Chapter 16

Applications of Tribology on Engine Performance

Sangeeta Das and Shubhajit Das

Abstract The improvement of engine efficiency has been of utmost necessity for automobile industries in order to control the increasing climate change and greenhouse emissions. Hence, the fuel efficiency may be increased by minimizing the energy losses from the engine. In spite of wide applications of reciprocating internal combustion (IC) engines in most of the ground and sea transport vehicles and electrical power generations, they have several shortcomings. The IC engines possess low thermal and mechanical efficiencies due to increased loss of fuel energy as heat and friction. They also release a substantial amount of particulate and NO_x (nitrogen oxide) emissions that gives rise to greenhouse effect. Amongst the various approaches of improving engine efficiency, the tribologists and lubrication engineers focused mainly on reduced engine friction as a vital and economic method. The achievement of efficient lubrication of moving engine components with least or no unfavorable effect on the environment is important to lessen friction and wear. The improvements in different tribological engine components and additives may lead to reduced fuel consumption, exhaust emissions and maintenance along with increased engine power outputs and durability. The tribological performance of an engine can be improved by employing materials of superior tribological properties for manufacturing different mechanical parts, improved surface coatings as well as developed lubrication technologies. This chapter presents the details of various components of reciprocating IC engines as well as the lubricants used and the remedial measures to reduce the engine wear and friction.

Keywords Internal combustion engine · Tribology · Engine efficiency

---

S. Das (✉)
Department of Mechanical Engineering, Girijananda Chowdhury Institute of Management and Technology, Guwahati, Assam 781017, India
e-mail: sangeeta_me@gimt-guwahati.ac.in

S. Das
Department of Mechanical Engineering, National Institute of Technology, Yupia, Arunachal Pradesh 791112, India

J. K. Katiyar et al. (eds.), *Automotive Tribology*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-15-0434-1_16

16.1 Introduction

In today's world, the automotive engine technology is mainly governed by two factors, viz. environmental safety and consumer gratification (Nakada 1994). Hence, the development in the field of automobile industry takes place based on the compatibility between efficient energy use, safety measures and environmental impacts. Due to increased environmental and safety issues, there exists various strict standards for fuel efficiency, emissions, safety and durability. However, the ever-increasing consumer demands on greater trustworthiness, reduced maintenance, better comfort and reduced fuel consumption leads to the developments of newer technologies for better fuel economy that satisfies both consumer and environmental issues.

The fuel efficiency can be increased and the amount of fuel required to drive a vehicle can be decreased by minimizing the energy losses from the vehicle. The engine performance is optimized by improving its tribological performance to improve fuel efficiency as most of the energy is lost from the engine itself. The different tribological engine components involving interacting surfaces are bearings, pistons, transmissions, clutches, gears, wiper blades, tyres and electrical contacts. Moreover, good lubrication between moving and interacting parts of an engine helps in improving the performance of an internal combustion (IC) engine. Recently, nano lubricants are an emerging technology in the field of automotive lubricants. The lubricants must be able to resist high temperatures, and be stable under engine conditions. There is a requirement of new tribo-materials for automotive components that runs at higher temperatures and pressures. Furthermore, the tribological behavior of existing materials for various tribo-components can be improved by means of surface coating.

