already axially ground, is copy turned simultaneously on the inside and outside diameters. After a segment equivalent to the free gap is cut from the ring it assumes the free shape that will give it the required radial pressure distribution when fitted into the cylinder. Once inside the cylinder the ring is completely light tight on its outside diameter and exerts the predefined radial pressure against the cylinder wall.

Besides using double cam turning, ring blanks can also be shaped by machining the inside and outside diameters separately. This involves cam turning the outside diameter of the noncircular blank and machining the inside diameter with the ring in the compressed state. The gap is cut out in a step between O.D. and I.D. machining. Heat forming as a means of shaping piston rings should be mentioned to complete the range of options, but this process is seldom used.

Steel piston rings are made from a profiled wire. The rings are first coiled into a circular shape and then the gap is cut out. The necessary shape is obtained using a heat treatment process in which the rings are mounted onto an arbor appropriately designed to impart the required radial pressure distribution.

Profiling of the running faces of taper faced, Napier and slotted oil rings is carried out, depending on the ring design, on automatic O.D. lathes or profile grinding machines using special profile cutting tools before or after coating.

1.9 Testing on Piston Rings:

The various types of testing performed on the piston rings are mentioned below,

1.9.1 Chemical Composition

The spray coating is removed from the ring for analysis by stretching the ends of the ring apart or striking it until the coating comes free. The coating is then crushed. If the coating is contaminated with base material the analysis must be suitably corrected. The analysis is performed using analytical procedures (e.g. AAS) appropriate to the elements being tested.

1.9.2 Coating Porosity

The porosity of spray coatings is evaluated on the un-etched microsection. It is important for the evaluation to be carried out on representative areas of the coating. In the case of inlaid spray coatings the areas near to the inlay groove walls are not to be considered as representative because in these regions turbulence is generated in the spray jet during spraying and this can result in greater porosity. The specifications define maximum values for the porosity of representative areas of coating on full-face sprayed, half-inlaid and fully inlaid piston rings.

The porosity in the inlay groove wall region may be twice the value of the representative area. The size of the inlay groove wall region y is defined by the function y = cx, where c is an empirically determined constant and x the actual coating thickness. **For the inlay groove wall designs used up to now the value for c is 1.25.**

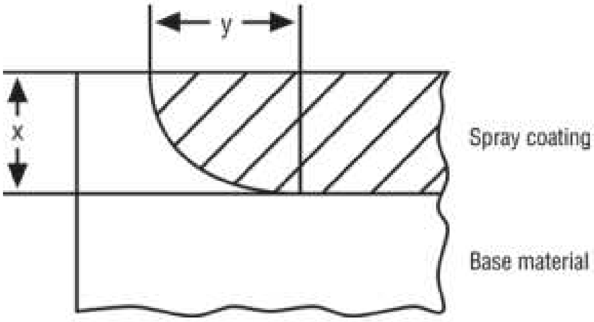

Figure 1.8, Coating Porosity Calculation

a) The pores in the coating areas are measured with a quantitative image analyzer. The surface area of all measured pores is set in relation to the area of the measurement field. The average of 30 measurement fields with a cumulative area of about 1.5 mm² is calculated for each ring.

b) The pores in the coating areas are estimated by comparing them against a classification chart containing photomicrographs of known porosities.

1.9.3 Pore Size

Pore sizes are stated as a size distribution percentage. All pores in representative measurement fields are measured for size in the unetched section and placed into size classes. The measurements are best performed by quantitative image analysis. The number of all measured pores is set equal to 100%. The material specifications for the respective spray coatings state the percentage of pores smaller than a specific value. An additional value is stated for the maximum size of individual pores. The specification further states the maximum pore size in the radial direction relative to the coating thickness.

1.9.4 Microstructure and Phase Distribution

The microstructure and the phase distribution of spray coatings are assessed on the etched micro-section. As these variables are difficult to quantify, the evaluation is performed by means of comparison against a classification chart for the spray coating concerned. The photomicrographs contained in the specifications represent only „averages“.

