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Power Cylinder Effects on Friction and Fuel Economy

RATIONALE

Improved fuel economy is a very important part in the development of modern combustion engines. This document covers the mechanisms from the power cylinder which contribute to the mechanical friction of an internal combustion engine. It will not discuss in detail the influence of other engine components or engine driven accessories on friction.

In this revision, numerous examples that have very little effect on fuel economy were deleted. New significant factors were added that were not in the previous version of the standard. This includes topics like using advance honing techniques.

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1. SCOPE

This document covers the mechanisms from the power cylinder, which contribute to the mechanical friction of an internal combustion engine. It will not discuss in detail the influence of other engine components or engine driven accessories on friction.

1.1 Purpose

In internal combustion engines, the ability of an engine to generate its power potential to its fullest is hindered by the inherent internal friction of the sliding components and the friction of the engine driven accessories. In an era where power and fuel economy are key performance attributes, any operating condition that hinders the ability of an engine to achieve these attributes is of primary interest to the engine designer. Any sliding surface in the engine contributes to the friction of an engine. According to Taylor (1986), the friction of an internal combustion engine is partitioned between the piston and ring assembly and the bearing, valve, and gear trains with the piston assembly accounting for 75% of the friction. Since the power cylinder friction is a major contributor to the overall mechanical friction of the engine, any friction reduction goes directly to brake power with no increase in emissions, will add thermal efficiency at no cost to the customer, and can potentially improve durability. Any attempt to minimize the friction of an engine logically starts with decreasing the friction of the piston assembly. This document focuses on the friction of the piston and ring assembly sliding in a lubricated bore, in an attempt to communicate the current best thinking on the subject of power cylinder friction. With this understanding, the engine designer or engine development engineer will be able to minimize the friction of the power cylinder assembly, thereby contributing to the power output or fuel economy of an internal combustion engine.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1588 Internal Combustion Engines - Piston Rings - Vocabulary

SAE J2612 Internal Combustion Engines - Piston Vocabulary

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 Other Publications

Taylor, C.F. (1986). The internal combustion engine in theory and practice: Volume 1. *MIT Press*.

Bushan, B. and Gupta, K.K. (1991). Handbook of tribology, materials, coatings, and surface treatments. *McGraw-Hill*.

Richardson, D.E. (2000). Review of power cylinder friction for diesel engines. *J. Eng. Gas Turbines Power, 122*(4), pp. 506-519, https://doi.org/10.1115/1.1290592.

3. DEFINITIONS

Refer to SAE J2612 for the piston nomenclature.

Refer to SAE J1588 for the piston ring nomenclature.

4. BASICS OF FRICTION

4.1 Friction is the resistance to relative motion of contacting bodies. Friction force and friction power loss are two basic methods to characterize friction. Friction power losses are of most concern regarding fuel consumption. Friction forces can be very high but have a small effect on power losses. Friction forces may be better correlated to wear and durability.

4.2 Friction experienced during a sliding condition is known as sliding friction, and the friction experienced during a rolling condition is known as rolling friction. The friction in the power cylinder is exclusively sliding friction (refer to Bushan and Gupta, 1991).

4.3 The friction between lubricated sliding surfaces can be classified into the following lubrication regimes: hydrodynamic, mixed lubrication, and boundary lubrication.

- Hydrodynamic lubrication between sliding surfaces occurs when the lubricating film thickness is sufficient in thickness to avoid asperity contact. Friction in this regime is caused by shear resistance of the oil film. Boundary lubrication occurs when the film thickness is insufficient to separate the adjacent sliding surfaces and friction is dominated by asperity contact.
- Mixed lubrication occurs when the film thicknesses transition between the hydrodynamic and boundary regimes.
- Friction tends to be highest in the boundary regime and is characterized by high wear rates. Within the mixed and boundary regime, friction is due to the various combined effects of adhesion between the contacting surfaces, ploughing by wear particles and hard surface asperity, and asperity deformation. The relative contribution of these components depends on the specific material used, the surface topography, the conditions of sliding interface, and the environment.

4.4 The components that affect the power cylinder friction are the piston, piston rings, cylinder bore, wrist pin, and the lubricant. The piston assembly slides against the lubricated cylinder bore and wrist pin, and it is this sliding contact that generates the mechanical friction of the power cylinder. By the inherent design of the internal combustion engine, the piston undergoes a wide range of velocities; with zero velocity at top dead center (TDC) and bottom dead center (BDC) and maximum velocity at mid-stroke. Due to this wide range of piston speeds, the piston, rings, and cylinder bore experience all the lubrication regimes as described above within an engine cycle. The wrist pin, due to its intermittent motion, usually resides within the mixed lubrication regime.

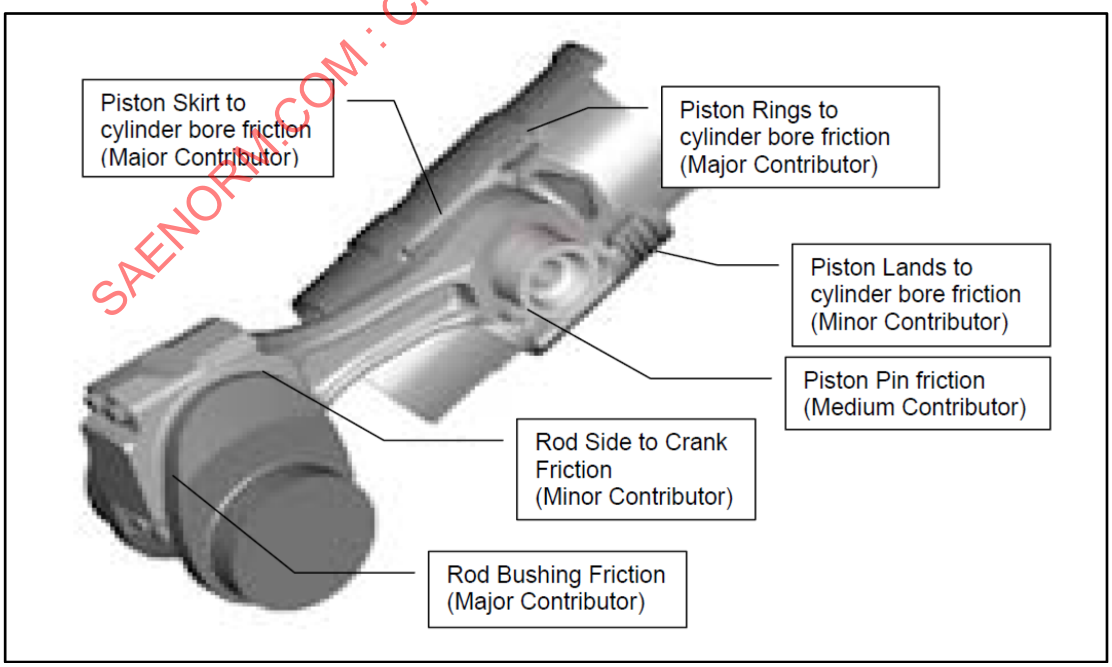

Figure 1 - Locations of power cylinder friction

5. POWER CYLINDER COMPONENT - EFFECTS ON FUEL ECONOMY

The following power cylinder components each can contribute to friction and fuel economy. These effects will be described in subsequent sections.

Components:

- Piston
- Rings
  - Top compression ring
  - Second compression ring
  - Oil control ring
- Cylinder bore
- Oils
- Oil jets
  - Under-crown spraying
  - Gallery cooling sprays
  - Cylinder wall jet
- Piston pin
- Connecting rod

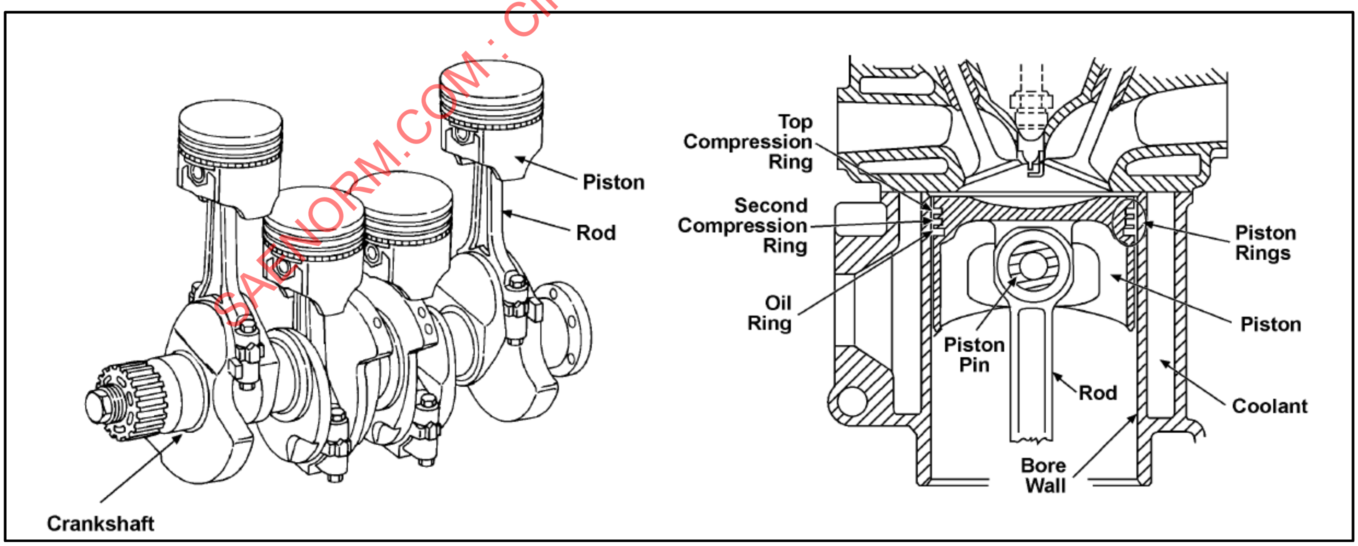

Figure 2 - Power cylinder

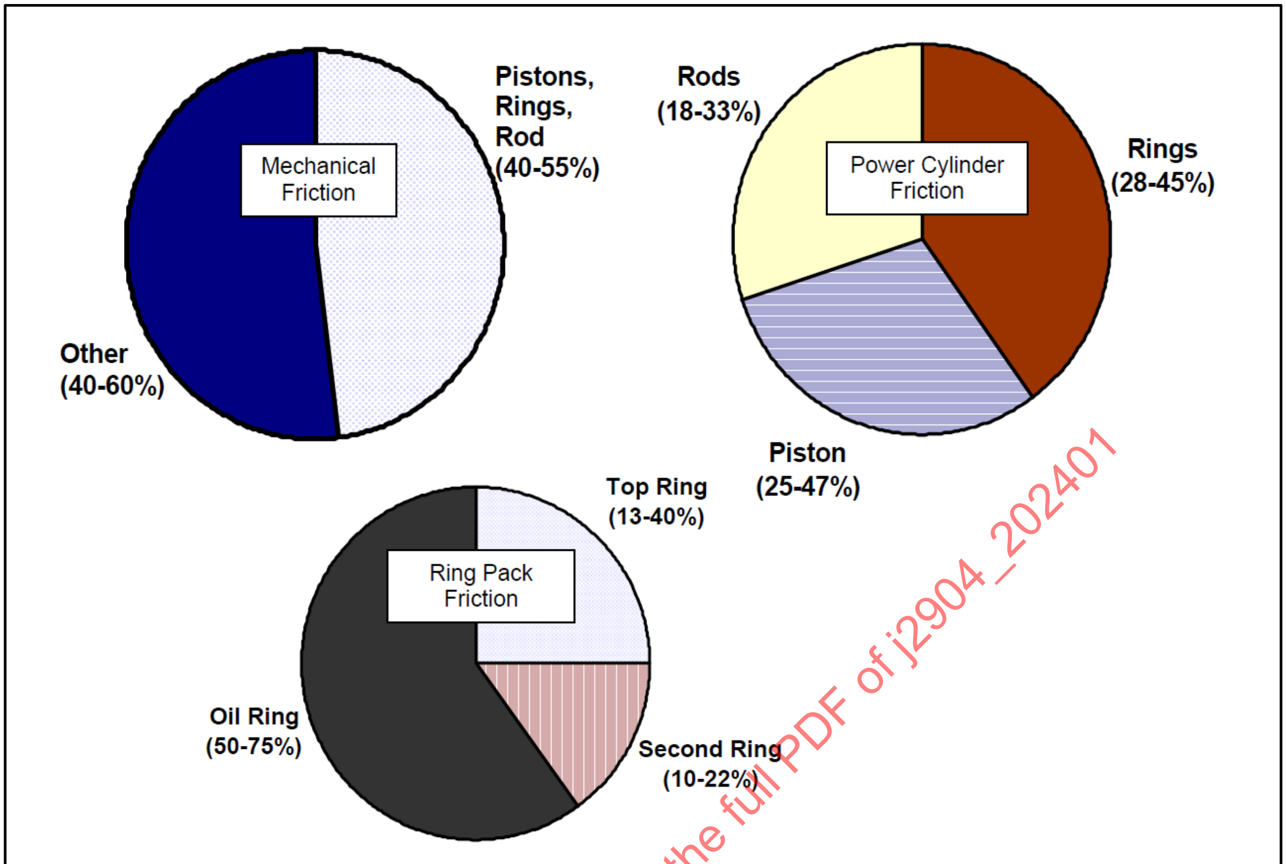

Figure 3 - Friction contribution of the power cylinder components (Richardson, 2000)