16.2 Automotive Tribology and Its Importance

The major power units in most petrol and diesel engines are the reciprocating IC engines because of its extreme reliability and versatility characteristics. In spite of this, it has several drawbacks that may influence the national and international economies. The drawbacks are low thermal and mechanical efficiencies of the IC engines due to loss of a significant fraction of the energy of fuel as heat (Taylor 1998). As a result, a large amount of fuel needs to be consumed to overcome the losses that lead to the emission of enormous harmful particulates, nitrous oxide and hydrocarbon and can cause greenhouse effect. The mechanical losses are mainly due to the frictional losses between the piston rings and the cylinder liner assembly. The most of the chemical energy of the fuel gets converted into thermal energy and then to mechanical energy in the cylinder and piston assembly of the IC engine (Kumar et al. 2018). A little wear of material from the moving parts in IC engines can decrease the performance or even entire breakdown of the engine. The consumption of 12–13 MBBL/day of oil by nearly 250 million of vehicles on US road is lost in overcoming engine friction (~10%) and friction in the driveline (~5%). Thus, the petroleum consumption can be reduced from 150,000 to 200,000 BBL/day by reducing the engine and driveline friction by 10% (Fenske 2014). Hence, the concepts of tribology need to be developed to lessen the coefficient of friction (COF) and wear at the interfaces of various moving components of an IC engine.

The theories of tribology can be used to deal with a minor problem that may arise at the level of structural integrity of the moving parts of an IC engine. Otherwise, the consequences of the damage of the moving components itself may lead to the entire failure of the engine. A significant development in tribology leads to systematic design and performance analysis based on the stress-strain study of the various moving components of an IC engine. At present, the engine components are not required to be lubricated with oil or grease very often and that has been possible due to the proper understanding of the working of the tribological components and their design analysis. It is achievable due to the better understanding of the effect of viscosity and the mechanism of generation of effective lubricant film thickness between the moving contacts. The tribology can be successfully applied to each and every engineering component in moving contact and hence can be used for enhancing the performance of engines. The benefits of improved tribological performance includes low fuel intake, high engine output, reduced harmful exhaust emissions and maintenance to design highly durable and reliable engines.

16.3 Components of IC Engine Subjected to Friction and Wear

The stringent government regulations for fuel emission and economy have motivated the need for engine friction mechanism research aiming for higher efficiency, reliability and performance. An engine's mechanical efficiency is directly compromised by frictional losses, since power is wasted to overcome friction within the engine. Thus, it is important to reduce the engine friction which will lead to increase the fuel economy. The IC engine manufacturers encounter complex design considerations due to change in engine components temperature. During operation, the engine components become relatively hot due to friction and combustion of gases within the cylinders. The lubrication conditions also change due to change in oil viscosity. In an IC engine, out of all the energy losses, frictional loss alone is in the range of 4–15% (Kumar et al. 2019). A large amount of fuel energy is wasted in the form of heat losses. The mechanisms that cause mechanical loss in engines include piston-crank mechanism, piston ring-cylinder-liner fuel pump and other auxiliary assemblies. The numerous parts of the IC engine rely mainly on the interaction of their surfaces to function. These includes many tribological components such as bearings, pistons, clutches, gears, transmissions, wiper blades, tires and electrical contacts. The losses contributed by different engine components are shown in Fig. 16.1.