1.9.5 Unmelted Particles and Reaction Products

As a result of the spray process, plasma and flame sprayed coatings contain unmelted or only partially melted spray particles as well as reaction products usually of an oxidic nature.

Unmelted particles are recognizable as more or less round inclusions in the coating structure; reaction products can be present as thin layers between the coating lamellae. The permissible size and number of unmelted particles per sectional area is stated. The permissible shape and amount of reaction products is defined with the aid of reference micrographs (classification chart).

In the case of HVOF sprayed coatings it is the specific aim not to melt the spray powder but rather to compact the softened particles. Therefore unmelted particles in HVOF spray coatings are not a negative quality characteristic.

1.9.6 Micro-cracks and Fissures

Micro-cracks in the structure of spray coatings are short cracks discernible at 100x or greater magnification running between the coating lamellae or transversely across them. Fissures are lengthy cracks within fairly large coating areas or between the coating and the substrate metal.

The evaluation of spray coatings for microcracks and fissures is carried out on the unetched microsection. Microcracks are allowable, fissures are not.

Note: A ghost line at the coating to base material interface may be caused by relief formation during specimen preparation and will prevent a clear evaluation of the adhesion of the coating to the base material. If there is any doubt, the section must be suitably illuminated at an angle or an SEM micrograph taken in order to discriminate between a ghost line and a genuine fissure.

1.9.7 Coating Hardness

The coating hardness is measured according to Vickers as defined in DIN ISO 4516 and is stated as the average of 10 useful individual measurements per ring. The average must lie within the tolerance stated in the appropriate coating specification.

1.9.8 Particle and Phase Hardness

The hardness of individual particles and phases is measured on the etched section usually with HV 0.05. For very small particles and narrow phases it may be necessary to use a lower test force. In accordance with DIN ISO 4516 the test force is applied with an impact velocity of the indentor onto the specimen of 15-70 μm/sec. The equipment setting must not be altered for the duration of the test. The test force is allowed to act for 10 to 15 sec during which time no jolts or vibrations must be permitted to interfere with the applied force.

The average of 10 useful indentations is taken for each phase. The averages must lie within the tolerances stated in the specification.

1.9.9 Running Face Porosity, Voids, Cracks, Bond Defects between Coating and Inlay Groove Land (on Inlaid Rings)

These features, distinguishable on the running face, are influenced by the coating quality and above all by the machining. Such running face defects are tested by visual inspection, if appropriate with magnification. Guide values are laid down in DIN ISO 6621-5 for the evaluation of porosity and voids in the running face and for assessment of the running face edges and the outer edges at the ring gap. Macroscopic cracks in the running face are not permissible. If there is any doubt, a decision is made based on a suitable crack testing procedure. There must be no bond defects visible on the running face in the form of fissures between the coating and inlay groove land. However, allowance must be made for the occurrence of a partly discontinuous bond as a result of the unavoidably greater porosity of the coating structure caused by turbulence in the spray jet in the inlay groove wall region.

1.9.10 Coating Thickness

The thickness of spray coatings is determined with a device for measuring non-ferromagnetic coatings on ferromagnetic base materials (e.g. Permaskop). Standard reference values for different ring designs (full- face sprayed or inlaid) are obtained based on microscopic coating thickness measurements on radial cross- sections. The coating thickness is measured in the middle of the coating at three points around the ring circumference in accordance with DIN ISO 6621-2 and -4. The measured values must correspond to the drawing specification, with permissible tolerances stated in DIN

ISO 6621-5. The piston rings must be sufficiently demagnetized prior to measuring. If there is any doubt, the coating thickness must be determined on the radial cross-section.

1.10. Types of wear of the coating:

The study of the processes of wear of coating is part of the discipline of Tribology. The complex nature of coating wear has delayed its investigations and resulted in isolated studies towards specific wear mechanisms or processes. Some commonly referred to wear mechanisms of coating (or processes) include [59]:

1. Adhesive wear ,
2. Abrasive wear
3. Surface fatigue
4. Fretting wear
5. Erosive wear

A number of different wear phenomena of coating are also commonly encountered and represented in literature. Impact wear, cavitations wear, diffusive wear and corrosive wear are all such examples. These wear mechanisms; however, do not necessarily act independently in many applications. Wear mechanisms of the coatings are not mutually exclusive. "Industrial Wear" is the term used to describe the incidence of multiple wear mechanisms occurring in unison. Wear mechanisms and/or sub-mechanisms frequently overlap and occur in a synergistic manner, producing a greater rate of wear than the sum of the individual wear mechanisms.