5.1 Piston

The piston contributes to roughly 50% of the power cylinder mechanical friction. The friction between the piston and the cylinder wall is the primary contribution of the piston to the overall engine friction. However, the interface with the piston pin can also contribute.

5.2 Ring Pack

The ring pack contributes to most of the remaining power cylinder friction, with the contribution between the piston and ring pack approximately equally balanced. The top ring and oil control ring are the main contributors to friction for the ring pack. The contribution between the oil ring and top ring varies between engine designs but, in general, are similar in their effects on friction.

5.2.1 Top Ring

The primary function of the top ring is to seal the combustion gases. Therefore, it is exposed to the high cylinder pressures. As a result, the friction from the top ring is mainly due to gas pressure loading and occurs mainly during the expansion stroke.

5.2.2 Second Ring

The second ring primarily scrapes the excess oil off the bore surface that passes by the oil ring and therefore controls the amount of oil available for the top ring. The second ring also controls the pressure balance between the top ring and second ring, which affects the dynamic stability of the ring pack. However, this ring is a small contributor for friction relative to the top ring and oil ring. Therefore, it is important to design this ring to allow good oil control and ring pack stability; which, ultimately, will enable friction reduction by allowing the top ring and oil control ring to be designed for reduced friction.

5.2.3 Oil Ring

The oil ring reduces the oil film thickness from that required for piston skirt lubrication to that required for compression ring lubrication. The oil ring requires a high tangential load to produce enough unit pressure on the oil rails to effectively scrape oil. This high tangential load produces a high frictional force. With a more efficient scraper design for the second ring, the oil ring tangential loads may be reduced without significant degradation of oil control for the ring pack. Likewise, reduced rail widths on the oil control ring will also allow reduced tangential loads for equivalent oil control capability.

5.3 Cylinder Bore

The interaction of the piston and rings with the bore surface affects the gas and oil sealing of the cylinder. As a result, it is the function of the cylinder bore to provide a good sealing surface with sufficient but not excessive oil retention for the lubrication of the piston and rings. The conditions of the bore (temperatures, distortion, surface finish, rigidity, etc.) also need to be optimized for proper friction. Since the cylinder bore is also the frictional mating surface for both the piston and rings, it is critical for the bore to be designed for minimal bore distortion and with a surface finish texture designed to avoid asperity contact and control oil film thicknesses throughout the entire engine cycle for the rings and piston. The tension required in the rings to create a seal is a function of the roundness errors in the cylinder bore. Higher order distortion (fourth order and higher) is more difficult to seal, so for a low friction assembly, it is important to minimize this distortion.

5.4 Oil Properties

The properties of the oil play a significant role in friction. The properties must be optimized to lubricate the cylinder sufficiently but minimize friction. Factors that will affect the friction are viscosity, volatility, misting characteristics, and surface tension. While the engine designer does not have control of these properties, they must be aware of them so that an accurate specification can be stated for optimum operation of the engine.

6. OTHER EFFECTS ON FUEL ECONOMY

There are other components and factors that can also significantly affect friction listed below. These are not discussed in detail in this document, but it is important to understand their influence when diagnosing friction problems or optimizing the friction of an engine. These other systems must be isolated in order to optimize or determine the friction contribution by the power cylinder system.

- Valve train (valves and valve guides, cam shaft, rollers, rocker arms, etc.)
- Crankshaft (main bearings, big end bearing on the connecting rod)
- Pumps and accessories (oil pump, water pumps)
- Gear train

7. FRICTION CONTRIBUTION FIGURE

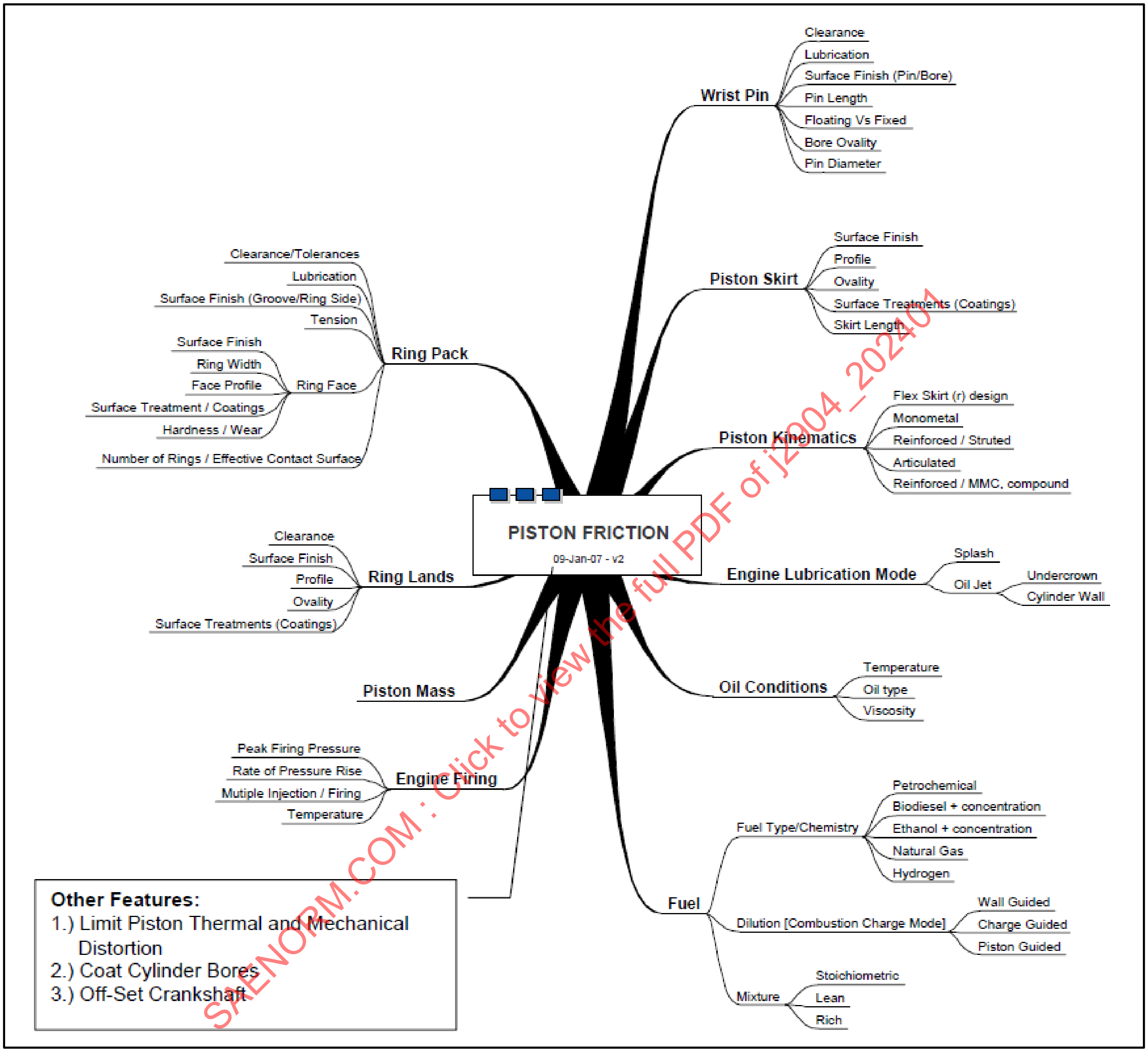

Figure 4 - Power cylinder friction contributions (need to compare to the document)

8. PISTON EFFECTS ON FUEL ECONOMY

8.1 Piston Mass (Minor Effect)

The piston mass will affect the inertia forces on the piston. The thrust force will therefore change as the piston mass is changed, which will affect friction. In addition, the position of the center of gravity can also affect the piston's secondary motion and alter friction. The inertial loads of the piston will affect the friction in the rod bearings. The piston mass will be affected by the piston type, bowl design, ring land design, and material.

8.2 Piston Cooling (Minor Effect)

The cooling of the piston will affect the temperatures of the interfaces to the pistons. This will affect friction. Hotter pistons will result in less viscous oils and thinner oil films but also greater thermal expansion, creating higher skirt contact forces.

Pistons can be cooled by piston galleries. The location and shape of the galleries will have a significant effect on how well the gallery cools the piston.

8.3 Piston Ring Grooves

8.3.1 Angles (Medium Effect)

The keystone ring groove will have a reaction force from the pressure acting on the ring in the horizontal direction (see Figure 5). This will create a higher force acting on the cylinder bore, which will result in higher friction and wear than a rectangular ring.

Conventional wisdom is that rectangular ring grooves are better for oil and blow-by control. However, in some cases, keystone ring grooves are needed to prevent ring sticking, especially in diesel engines. If rings stick, thrust forces from the piston will be transferred to the ring. With increased thrust forces on the ring, ring friction will significantly increase.

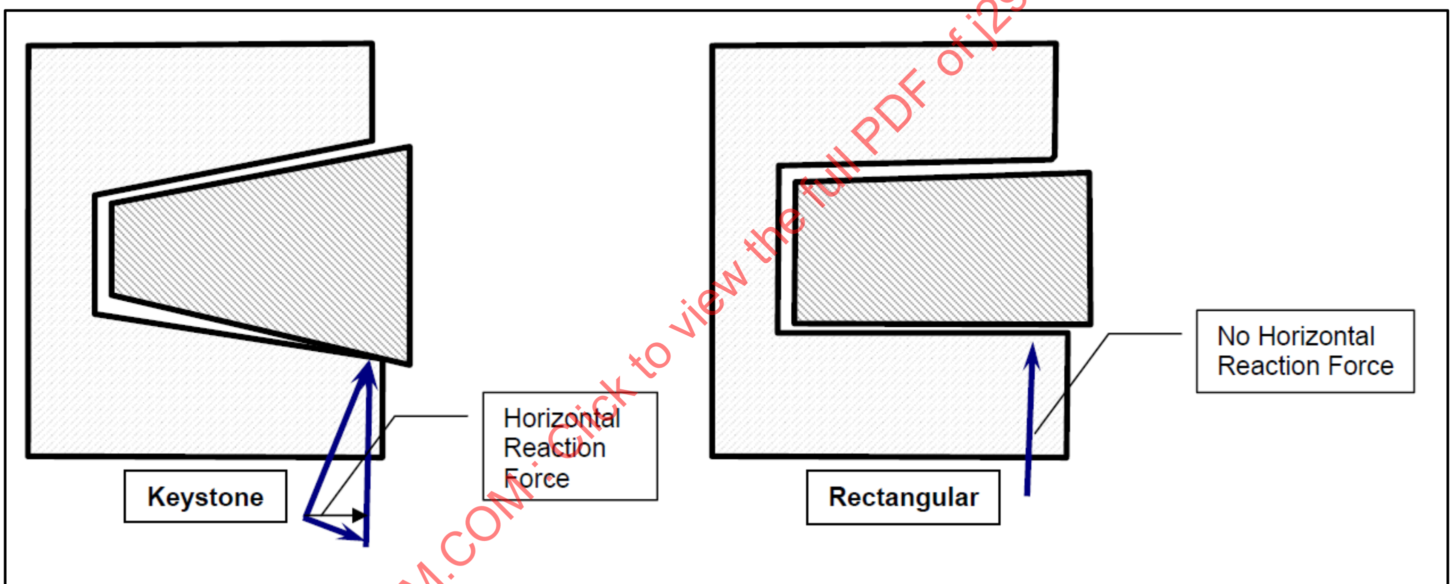

Figure 5 - Angles of rings and grooves

8.3.2 Surface Conditions (Medium Effect)

If the surface roughness or waviness is excessive, friction will increase between the ring and groove. This friction will affect the secondary dynamics of the piston and transfer thrust loads to the rings. This effect may cause increased unit pressures on the ring faces and cause increased friction between the ring and cylinder bore.