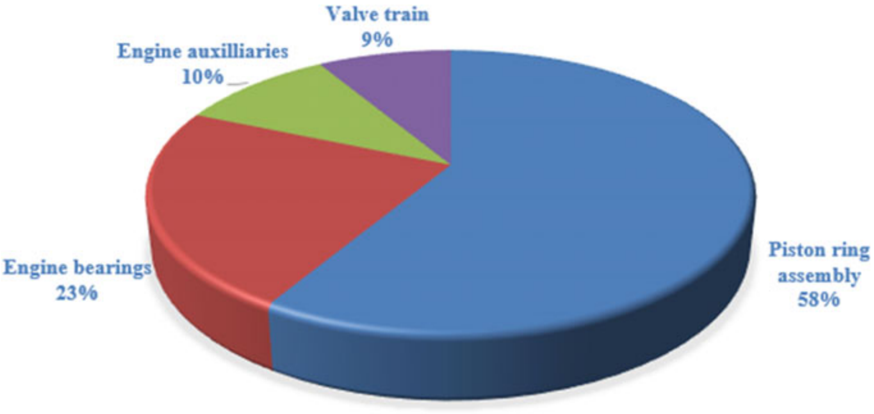

Fig. 16.1 Approximate quantities of losses in different engine components

16.3.1 Piston Rings

One of the important elements in the IC engine are the piston rings. The sliding surfaces between the piston rings and the cylinder liners may be among the most complex tribological phenomena in the IC engines. It is even more severe with an increase of the engine power. The piston assembly comprises sliding between the cylinder walls and the reciprocating piston and also sliding between the piston pin and the piston bore. The friction between the piston rings and the cylinder liners significantly contribute to the mechanical power losses of the engine. Sliding between piston ring and cylinder wall is often said to be the largest contributor to frictional energy losses (Rosenberg 1981; Wong and Tung 2016). It is also the contact where the wear problem called scuffing sometimes occur in the marine low speed, two-stroke engines. A piston ring acts as a dynamic seal as it slides against the wall of the cylinder bore. The main function of the piston rings is to facilitate smooth running of the reciprocating parts. It aids to prevent the escape of the combustion gases into the crankcase from the combustion chamber. It also prevents leakage of the lubricating oil into the combustion chamber from the crankcase. To keep friction and wear low, the seal is normally lubricated. The lubrication should be controlled such that excessive oil does not remain on the walls as it leads to high oil consumption due to evaporation and combustion. Also, there is transfer of heat by the rings from the piston to the liners which stabilizes the piston in the cylinder bore. Loss of energy to friction between piston ring and cylinder liner constitutes 20–40% of total mechanical losses and is regarded as the greatest mechanical loss (Cakir and Akcay 2011).

Friction is important in terms of engine efficiency and fuel economy. The kinetic energy that is lost due to friction is mainly converted into heat that is conducted away. It also results in vibration and emission of sound, both leading to dissipation of energy. Some of the energy is converted within the material surfaces and wear debris by plastic deformation, material intermixing and tribo-chemical reactions. In an IC engine, the sliding velocity, load and viscosity are dynamic and change rapidly. Other parameters like piston ring shape, surface topography, oil availability, ignition timing, secondary motions of the piston and piston rings and properties of the surface layers affect the mode of friction level. The strongest wear of the cylinder liners takes place on top of the piston ring, where the chemical, thermal, erosive, abrasive and adhesive conditions are the severest. At low cylinder surface temperatures, the tribo-chemical wear of the cylinder liner increases drastically due to increase in Sulphur content of the fuel. There are five forms of wear that occur in IC engine components namely abrasion, adhesion, fatigue, corrosion and lubrication breakdown. Abrasion, adhesion and fatigue involve mechanical damaging of surfaces. The wear rate in the piston ring/cylinder wall is generally in the range of nm/hour, which is comparatively very low (Shakhvorostov et al. 2006; Scherge et al. 2006; Dienwiebel et al. 2007). If hard particles get into the lubricating oil, abrasion can lead to high wear rates.

Adhesion is that part of the wear leading to material being moved around rather than removed. Adhesion is also part of scuffing failure, although the scuffing procedure is more complex than only adhesion. Tribo-chemical wear or corrosion is also important especially in the marine engine running on heavy fuel oil, which has a high sulphur content leading to high levels of sulphuric acid in the combustion chamber. Decreasing the friction in the piston assembly is an important way of improving the mechanical efficiency. A 10% reduction in mechanical losses can reduce fuel consumption by 1.5–2.5% (Andersson 1991; Mishra et al. 2009). With increase in the engine power, the tribology of the sliding surfaces of piston rings and cylinder shows extremely complicate phenomena. Due to dynamic operating conditions in IC engines, changes occur in the lubrication regime depending on the position of the piston in the cylinder. When the piston changes direction, at dead center, the friction coefficient increases due to zero piston speed. The hydraulic lubrication regime changes to mixed lubrication or limit lubrication regime. Cold starting, speed changes, sudden loads are some of the factors which cause changes to the lubrication regime in IC engines (Taylor 1993; Priest and Taylor 2000). It is always preferred to have a hydrodynamic oil film at the interface between the rings and the liners as the performance, durability and exhaust emissions are greatly affected by it.