1.10.1. Adhesive wear of coating:

Adhesive wear is defined as the transfer of material from one surface to another during relative motion by a process of solid-phase welding or as a result of localized bonding between contacting surfaces. Particles that are removed from one surface are either permanently or temporarily attached to the other surface [29]. Adhesive wear of coating occurs when two body slides over each other, or are pressed into one another, which promote material transfer between the two surfaces. When either one of two surfaces of tribo-elements in sliding or rolling contact has thin soft surface layer that can partly transfer to the counter surface by adhesion, relative displacement takes place at the interface between the surfaces of coating and transfer layer with smaller shear strength of the soft material than that of the underlying element material. Low friction is obtained as a result, and wear of the tribo elements is much reduced. Soft metal coating is introduced for this purpose, and Au, Ag, Pb and In are representative ones [30]. However, material transfer in coating is always present when two surfaces are aligned against each other for a certain amount of time and the cause for material transfer or wear-categorization have been a source for discussion and argumentation amongst researchers for quite some time and there are frequent misinterpretations or misunderstandings due to overlaps and symbiotic relations between "wear" and physical-chemical mechanisms as previously mentioned. Having described the restriction on the subject wear, we can focus on what causes material transfer in wear of coating.

Adhesive wear of the coating can be described as plastic deformation of very small fragments within the surface layer when two surfaces slides against each other. The asperities (i.e., microscopic high points) found on the mating surfaces will penetrate the opposing surface and develop a plastic zone around the penetrating asperity [31].

Dependent on the surface roughness and depth of penetration will the asperity cause damage on the oxide surface layer or even the underlying bulk material of the coating surface. In initial asperity/asperity contact, fragments of coating are pulled off and adhere to the other, due to the strong adhesive forces between atoms. It is thereby clear that physical-chemical adhesive interaction between the surfaces plays a role in the initial build-up process but the energy absorbed in plastic deformation and relative movement is the main cause for material transfer and wear of the coating.

Adhesive wear is the most common form of wear of coating and is commonly encountered in conjunction with lubricant failures. In engineering science, some aspects of adhesive wear is commonly referred to as welding wear due to the exhibited surface characteristics and the Tribology process is usually referred to as galling and is a common fault factor in sheet metal forming (SMF) and other industrial applications.

The tendency of contacting coating to adhere arises from the attractive forces that exist between the surface atoms of the two materials. The type and mechanism of attraction varies between different materials. Most solids will adhere on contact to some extent, however, oxidation films and contaminants naturally occurring; generally suppress adhesion. Surfaces also generally have low energy states due to reacted and absorbed species. The mechanism of adhesive wear of coating occurs due to contact possibly producing surface plastic flow, scraping off soft surface films or breaking up and removing oxide layers. This brings clean regions into contact and introduces the possibility of strong adhesion. The removal of material from coating surface, or wear, takes the form of small particles. These small particles are usually transferred to the other surface but may come off in loose form.

1.10.2. Abrasive wears of coating:

The abrasive wear of a material is defined as the progressive loss of material due to abrasive action of hard particles present between the counter surfaces. The abrasive wear depends on various factors like abrasive size, rake angle of abrasives, applied load and shape, size, volume fraction of the dispersed phases. In addition to these factors the abrasive wear rate of a material also depends on the surface hardness and materials properties like fracture toughness [32]. Abrasive wear of coating occurs when a hard rough surface slides across a softer surface. ASTM (American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface. Abrasive wear of coating is commonly classified according to the type of contact and the contact environment. The type of contact determines the mode of abrasive wear of coating. The two modes of abrasive wear of coating are known as two-body and three-body abrasive wear. Two-body wear occurs when the grits, or hard particles, are rigidly mounted or adhere to a surface, when they remove the material from the surface of coating [33]. The common analogy is that of material being removed with sand paper. Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface of coating. The contact environment determines whether the wear is classified as open or closed. An open contact environment occurs when the surfaces are sufficiently displaced to be independent of one another.