8.3.3 Parallelism (Minor Effect)

If the ring groove width becomes smaller because of poor parallelism, the ring may become pinched in the groove. This will cause friction between the ring and the groove, transferring thrust loads to the rings. Increased thrust forces on rings can lead to increased friction.

8.3.4 Ring to Groove Clearances (Minor Effect)

The clearances between the piston, rings, and bore can affect friction. These should be designed to provide adequate clearances to avoid thrust forces from the piston being transferred to the rings. For instance, if the root diameter in the ring groove is too large or the side clearances are too small, the ring may be pressed against the bore, increasing friction, or resulting in scuffing. If there are adequate clearances, there will be no significant effect on friction.

8.4 Piston Lands

8.4.1 Diameters (Major Effect)

The diameters of the ring lands affect the clearance between the lands and the cylinder bore. If the clearance is too small, land contact may occur, which can increase friction due to asperity contact which also may cause scuffing. Furthermore, the land might scrape oil upward and result in high oil consumption. In some cases, carbon will build up on the lands when the clearance is incorrectly specified. This will increase friction.

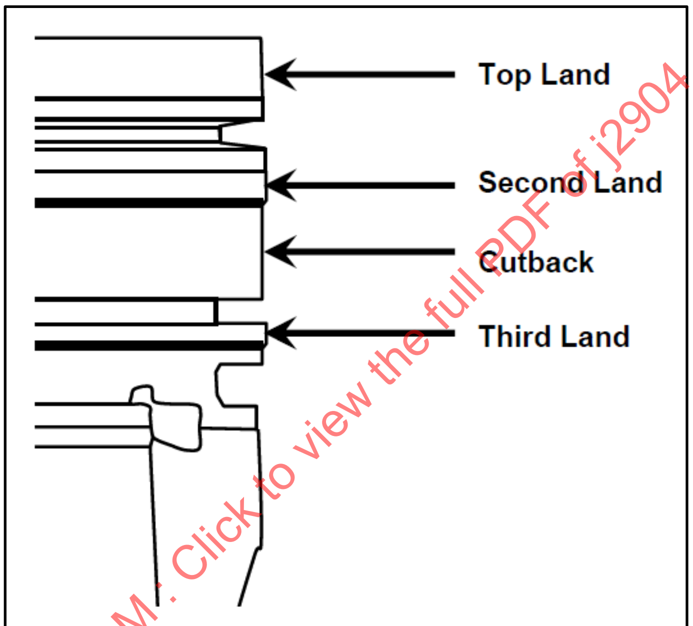

Figure 6 - Land diameters

8.4.2 Piston Top Land Axial Profiles (Major Effect)

Typically, the top of the piston will have higher temperatures than the lower regions. Therefore, the piston lands are typically profiled where the upper lands are cut back more than the lower lands to compensate for the higher temperatures. If the profile of the land is incorrect, land contact to the bore can occur, which will lead to increased friction.

The top land profile may be cylindrical, tapered, balcony, or barrel shaped.

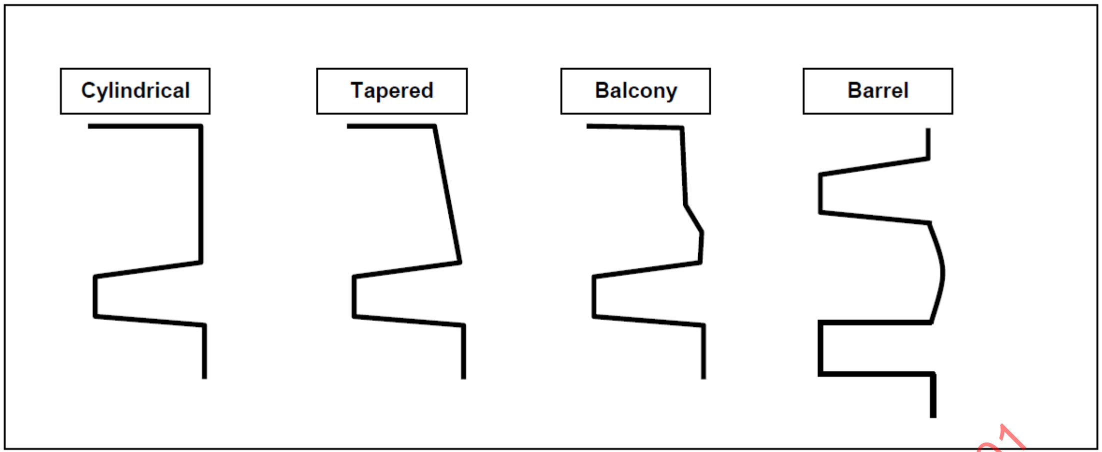

Figure 7 - Land profiles

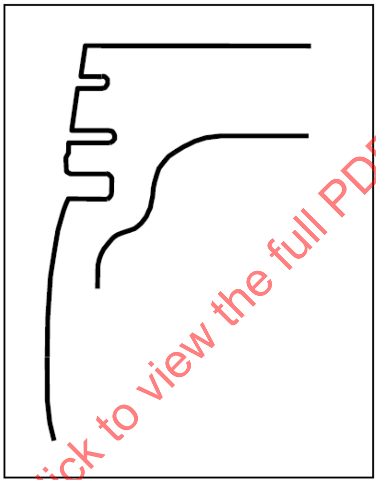

Figure 8 - Land and skirt profile example

8.4.3 Piston Top Land Volume (Major Effect)

The volume of the top land of the piston can be defined as the volume between the top of the piston to the top side of the top ring. This volume can affect the combustion process and significantly affect fuel economy.

8.4.4 Piston Land Circumferential Profiles (Major Effect)

At times, ovality is necessary on the piston lands to compensate for the thermo-mechanical deformations of the piston and to enhance such things as scraped oil drainage and inter-ring gas pressure. The bore can also deform into an oval shape during operation. The ovality of the piston should be chosen to provide adequate clearance for the piston in the bore under these conditions. If there is insufficient ovality, increased land contact to the bore can occur towards the pin axis, which will increase friction.

On an articulated piston and some monoblock designs, the second land is the guiding land and should have the appropriate ovality to stabilize the piston. If the ovality is excessive, unit pressures will increase in the thrust plane on the second land, resulting in increased friction.

8.4.5 Piston Land Coatings (Minor Effect)

If, during the motion of the piston, a piston land contacts the cylinder bore, there may be a potential benefit to adding a coating on the piston land to reduce friction. Contact can be identified by polishing on the land after running in the engine.

8.4.6 Piston Guidance by a Land (Major Effect)

The piston may be guided by one of the lands depending on the piston design. An articulated piston will have one guiding land because of its design. The one-piece piston is typically guided by the skirt but can at times have a contribution from a land. The profile of this land is important because it will interact with the cylinder wall and as a result affect friction. Land profile can be cylindrical, tapered, balcony, or barrel shaped.

8.5 Piston Skirt

8.5.1 Piston Guidance or Piston Secondary Motion (Major Effect)

The skirt will guide the piston in the bore. The stability of this guidance is determined by the piston secondary motion or lateral/tilting motion in the cylinder bore. The secondary motion affects the kinetic energy due to piston slap and the load distribution along the skirt. As the impact energy and unit loads change, friction will be affected. Additionally, if the piston moves such that the top land scrapes the cylinder wall, then high friction can result.

8.5.1.1 Skirt Rigidity (Major Effect)

The stiffness of the skirt plays a direct role in how loads are distributed along the skirt and therefore affects friction. The secondary motion is affected by the rigidity of the piston skirt, as well as the rigidity of the bore. The rigidity of the piston skirt is affected by the piston type, reinforcements/strutted, thickness, and material.

8.5.1.2 Pin Offsets (Major Effect)

A piston pin offset can significantly affect how the piston moves within the cylinder bore and affects the connecting rod angle, thus affecting the component of force acting laterally on the piston skirt (the thrust force) and as a result may significantly affect friction.