Wear of the cylinder liner is caused to a great extent by the action of the piston rings. A higher friction coefficient in IC engines also increases loss of material due to wear of component surfaces. The wear of piston rings and cylinder liner increases due to three body abrasive wear caused by the presence of small amount of solid particles in the lubricating oil, which are added by component wear, ambient air dust particles and contaminants from the oil sump or combustion chamber. A good lubricating property of fuel plays an important role in reducing wear and friction losses. Strong adhesive forces between the piston rings and liner occur due to inadequate lubrication, leading to high frictional losses and metal scuffing, resulting in high wear. Apart from sliding wear, piston ring surfaces degrade due to blow by of hot gases from the high temperature combustion chamber, which carry soot along with them. Improving the lubricating properties of the fuel will reduce the mechanical friction losses within the fuel pump.

16.3.2 Journal Bearings

Engine bearing performance is affected mainly by mechanical configuration and hydrodynamics of the oil film. In plain journal bearing, the hard shaft rotating in a soft bearing shell are separated by a lubricant. The journal bearings mainly operate in pure hydrodynamic lubrication regime for increased life span. But then, in present automobile industry, there is a necessity of fuel consumption and emissions due to restrictions by legislation and customer satisfaction. Studies suggest the journal bearings must be operated in the transition between pure hydrodynamic lubrication and mixed lubrication regime to reduce friction coefficient. However, this may lead to wear and durability problems due to metal-metal contact. Thus, efficient journal bearings can be designed using simulation approach that can describe complex behavior of mixed elasto-hydrodynamic lubrication for a wide range of operating conditions (Sander et al. 2016). Journal bearings including those of the connecting rods, camshaft and crankshaft are affected by dust particles. The hard contaminant particles, which get into the clearance between the journal and the bearings, are pressed by the harder surface into softer surface leading to abrasive wear. The particle size has a major effect on the wear of the engine bearings. The most severe wear in the bearing is caused by particles with sizes in the range from 10 to 35 μm. The bearing location affects the wear rate in connecting rod bearings. A reduction in the sliding surface area of the crankshaft or connecting rod bearings or increasing bearing clearance will reduce engine friction. However, these methods increase the possibility of wear, seizure or knocking in the bearings.

In recent trends, the engine downsizing leads to smaller engines and its components that results in higher stresses on the components and the lubricated contacts. For example, the big-end bearing of the connection rod has to withstand specific loads above 100 MPa that may expect to increase in future. As a result, the lubrication gap in journal bearing decreases below 1 μm that may cause metal to metal contact. With the increasing use of start-stop cycle, the bearing wear accelerates as the bearing has to overcome the boundary and mixed lubrication regime at the starting of the engine before a hydrodynamic film has formed (Sander et al. 2016). The prediction techniques used in engine bearing has been improved in recent years due to augmented computing power and precise methods that directly benefits the designer. Due to this, more realistic bearing conditions can be considered and better bearing performance prediction is possible. The use of computer aids in presenting data in an improved way for good interpretation of the results (Martin 1983). The journal bearing design approaches to reduce power loss and increase load carrying capacity include artificial texturing, axial and circumferential grooves and bushing specific shapes (e.g. three-lobe bearings) (Bompos and Nikolakopoulos 2016). Ghorbanian et al. (2011) studied a problem of complex hydrodynamic modeling of journal bearings in IC engines along with an optimization process described by numerous variables and constraints that are to be parallelly modified and satisfied.