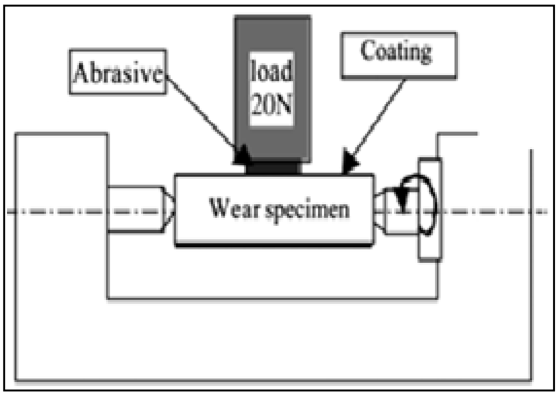

Figure 1.9 Abrasive wear of thermal spray coating (Reference 33)

There are a number of factors which influence abrasive wear of coating and hence the manner of material removal. Several different mechanisms have been proposed to describe the manner in which the material is removed. Three commonly identified mechanisms of abrasive wear of coatings are:

1. Plowing
2. Cutting
3. Fragmentation

Plowing occurs when coating material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal from the coating surface. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles. Cutting occurs when coating material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves. This mechanism closely resembles conventional machining. Fragmentation occurs when material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the coating material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling.

1.10.3. Surface fatigue wear of the coating:

Surface fatigue wear of the coating is a process by which the surface of coating is weakened by cyclic loading, which is one type of general material fatigue. Fatigue wear in coating is produced when the wear particles are detached by cyclic crack growth of micro cracks on the surface of the coating. These micro cracks are either superficial cracks or subsurface cracks. It is extremely important to improve the resistance of the material against fracture in aerospace applications.

In the case where this alloy is, for example, used for turbine engine blades, the fretting fatigue, which is caused by the combination of cyclic fatigue stress and frictional wear, occurs at turbine engine blade roots. As a result, many small cracks will easily initiate on the material surface. Also, it has been reported that the fretting fatigue life decreases remarkably as compared with plain fatigue life [34]. The use of high strength steels instead of tool steels brought out a new aims for material scientists – increase endurance of the tool materials in cyclic loading (cold forging, stamping and blanking). To solve the fatigue damage problems of high-speed steels (HSS) the powder metallurgy (PM) routes are used. As a result of the finer and more uniform microstructure that PM-HSSs exhibit, as compared to their conventionally produced counterparts, they also present enhanced cross-sectional hardness uniformity (wear resistance), fracture toughness and fatigue strength [35].

1.10.4. Fretting wear of coating:

Fretting wear of the coating is the repeated cyclical rubbing between coating and another surface, which is known as fretting, over a period of time which will remove material from one or both surfaces in contact. It occurs typically in bearings, although most bearings have their surfaces hardened to resist the problem. Another problem occurs when cracks in either surface are created, known as fretting fatigue [35]. It is the more serious of the two phenomena because it can lead to catastrophic failure of the bearing. It is extremely important to improve the resistance of the material against fracture in aerospace applications. In the case where this alloy is, for example, used for turbine engine blades, the fretting fatigue, which is caused by the combination of cyclic fatigue stress and frictional wear, occurs at turbine engine blade roots [36]. As a result, many small cracks will easily initiate on the material surface. An associated problem occurs when the small particles removed by wear are oxidized in air. The oxides are usually harder than the underlying metal, so wear accelerates as the harder particles abrade the metal surfaces further. Fretting corrosion acts in the same way, especially when water is present. Torsional fretting wear tests of the coating were conducted on a flat-on-ball contact on a torsional fretting rig with a controlled environmental chamber.