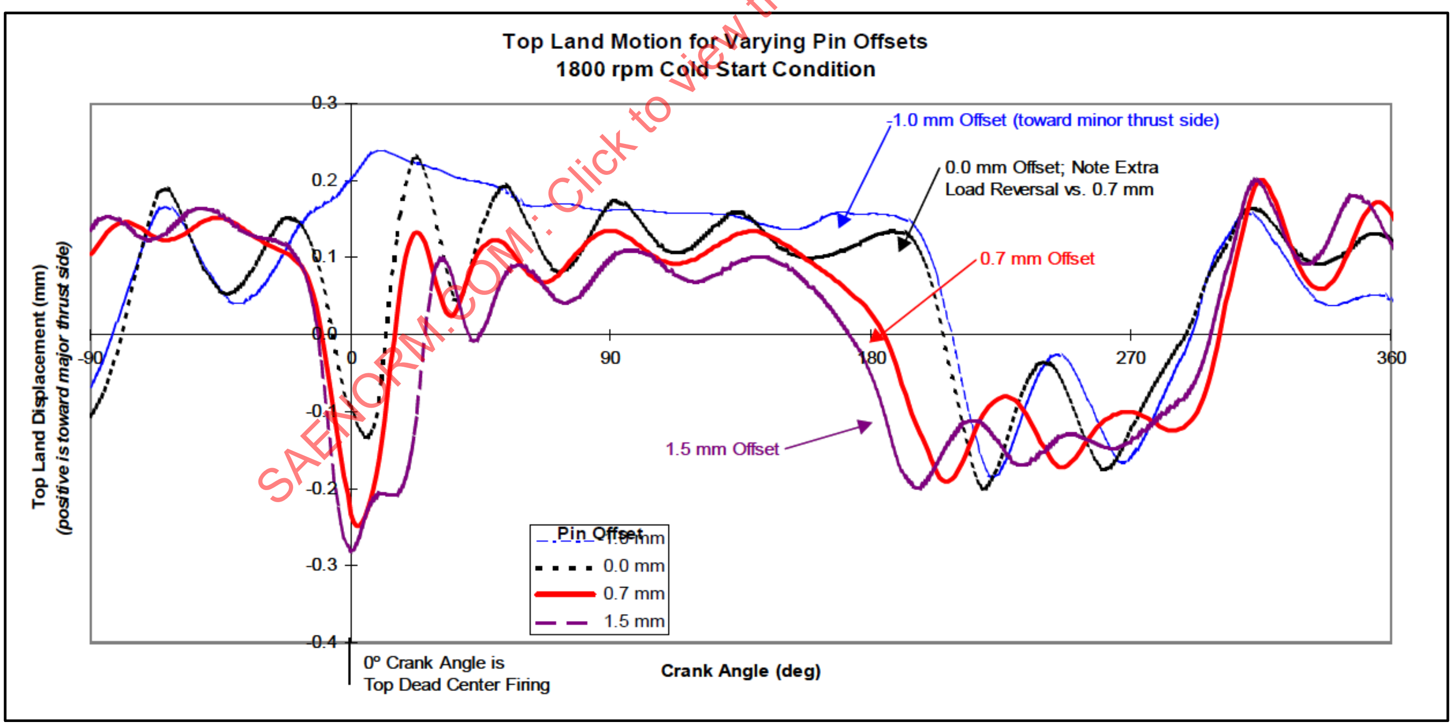

Figure 9 - Example of the effect of pin offset on piston motion

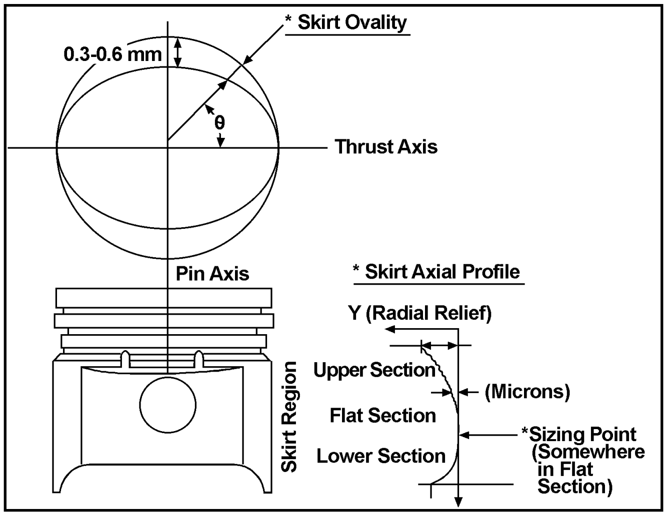

Figure 10 - Piston profiles

8.5.1.3 Skirt Major Diameter (Major Effect)

The clearance between the piston and the bore affects the unit loads on the piston and oil film thicknesses. Additionally, the clearance will also affect the piston secondary motion and impact forces. Also, as the clearance changes, the load distribution on the skirt profile changes. The major diameter of the skirt therefore affects friction significantly.

8.5.1.4 Skirt Axial Profile (Barrel) (Major Effect)

The axial profile of the skirt is designed to create good hydrodynamic lubrication with the bore to minimize contact wear while providing guidance for the piston to minimize secondary motion. An optimized profile will maximize the portion of the engine cycle that the piston skirt remains in the hydrodynamic lubrication regime. The friction coefficient for hydrodynamic lubrication can be one-tenth of the friction coefficient for boundary lubrication due to the effects of asperity contact. If the contact wear increases, or if the secondary motion increases, friction can increase.

The piston will typically be designed with an axial profile so that the diameter is larger in the lower regions of the skirt than at the top. This is done primarily for thermal expansion. However, this may also allow the skirt to ride over the oil film going up and scrape oil downward as the piston is moving down. These features will affect friction.

Piston profiles can also affect noise (croaking). Therefore, the profile needs to be designed for good piston stability, oil lubrication, and noise.

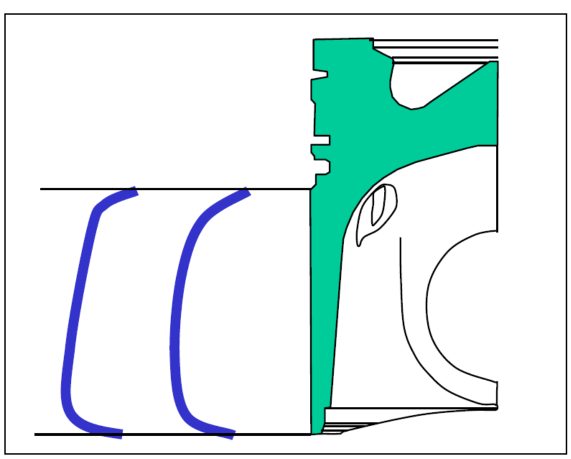

Figure 11 - Skirt axial profiles

8.5.1.5 Circumferential Contour (Cam or Ovality) (Major Effect)

The circumferential contour will affect the width of the contact zone on the skirt and directly affects the unit loads. If the unit loads increase enough to cause asperity contact, friction will increase.

The circumferential contour will affect how oil may drain downward after being scraped by the oil ring. Therefore, how the oil will drain past the piston through the circumferential contour will affect friction.

Offset of the axis of ovality can reduce the conformance of the piston to the cylinder bore and increase friction.

Offset of the axis of ovality can induce off plane forces on the rings as the piston is misguided through the cylinder, thus allowing lift off of the rings from the piston groove face(s).

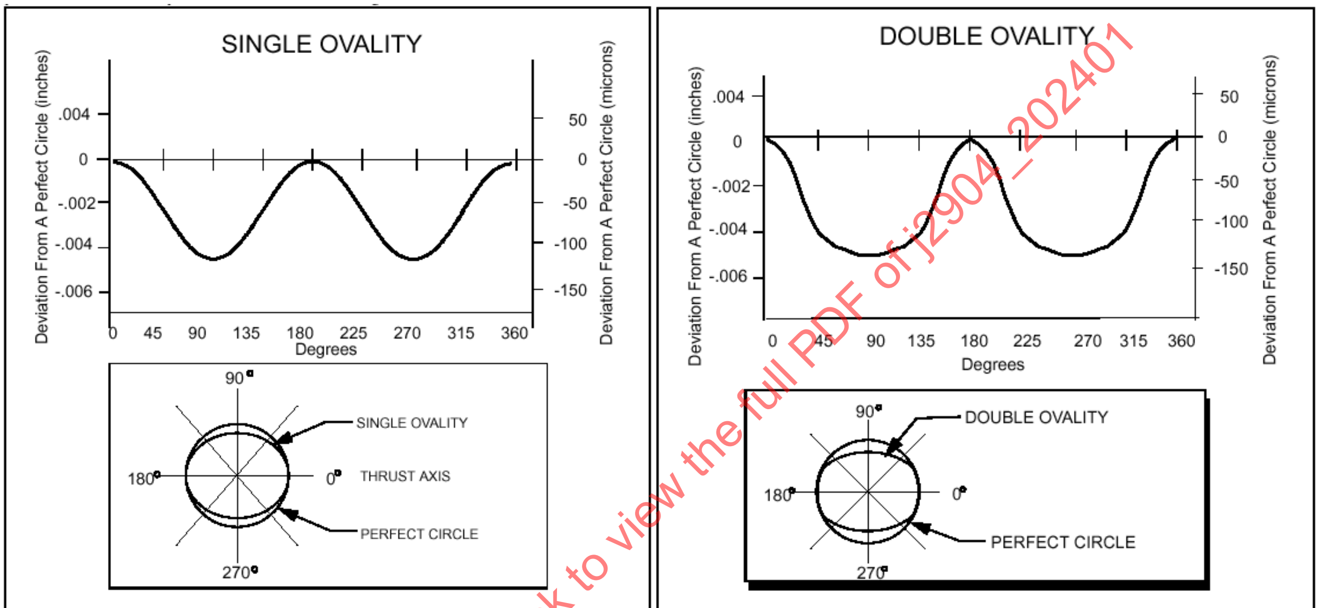

Figure 12 - Skirt circumferential contours

8.5.2 Skirt Size (Major Effect)

The size of the skirt can be defined by the length of the skirt and the width if the piston has a skirt pad (as defined with window features). The skirt size will affect the unit loads on the skirt, which affects friction. Additionally, the size of the skirt will also affect the surface area available for friction and affect the area of oil film sheared as the piston moves up and down the bore.

8.5.3 Skirt Flexibility (Medium Effect)

The skirt flexibility will affect how the oil film between the piston and the cylinder wall develops. If the skirt is too stiff, then the skirt will tend to break through the oil film in the center of the skirt. If the skirt is too flexible, it may collapse in the center, causing the skirt to break through the oil film on the edges where the pin bore makes the skirt become stiff again. When the piston skirt and the cylinder bore contact, friction will increase. Adjusting the flexibility to reduce contact will improve friction.

8.5.4 Skirt Surface Finish (Medium Effect)

If the asperity heights of the surface finish are high relative to the available oil film thickness, friction due to asperity contact will occur. Therefore, surface finish on the skirt is a medium effect on friction. The piston skirt surface finish will hold oil, which may help promote hydrodynamic lubrication.

8.5.5 Skirt Coatings (Major Effect)

If, during the motion of the piston, the piston breaks through the oil film, then piston skirt coatings may help to reduce friction by reducing the coefficient of friction between the skirt and the cylinder bore. However, if an oil film separates the piston from the cylinder bore at all times, then there will be no effect on friction.

8.5.6 Skirt Chamfer (Minor Effect)

The chamfer at the bottom of the skirt may affect the oil entrainment and lubrication of the skirt and thus might have a slight effect on friction.

The chamfer at the top of the skirt can also influence friction because of the oil reservoir that it creates.

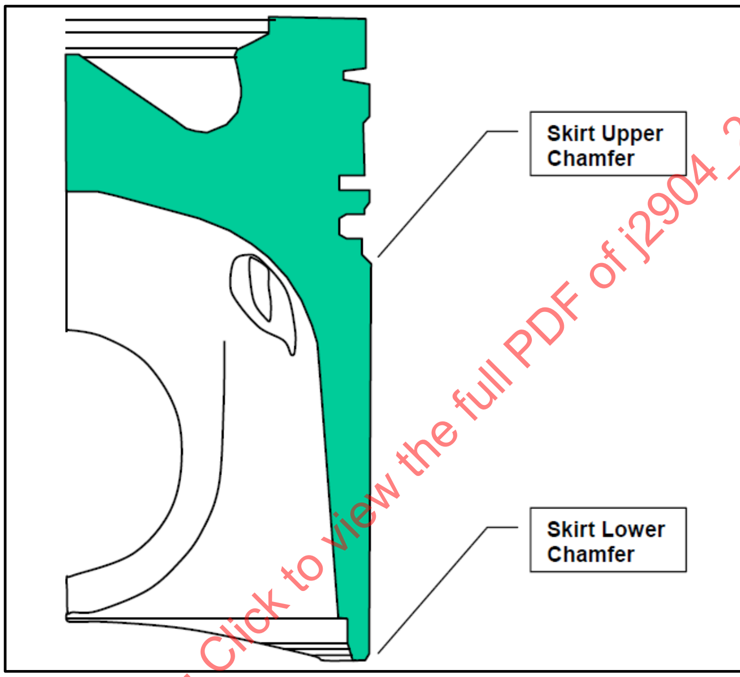

Figure 13 - Skirt chamfers

8.6 External Effects on Piston Friction

8.6.1 Crankshaft Offset (Major Effect)

The crankshaft offset can also affect the friction of the piston. The crankshaft offset will affect the piston secondary motion and thrust forces. By changing crankshaft offset, the cylinder pressure trace can be shifted relative to the connecting rod angle, thereby altering the secondary motion of the piston.

8.7 Piston Pin Bore (Minor Effect)

8.7.1 Unit Pressure on the Pin Bore (Minor Effect)

The unit pressure of the pin bore is defined as the total force pushing down on the piston divided by the projected area of the upper half of the piston pin bores. When unit pressure is too high, the piston will not be able to adequately support the loads. This can result in high friction and/or scuffing of the pin bore. This can result in increased friction in the pin bore. If this affects the motion of the piston, then the friction between the piston and the cylinder bore can be affected. Scuffing is an indication of very high friction.