A ratio of bearing length L and bearing internal diameter D in the range of 0.4–0.6 is normally preferred for dynamically loaded bearings. This is because any value below this range will cause excessive loss of lubricants from the ends of the bearings. On the other hand, any value above this range may result in alignment problem that may lead to edge loading. With high value of diametral clearance, there occurs a reduction in load carrying capacity, oil whirl, excessive damage to due to cavitation erosion, etc. In contrast to this, a low diametral clearance value restricts the quantity of oil flow in the bearing that increases the lubricant temperature and reduces its viscosity that in turn reduces the film thickness. In actual practice, it is impossible to achieve an ideal single clearance value due to inevitable limitations in manufacturing processes. Hence, the engine bearing must be designed for maximum and minimum values of clearance (Hirani et al. 1999). In practice, impairment of a bearing may often be the outcome of several mechanisms operating concurrently. The related literature and real-world experience show that the plain bearing damages are mainly triggered by wear, either as a direct cause or as a result of various anomalies in design, manufacture, assembly, operation and maintenance of the engine and bearings. The wear is a very complex process originated by the act of different mechanisms, and can be established by different wear types which are often related: adhesive wear, abrasive wear, surface fatigue wear, erosive wear, cavitation wear, fretting wear, oxidative wear and corrosive wear (Vencl and Rac 2014).

16.3.3 Valve Train

The operating conditions of modern engine valve trains are becoming severe due to design alterations driven by different parameters like increased fuel economy, environmental policies and higher output. The valves damage during operation due to abrasive wear of the seat face and the stem, stem corrosion, damage of the seat face caused by products of combustion, damage of the seat face caused by blobby exhaust gases and burning, bursting of the seat face, and breakage of the valve head or the stem. These types of damage arise due to physicochemical interactions of the working medium at high temperature. They are also the result of mechanical stresses caused by the occurrence of excessive temperature gradients (Siczek 2016). In conventional engine design, the cam and follower slide over each other under the boundary lubrication condition. At low camshaft speed, valve train friction can contribute significantly to overall engine friction. To reduce the cam and follower wear, roller followers were used instead of slipper type of followers in some of the production engines. Valve train design with the roller follower type is now becoming popular in order to reduce friction in valve trains where the friction is reduced by half. The performance of roller follower valve train is subjected to rotational efficiency of rollers that is mainly governed by oil film thickness. The best way to reduce the friction at cam/tappet interface is to replace the conventional flat faced tappet with roller followers (Khurram et al. 2019). In a valve train, the valve spring load can be decreased by reducing the mass of the reciprocating part. Reducing the spring load reduces friction because of the lower surface pressure between the cam and the follower. In direct acting valve train, poor lubrication results in asperity contact which leads to higher frictional heating of material surfaces resulting in polish wear and scuffing of the tribological components (Dyson and Naylor 1960). The performance of the valve train is also affected due to temperature rise in cam contact area. The rolling motion of roller in the roller follower valve train ensures better lubrication which results in reduced friction force and wear (Chiu 1992; Ji and Taylor 1998).

A valve train system consisting of various contacting parts with interactions governed by different phenomena. Thus, requirement for a relevant prediction is an integrated model of the inertial dynamics (usually expressed in Lagrangian or Newton–Euler formulation), tribology (governed by Reynolds equation), contact mechanics, surface characteristics and physical chemistry of the lubricant. This method is commonly referred to as multi-physics. From tribological point of view, one type of solution includes the solution of Reynold's equation that includes accurate prediction of dynamic behavior of the mechanism. The correct application of this approach has proven to be very accurate although any simulation is time consuming and requires advance computer programming skills. In the second approach, the behavior of the tribological concurrences is predicted using extrapolated oil film thickness formulae. This include equations obtained through regression of numerical studies that correlates the applied load, entrainment velocity, lubricant viscosity and mechanical properties of contact surfaces for different contact geometries and oil film thickness. In spite of various limitations due to simplifying assumptions, such formulae are relatively easy to use that gives relatively accurate and quick results (Teodorescu 2010).