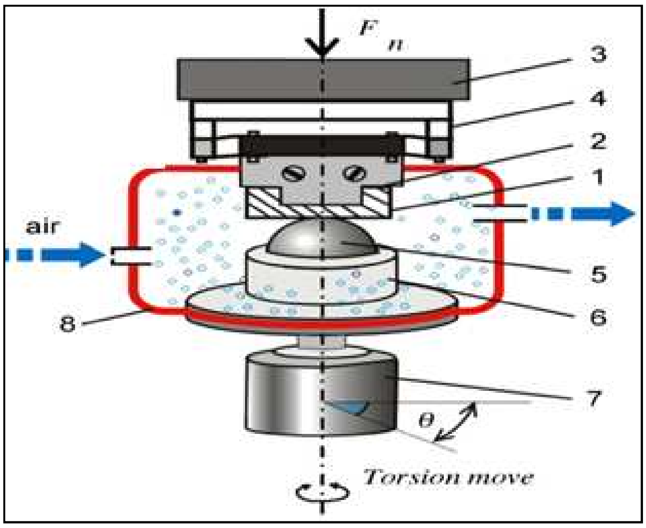

Figure 1. 10 Fretting wear of thermal spray coating (Reference 8)

A plate specimen (1) was fixed on the upper holder (2) to link a six-axis torque/force sensor (3) (three loads of *x*, *y* and *z* direction; three torques of *x*, *y* and *z* direction) through a spring suspension (4). A ball specimen (5) was mounted on the lower holder (6), which fixed on the low-speed reciprocating rotary motor system (7). The flat specimen rotated following the motion of the motor at a constant rotary velocity (in the range of 0.01–5◦/s). In order to ensure pure torsional fretting, the centerline the ball specimen was superposed strictly to the rotary axis of the motor system at all times [8]. Angular displacement of the contact pair was measured by a sensor in the motor system and unprotected bearings on large structures like bridges can suffer serious degradation in behaviour, especially when salt is used during winter to deice the highways carried by the bridges. The problem of fretting corrosion was involved in the Silver Bridge tragedy and the Mianus River Bridge accident.

1.10.5. Erosive wear of coating:

Erosive wear of the thermal spray coating is caused by the impact of particles of solid or liquid against the surface of coating [13]. The impacting particles gradually remove material from the coating surface through repeated deformations and cutting actions. It is a widely encountered mechanism in industry. A common example is the erosive wear associated with the movement of slurries through piping and pumping equipment (fig 1.11).

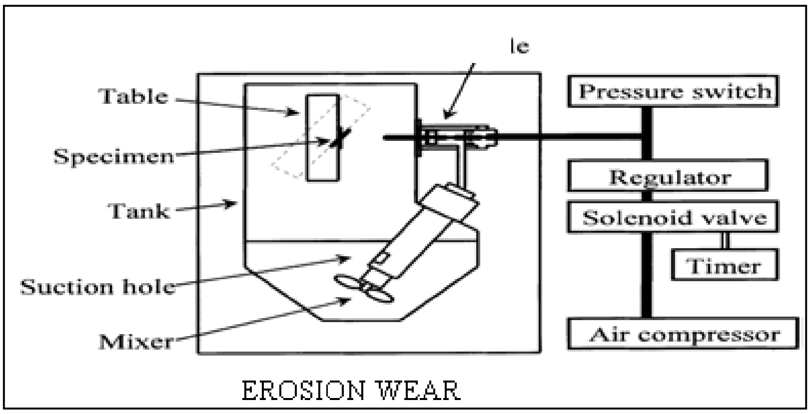

Figure 1.11 Erosion wear of thermal spray coating [13]

The rate of erosive wear is dependent upon a number of factors. The material characteristics of the particles, such as their shape, hardness, and impact velocity and impingement angle are primary factors along with the properties of the surface of the coating [13,28]. The impingement angle is one of the most important factors and is widely recognized in literature. For ductile coating materials the maximum wear rate is found when the impingement angle is approximately 30°, whilst for non ductile coating materials the maximum wear rate occurs when the impingement angle is normal to the surface.