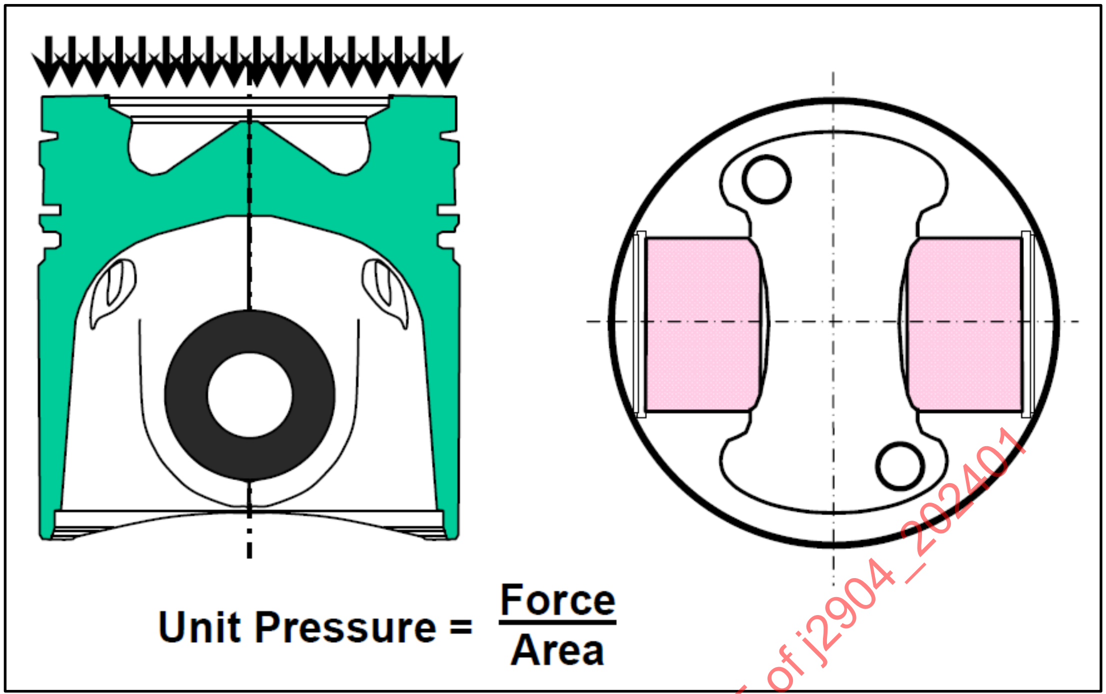

Figure 14 - Illustration of the unit pressure calculation

8.7.2 Pin Bore Design (Minor Effect)

The pin bore design will significantly affect the loading ability of the pin bore and as a result affect pin bore friction. See examples of pin bore designs in Figure 15.

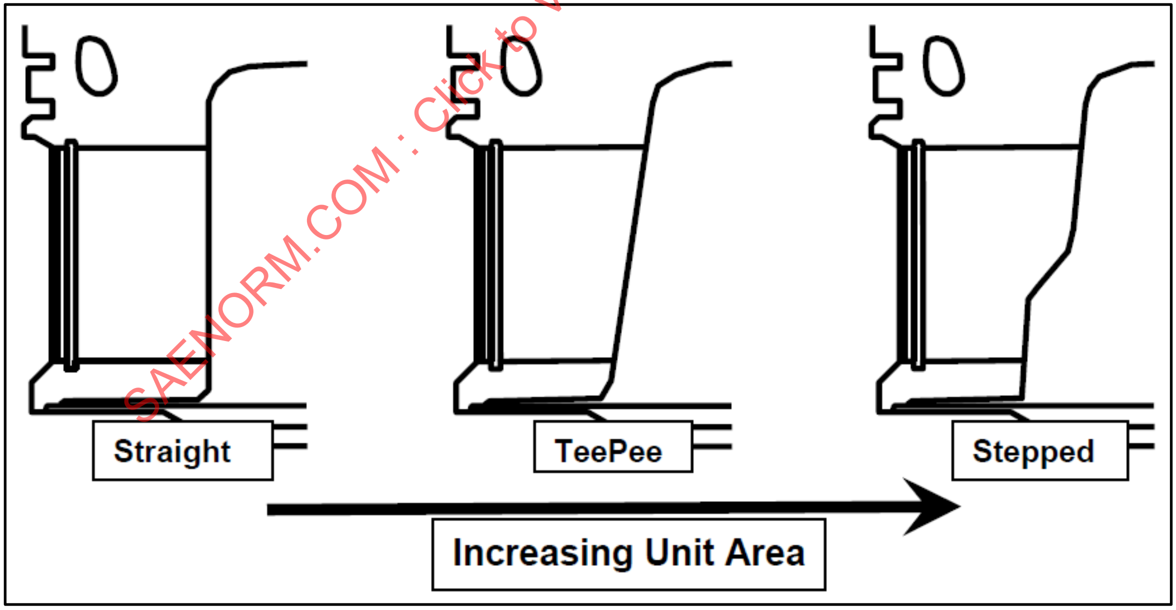

Figure 15 - Examples of pin bore designs

8.7.3 Axial Piston Pin Bore Profile (Minor Effect)

The profile of the piston pin bore will affect how the loads are distributed. Regions of high contact pressure may result in high friction and/or scuffing and pin seizure.

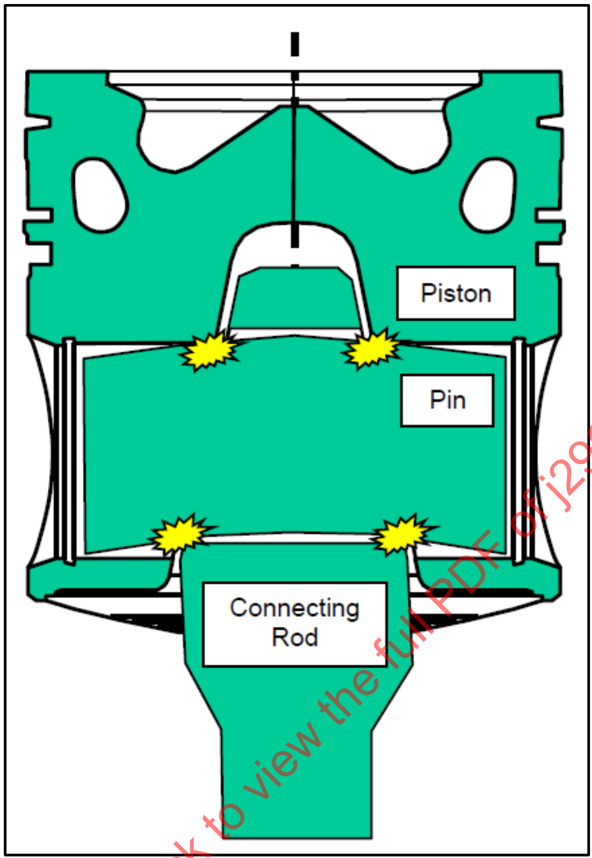

Figure 16 - Examples of pin bore contact locations

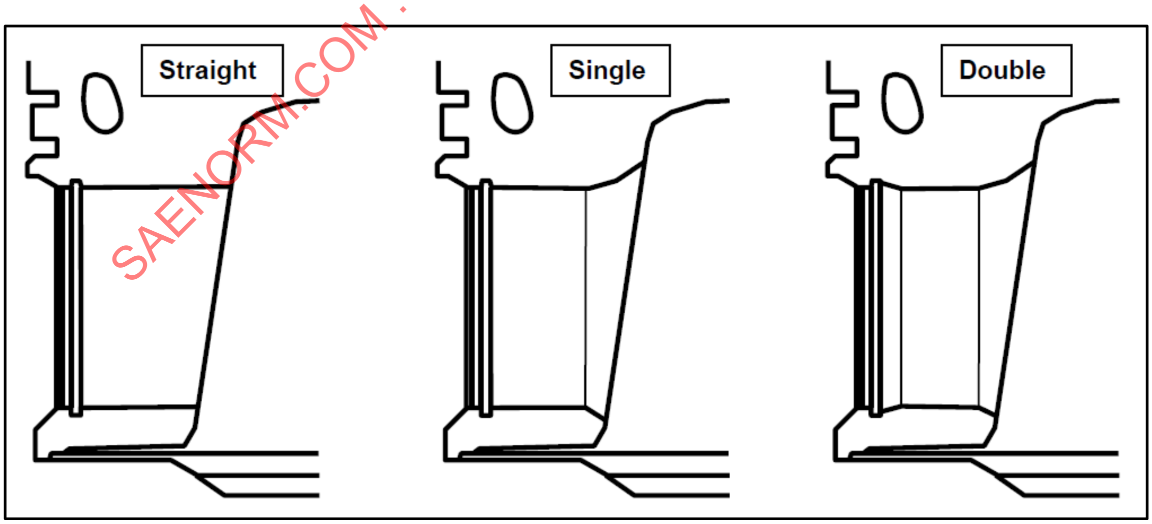

Figure 17 - Examples of different pin bore axial profiles

8.7.4 Circumferential Piston Pin Bore Profile (Minor Effect)

The circumferential profile of the pin bore will affect how well the pin bore is lubricated and also the circumferential loading patterns on the pin bore. This will affect pin bore friction. If it affects piston motion, then it will affect piston to cylinder bore friction.

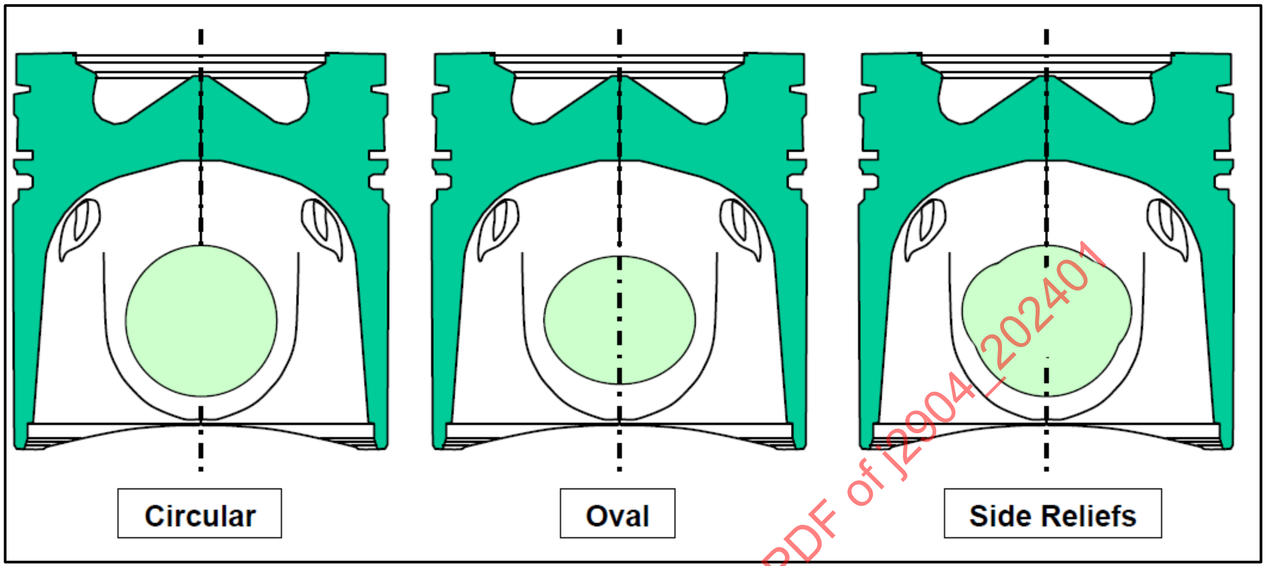

Figure 18 - Examples of different pin bore circumferential profiles

8.7.5 Pin Bore Clearances (Minor Effect)

The piston pin bore to pin clearances affect the lubricating film that will affect the pin joint friction. Smaller clearances will tend to lead to thicker oil films. However, if the clearance is too small, the parts can seize together.

8.7.6 Pin Bore Material Effect (Minor Effect)

The material of the pin bore can significantly affect the friction characteristics of the pin bore and also the scuffing potential. Pin bores may or may not have bushings. In aluminum pistons, bushings are installed typically for strength reasons. In steel pistons, bushings are often installed to improve seizure resistance.