The total valve train energy loss is the sum of the friction energy consumed by all its individual components. A typical valve train system consists of cam, tappet, pushrod, rocker-arm, valve and spring. The major losses occurring in the valve train shown in Fig. 16.2 includes losses between cam and tappet (1), between the tappet and its bore (3), in the rocker arm bearing (5), between the valve stem and the valve guide (7) and in the camshaft bearings. The friction forces at the two ends of the push rod (2, 4) and the friction between the valve stem top and the rocker arm end (6) are much lower than in the other components. They appear as a residual term in the overall balance of frictional losses (Teodorescu 2010).

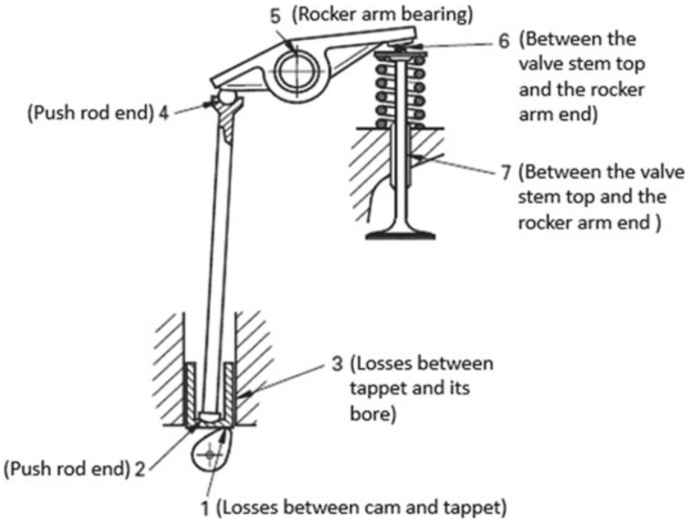

Fig. 16.2 Schematic of the push rod valve train and the major components of the friction losses (Teodorescu 2010)

16.4 Tribological Improvements of IC Engine

The improvement in automobile industry is mainly focused to satisfy customer's needs like better fuel economy and strict regulations of government for environment security. This can be achieved through the knowledge of tribology that can be applied to control frictional losses, wear and fuel consumption. Tribological study can be adopted to develop new engine oils with low or no sulphur, phosphorus and ash content for reduction of harmful emissions or to develop new surface materials with less or no dependence on sulphur and phosphorus containing oils (Komvopoulos et al. 2003). A small improvement in engine efficiency, emission level and durability make a vehicle more reliable having major effect on world economy and environment in the long run in future (Taylor 1998). Improved tribological performance can be achieved in three ways: enhancing the tribological properties of the materials used for the mechanical parts; coating surfaces to improve tribological behavior; or developing lubricants that improve tribological behavior. In order to achieve low fuel consumption and high engine reliability in automobile industry, the tribology study can be successfully implemented in reducing engine friction and engine size, hybridization and developing new engine combustion methods.

16.4.1 Engine Friction Reduction

The friction in the engine components can be reduced by various methods that may cause serious tribology related problems. These problems need to be addressed before applying the methods to engine design to reduce engine friction (Nakada 1994). The methods of friction reduction along with their problems are shown in Table 16.1. The three most important methods to reduce friction and wear in an engine are (i) mechanical design of micro geometries and major components like power cylinder, bearings and valve trains, (ii) surface and material engineering and coatings and (iii) lubricant and additive technologies (Wong and Tung 2016).