Figure 19 - Example of an aluminum piston with pin bore bushings

8.8 Piston Cooling (Medium Effect)

8.8.1 Connecting Rod Spray and Piston Cooling Nozzles (Major Effect)

The piston may have a cooling spray under the crown of the piston or from the connecting rod (see Figure 20). It also may have a cooling gallery. The way a piston is cooled might have a major effect on friction in the following ways:

- The cooling of the piston will affect piston temperature, which will have an effect on oil viscosity. If the oil's viscosity changes, the friction associated with oil shear is changed.

- The oil spray, if reduced from design levels, may increase thermal distortions of the piston, which can cause high friction. This could result in higher skirt friction because of inappropriate local clearances and/or shapes.

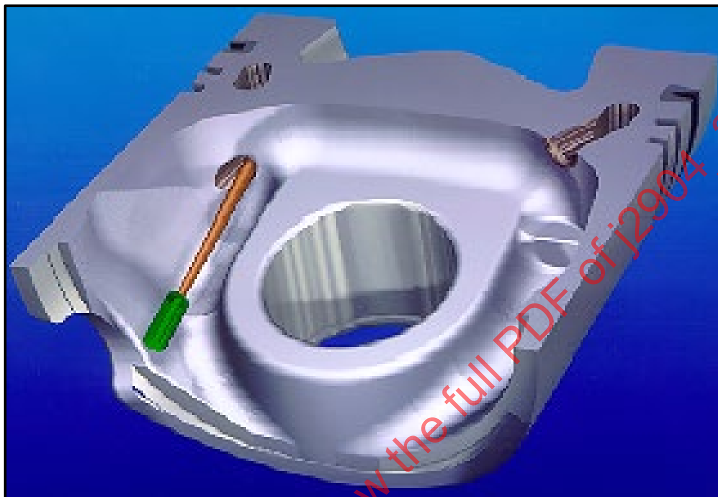

Figure 20 - Gallery cooled piston

8.9 Piston Temperatures (Major Effect)

Friction can be turned up and down by changing coolant temperature and thus the temperature of the system. Temperature and oil viscosity are inversely related.

8.9.1 Piston Thermal Distribution (Medium Effect)

The piston thermal distribution should be addressed as a system to reduce incidences and effects of incorrect clearances, excessive wear or friction, carbon buildup, and ring performance.

8.9.2 Oil Viscosity (Major Effect)

Piston temperatures will affect the oil viscosity. This will have a direct effect on friction.

8.9.3 Carbon Buildup (Minor Effect)

Carbon can build up on the piston lands. This can cause polishing of the bore surface if the carbon bridges between the piston and bore. Excessive polishing will increase friction. Sometimes a carbon scraper ring is put in the cylinder liner to scrape the carbon off the top land to prevent this carbon buildup and the resultant polishing.

9. PISTON RING EFFECTS ON FUEL ECONOMY

9.1 General Piston Rings

9.1.1 Circumferential Conformability (Minor Effect)

The conformability of a piston ring (compression ring or oil ring) might have an effect on friction. If the ring cannot conform to the distortions in the cylinder wall, it may result in areas of higher contact, which might cause friction.

9.1.2 Surface Conditions (Medium Effect)

The surface conditions of the face of the piston ring can affect friction. Rougher and harder surfaces may result in higher friction.

9.2 Compression Rings

9.2.1 Compression Ring Side Angles (Medium Effect)

The keystone ring will have a reaction force from the pressure acting on the ring in the horizontal direction (see Figure 5). This will create a higher force acting on the cylinder bore, which will result in higher friction and wear than a rectangular ring.

9.2.2 Compression Ring Closed Gap (Minor Effect)

Closed gap will affect the pressure buildup between the rings and thus affect friction because the pressure is acting on the back of the second ring.

9.2.3 Compression Ring Axial Width (Medium Effect)

A ring with a smaller axial width may have a smaller normal force and as a result less friction. This is highly dependent on the ring face design and the lubricating condition. This is because high pressure acts on the face, as well as the back of the ring. It is possible that there will be no net change in friction if there is no corresponding change in the ring face (see Figure 21).

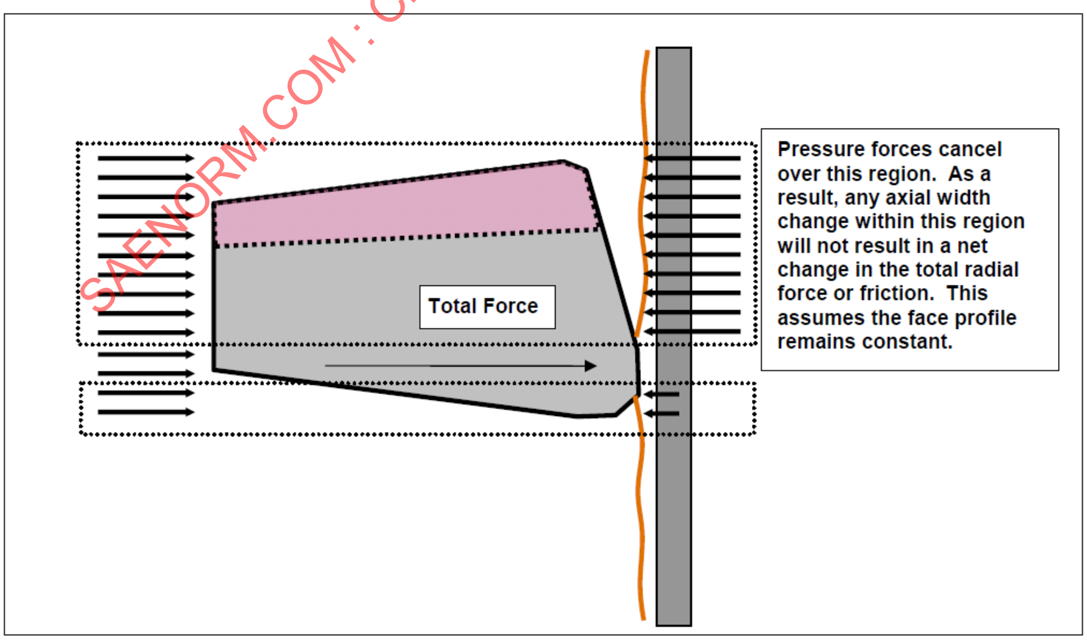

Figure 21 - Illustration of radial gas forces acting on the ring

9.2.4 Compression Ring Circumferential Shape (Minor Effect)

Compression piston rings in the free shape are not round. The circumferential shape is designed to give specific contact pressures around the ring. This pressure pattern will affect how a ring will contact the cylinder wall. It is possible to have a shape that will give regions of high pressure that might tend to break through the oil film. This will affect friction. The most common point of high contact is at the tips of the rings near the end gap.

An example of the calculated circumferential ring pressure pattern can be seen in Figure 22.

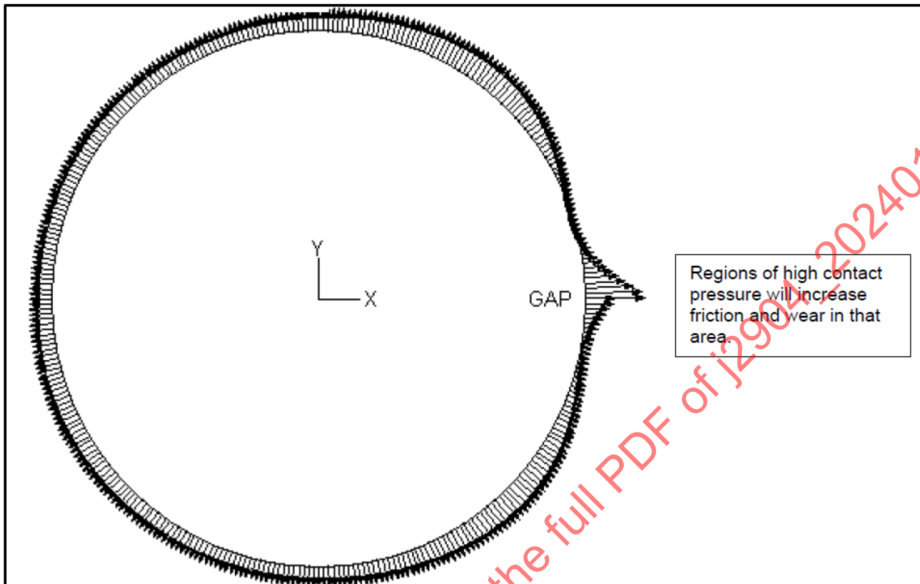

Figure 22 - Example of calculated ring pressure pattern

9.2.5 Compression Ring Tension of the Compression Ring (Medium Effect)

The tension of the ring is the force required to close a ring down to the bore diameter or gage diameter for the engine (see Figure 23). This represents the force exerted on the cylinder bore that is directly converted to friction. However, the contribution to friction is relatively small for diesel engines but is significant in gasoline engines at light load.

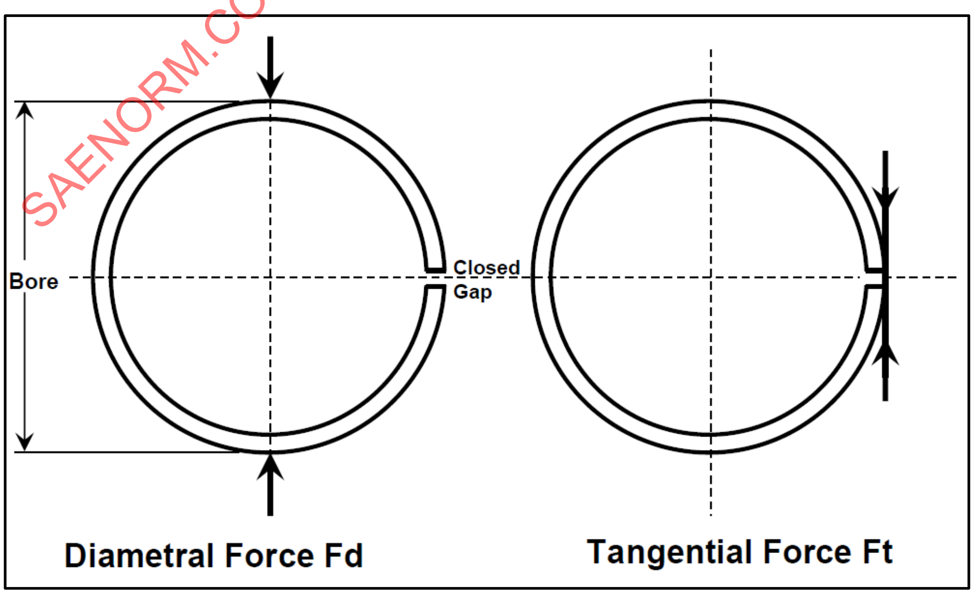

Figure 23 - Illustration of ring tension measurements

9.2.6 Compression Ring Face Profile (Medium Effect)

The profile of the ring face will determine the forces that are acting on each ring and the corresponding friction.

9.2.7 Top Compression Ring Face Profile (Medium Effect)

The top ring face will typically be barrel shaped. The top ring bears the high cylinder pressure and must be designed to develop an adequate oil film to not have excessive wear. A ring with a large barrel drop will tend to build larger oil films at mid-stroke, but these films will break down easier at the ends of the stroke. Conversely, a ring with small barrel drop will not develop as thick oil films at the mid-stroke but will result in thicker oil films at the ends of the stroke because of the squeeze film effect.

The highest friction forces occur near TDC, and this results in wear. However, friction power loss is friction force multiplied by speed. The speed is very low so the power loss is also low. At the mid-stroke, the oil films are thicker, so the friction force is smaller, but the velocity of the ring is higher. This affects friction power loss or fuel economy.

An offset barrel towards the bottom side of the ring face is sometimes used to promote oil scraping downward. This will affect the oil film and as a result the friction. Also, the higher barrel drop on the top side will allow high pressures to act on the face of the ring and counteract some of the net pressure acting on the ring. Therefore, the friction and wear may be reduced.

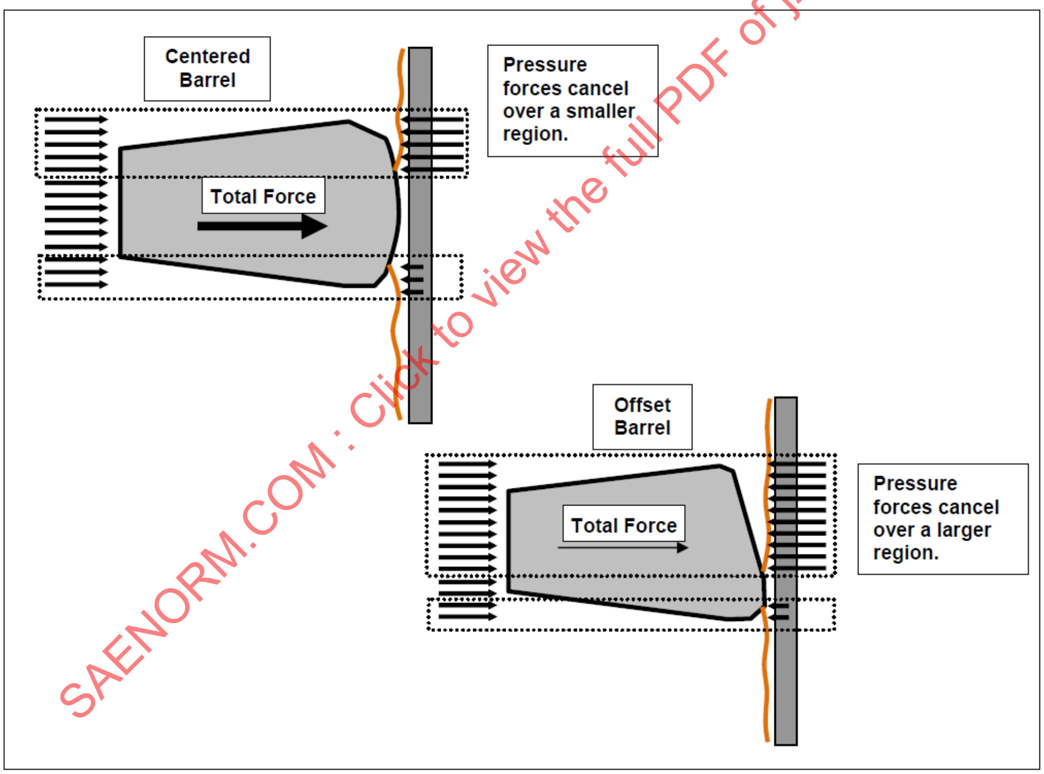

Figure 24 - Effect of face profile on net force acting on the piston ring

9.2.8 Compression Second Ring Face Profile (Medium Effect)

The second ring is not exposed to the high cylinder pressure, so a ring with a more aggressive oil scraping role can be used. The taper is designed to scrape oil as the ring moves down in the stroke and ride over the oil films on the way up. The purpose for this design is the net effect of scraping oil down away from the top ring. Therefore, the main effect of the taper faced second ring occurs when the ring is moving down because the ring is breaking through the oil film to scrape the oil downward. However, the overall friction of the second ring is not very large.

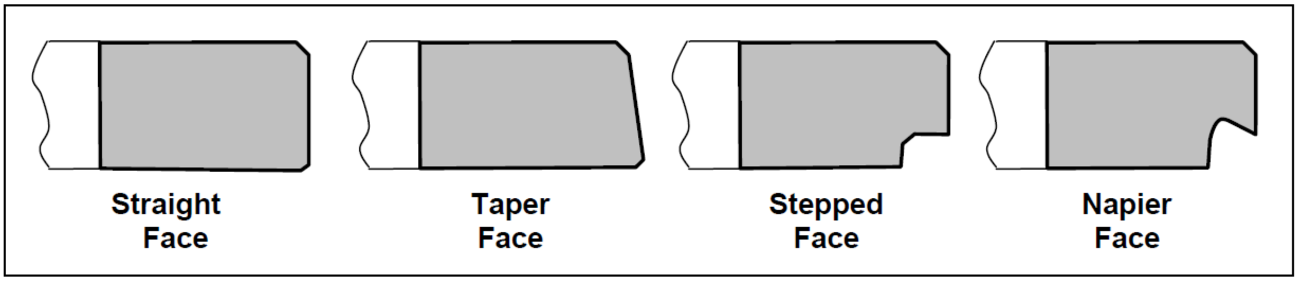

Figure 25 - Second ring face profiles

9.2.9 OD Chamfers (Minor Effect)

The bottom outside diameter chamfer on the ring face may affect the oil film developed. A sharp bottom side edge, particularly on the second ring, may break through the oil film and affect friction. Since the effect of friction is small, the benefit that this gives for oil consumption may make this feature desirable. Figure 26 shows a schematic of the OD chamfer.

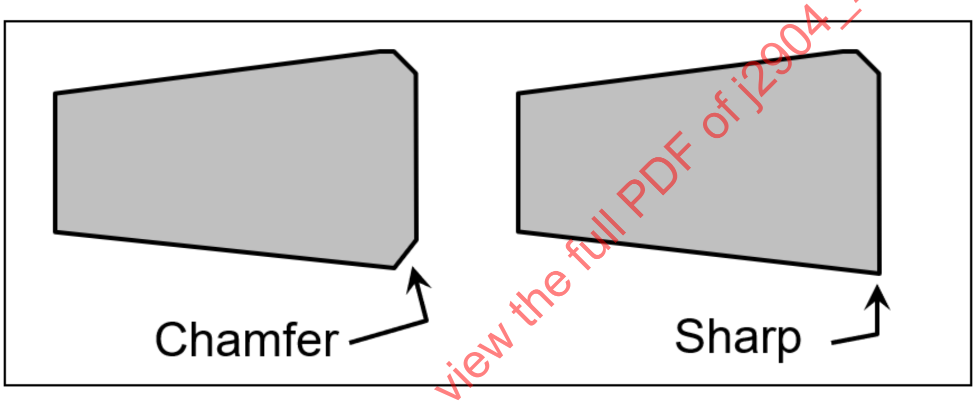

Figure 26 - Schematics of bottom side OD chamfers

Figure 27 shows different types of ring coatings. Typically, it is possible to get a sharper bottom outside diameter chamfer on rings with the semi-inlaid or inlaid coatings. The inlaid processing easily accommodates the sharp bottom corner because the bottom edge is the base iron material. If a coating is on the lower edge, a larger chamfer is typically required.

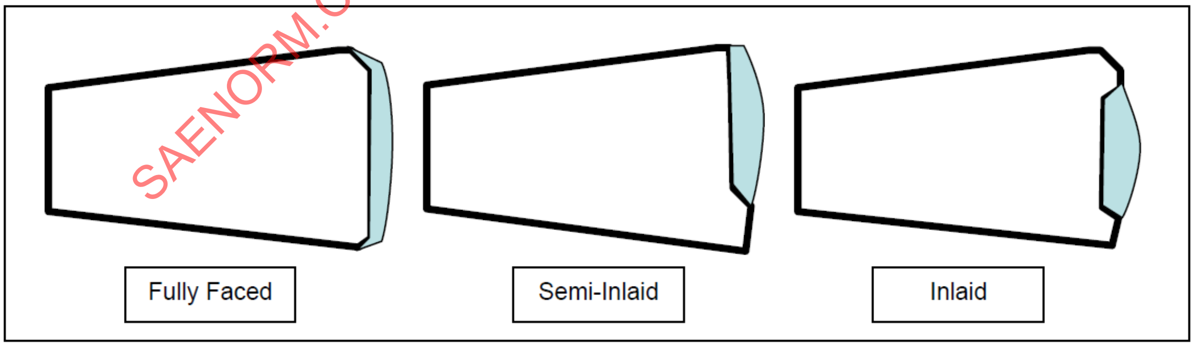

Figure 27 - Ring coating application examples

9.2.10 Roughness (Medium Effect)

The roughness of the ring face will affect friction when there is contact between the ring and the cylinder bore. This typically occurs at TDC. Higher roughness will result in higher friction.

9.3 Ring Materials (Medium Effect)

9.3.1 Piston Ring Face Coating Material (Medium Effect)

The piston ring face material will affect the coefficient of friction between the ring and the cylinder bore. This will affect the friction primarily at TDC. However, as mentioned above, while the friction forces may be high at TDC, the friction power loss (friction multiplied by speed) is lower.

The face coating will also affect the wear characteristics of the ring. As the ring wears, it will change the face profile on the ring, which will affect friction.

In general, diamond like carbon (DLC) and physical vapor deposition (PVD) coatings will have a lower coefficient of friction and lower friction.

9.4 Oil Ring

The oil ring is a significant contributor to friction. Because of the low surface area and high tension on the ring, it will easily break through the oil film. This is good for oil consumption but results in friction. Since this occurs over the entire stroke, the results on friction power loss are high.

9.4.1 General Oil Ring

9.4.1.1 Unit Pressure (Major Effect)

The unit pressure of the oil ring is critical for good oil control. The unit pressure is defined as:

$$\text{Unit pressure} = (\text{Tension})/(\text{Bore diameter})/(\text{Oil ring land width}) \qquad \text{(Eq. 1)}$$

This represents the pressure that the ring exerts on the cylinder wall. Sufficient unit pressure is needed to allow for good ring scraping of oil. However, a ring tension that is too high will result in high friction and wear. Therefore, the oil ring unit pressure design is a trade-off of low oil consumption and low friction.

Over time, the spring force acting on the oil ring will decrease because of wear on the ring body. As a result of the wear, the spring is no longer confined to the same area it was before and the force decreases. Eventually, this will cause an increase in oil consumption and a decrease in friction. This loss in ring tension should be considered in planning the life of the engine.

9.4.1.2 Oil Ring Tension (Major Effect)

Oil ring tension has a significant effect on the scraping ability of the oil ring. Increasing oil ring tension will force the ring to conform to the cylinder wall distortion better and as a result will reduce oil consumption. Once the ring has sufficient force to conform to the distortion of the cylinder, increasing tension will not decrease oil consumption anymore. However, increasing oil ring tension will also increase friction. Therefore, the tension of the oil ring should be just high enough to ensure adequate oil consumption and no higher to keep friction at acceptable levels.

9.4.1.3 Oil Land (Rail) Width (Major Effect)

The combination of the oil ring land width and oil ring tension control the unit pressure of the oil ring. This has a major effect on friction. The thinner the ring, the easier it is for the ring to break through the oil film. This is good for oil scraping but will cause friction (see 9.4.1.1).

9.4.1.4 Body Design (Major Effect)

The shape of the oil ring body or rail will significantly affect the conformability of the ring. The material of the body will significantly affect what shapes can be made for the body. Therefore, the material and shape combination can significantly affect conformability. If the ring cannot conform to the distorted bore sufficiently, then tension on the ring will need to be increased until it can. This will result in higher friction. A more conformable body design will require less tension and as a result lower friction.

9.4.1.5 Overall Oil Ring Width (Medium Effect)

The axial width of the oil ring will affect how the lands or rails contact the cylinder wall. The smaller the axial ring width, the more the lands or rails will stay in contact with the cylinder wall and thus scrape oil better. This may also affect friction.

9.4.2 Oil Ring Face Coatings

The face coating of the oil ring can affect fuel economy. DLC and PVD coatings are considered to have low friction and better fuel economy.

9.4.3 Two-Piece Oil Ring

A two-piece oil ring is typically used by diesel engines and in some gasoline engines. The two pieces are the body of the oil ring and the spring expander.

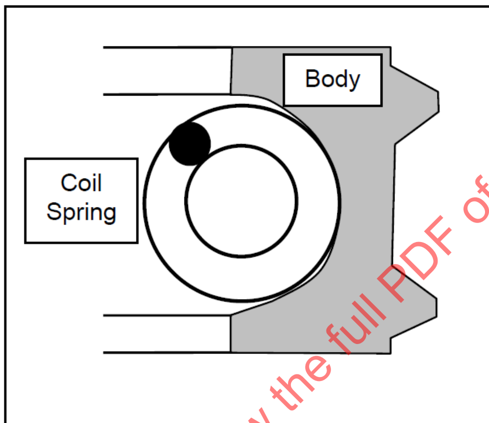

Figure 28 - Two-piece oil ring

The oil ring body is usually composed of two narrow lands or rails. Since these are narrow, they will tend to break through the oil film and scrape the oil off the cylinder wall. In most cases, the land profiles are flat. In some cases, the face profiles of the rings are tapered to enhance the downward scraping of the ring. How the rings break through the oil film will affect friction. Tapers on the face of the lands may improve short-term oil consumption and increase friction until the taper wears away.

The spacing between the lands will have an effect on how the ring scrapes the oil off the cylinder bore. The closer the lands, the more contact both lands will have while moving up and down in the bore. This will improve the scraping ability of the ring but at the same time affect friction.

9.4.4 Three-Piece Oil Ring

The three pieces of this type of ring are two rails and an expander spring. The expander spring has the effect of not only pushing the two rails radially against the cylinder wall but may also push axially against the ring groove depending on the lug design. The lug angle determines the amount of force that the rails apply to the sides of the oil groove. The force will affect how the ring seals the flow of gases and oil around the sides of the ring and will thus affect oil consumption. The side forces acting on the groove may affect the radial force of the oil ring and thus affect friction.

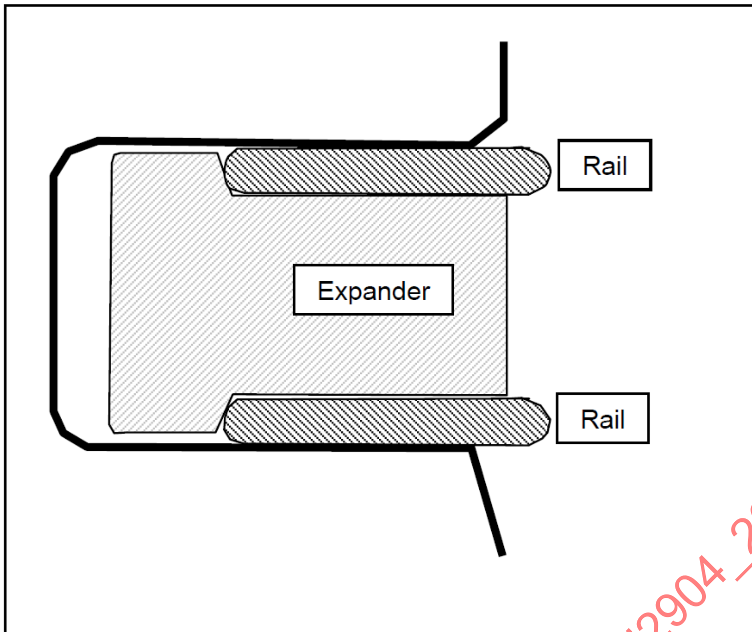

Figure 29 - Three-piece oil ring

10. CYLINDER BORE EFFECT ON FRICTION

10.1 Cylinder Bore Surface Finish (Minor Effect)

The surface finish of the cylinder bore and honing patterns affect how oil is retained on the cylinder bore and the development of the oil film. Therefore, it will affect friction. Sufficient oil needs to remain on the cylinder bore to adequately lubricate the ring and prevent scuffing or high friction. Rough surfaces will retain too much oil that might be consumed and cause high oil consumption. The rougher surface will provide more surface asperities that can interact with the rings and therefore have a higher sliding friction.

10.1.1 Peak Honed Bore Surfaces (Major Effect)

In automotive engines, it is common to have very smooth surface finishes on the cylinder wall to reduce oil consumption. The finer surface finish will have a lower sliding friction with the piston rings.

A critical measurement of the smooth bore surface finish is the roughness parameters, such as Ra or Rk, and some indication on the oil retention, such as Vo.

10.1.2 Plateau Honed Surface (Major Effect)

In diesel engines, it is common to have plateau honed surfaces. This is a surface composed of a smooth plateau surface with periodic deep valleys. This surface is produced by first a rough hone followed by a fine hone process.

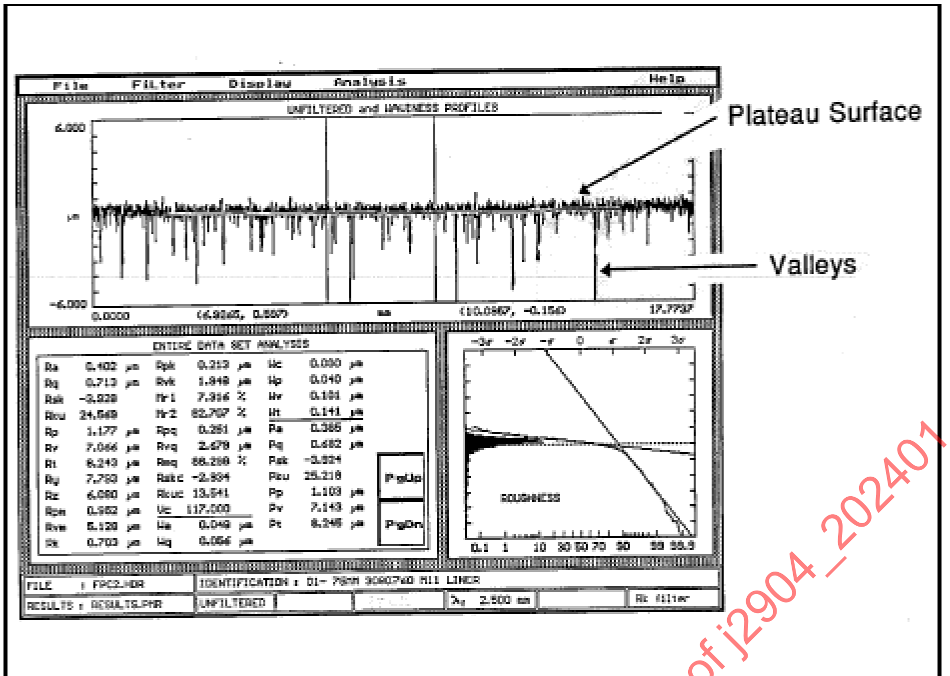

Figure 30 - Plateau honed surface

The valleys in a plateau honed surface are what provide the oil entrainment on the cylinder bore so that oil will be present during the piston stroke. The oil retention in the valleys can affect the long-term durability of the cylinder wall.

The smoothness of the plateau portion of the surface will affect oil consumption and friction. A surface that is too smooth may affect the scuffing potential of the surface, but a smooth plateau will minimize the sliding friction of the power cylinder system.

The critical measurement parameters for the plateau honed surface are parameters that characterize the roughness of the plateau and the valleys, the valley density, and bearing ratio of the surface.

10.1.3 Textured Surface (Medium Effect)

Cylinder bore surfaces using advanced texturing techniques such as dimpling, laser texturing, etc., have shown the potential for friction reduction. Texturing of the cylinder bore is typically focused on the top ring reversal region where the top ring breaks through the oil film. This is often combined with a very smooth surface outside the texture region.

10.1.4 Surface (Major Effect)

The surface condition of the cylinder wall can have a significant effect on oil consumption, friction, and wear. Excessive torn and folded material on the surface will result in high oil consumption and friction.

10.2 Cylinder Bore Honing Angle (Minor Effect)

The honing angle will affect how oil flows along the bore surface. A more horizontal honing may retain oil better. This may reduce friction but could possibly increase oil consumption. A more vertical angle may allow more oil to flow upward or downward.

If the honing angle affects the bore distortion, then this should be considered for its effect on friction. For example, if a more horizontal crosshatch angle tends to result in increased axial bore distortion, this might cause higher friction. If the steeper angle promotes more uniform axial cylindricity, this might improve the friction.

As the surface finish becomes smaller, the effect of the honing angle might be less significant.

10.3 Bore Distortion (Medium Effect)

If the ring cannot conform to the circumferential distortion of the cylinder bore, then there will be regions of high contact between the ring and the cylinder wall, which may result in higher friction (see Figure 31). The rings will be less likely to conform to any higher order distortions than a simple oval. The tension required in the rings to create a seal is a function of the roundness errors in the cylinder bore. Higher order distortion (fourth order and higher) is more difficult to seal, so for a low friction assembly, it is important to minimize this distortion.

If there are axial distortions in the ring travel region, the rings might not be able to expand and contract fast enough to follow the contour. This might cause an excessive force on the ring not being able to slide smoothly over the distortion.

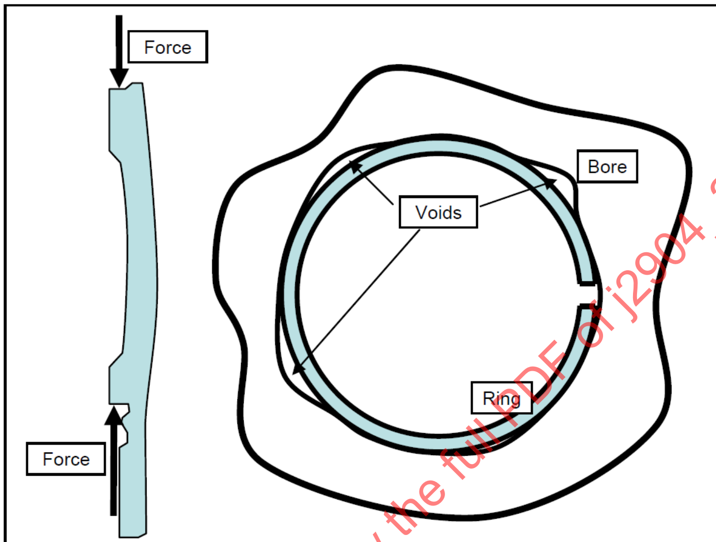

Figure 31 - Examples of the effects of bore distortion

It has been found that the distortion of the cylinder bore can change during engine operation. This is due to dynamic and thermal loading due to combustion in the cylinder. It is also possible that a growing permanent deformation has led to continuously deteriorating friction values.

Circumferential bore distortion can be analyzed using Fourier analysis to separate the various orders of distortion. The ring will not be able to conform to the higher order distortion. As a result, the acceptable levels of distortion will be lower at the higher orders of distortion.

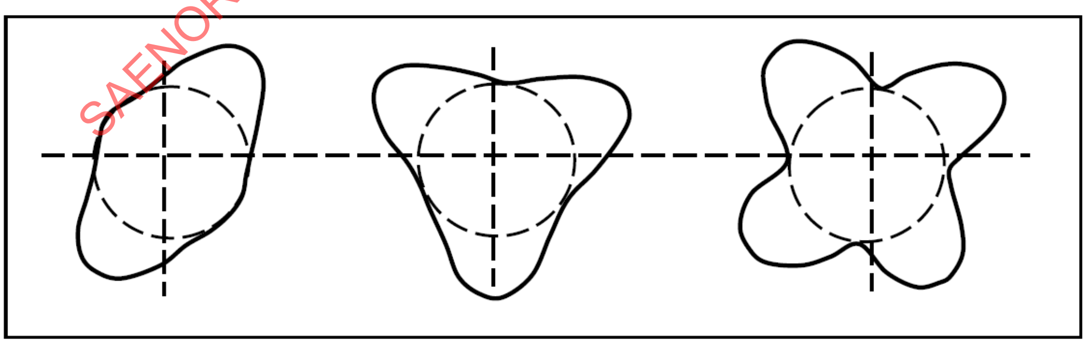

Figure 32 - Different orders of bore distortion