Component materials and system design

The automotive design is directly or indirectly related to value engineering. The main motive of a designer in designing any moving part of an IC engine is to meet the required functions (components life, noise and vibration, oil consumption, weight, etc.) simultaneously minimizing its cost. A component with improved performance might be adopted instead of its higher manufacturing cost. Besides these, the additional requirement of an engine design engineer is engine's reliability. In earlier days, tribological failure was a common problem. However, in modern automotive industry, there is no scope for poor reliability as consumer's expectations are considerably increasing (Adam's 2010). The various technological developments in automobile industries requires innovative system designs for the tribo-components to function well under more severe conditions. There is a necessity of development of new materials for different tribo-components that can be operated at high temperature, pressure and velocity (Enomoto and Yamamoto 1998). The knowledge of applied tribology is essential for design engineers to continuously improve a product as well as to critically assess supplier designs in automobile industry. Tribology can be applied to the design process at the very beginning by using improved design tools and methods. Design guides and computer programs are the main tribological design tools to calculate the parameters affecting performance of various components. Design

Table 16.1 Friction reduction methods and their related problems (Nakada 1994)

Components	Methods of friction reduction	Problems
Piston	Reduction of weight and sliding surface, surface treatment on piston skirt	Increased oil consumption, wear, seizure, slap noise; low reliability
Piston ring	Surface treatment and reduction in tension	Increase in oil consumption and decrease in reliability
Valve train bearing (crank and connecting rod)	Reduction of weight and sliding surface	Increased oil consumption, wear, seizure, slap noise; poor reliability
Engine oil	Low viscous oil with additives	Increased wear and seizure

guides aid in setting limits on physical dimensions, materials, stress levels etc. that are required in designing a component. Computer methods like finite element analysis can be successfully applied to the distortion and stresses of various components such as cylinder block and connecting rod (Willermet 1989).

From the viewpoint of materials, most of the primary structures in IC engine are made of easily available metallic elements like iron and aluminum (Becker 2004). Conventionally, an engine cylinder block subjected to maximum friction loss is made up of heavy cast iron. In order to reduce weight in automobiles, most of the metal structures are replaced by cheaper and corrosion resistant polymer components (Friedrich 2018). In recent days, an aluminum alloy engine block with or without cast iron cylinder liner insert is popularly used for passenger cars (Enomoto and Yamamoto 1998). Aluminum alloy 390 having high silicon content are used to manufacture cylinder blocks due to their good wear resistant property in spite of poor machinability. One of the major tribo-components that contribute to engine friction is piston skirt to cylinder block interface. The clearance between the piston and the engine block should be small enough to reduce vibration and noise. On the other hand, there should be adequate clearance between the two to prevent seizure. The advantage of using cast aluminum as a piston material is light weight to reduce engine vibration and high thermal conductivity to prevent piston overheating. In contrast, the high thermal expansion coefficient of aluminum makes the piston cylinder arrangement too loose at low temperature that had appropriate clearance at operating temperature. Hence, aluminum alloy containing copper and nickel is used that possesses low thermal expansion coefficient than pure aluminum but higher than cast iron. At present, the upper compression rings are made up of either nitrided stainless steel or molybdenum coated cast iron as they are subjected to severe wear in comparison to lower rings (Becker 2004). The advantage of using Cr–N ion plating having low friction coefficient (~$0.01 - 0.015$) is that the wear of the top piston ring is reduced by 90% and that of cylinder bore is reduced by 15% in comparison to conventional Cr plated ring (Enomoto and Yamamoto 1998).

The cylinder heads that are generally made of cast aluminum cannot withstand the high temperature and loads at the valve seating area. This can be resolved by inserting a valve seat, made up of steel containing one or more element like cobalt, chromium, vanadium etc. and medium to high carbon (0.5–3 wt%), into the cylinder head. Generally, the cam shafts are made of gray cast iron with induction or flame hardened cam lobes and the lifter surface is made of hardened cast iron or hardened steel. Also, powder metal for cam lobes and ceramics for lifter surface can be a viable alternative. The journal bearing and the shaft should simultaneously be hard and soft for better embeddability of small particles to remove them from coming into contact (Becker 2004). The problem of seizure in bearing due to wear and reduced oil thickness can be overcome by improving the topography of the plated surface and dispersion of fine hard particles in a plated layer. The wear resistance of bearing can be considerably improved by dispersing Si_3N_4 fine powder in Pb–Sn–In composite electro-plating and Co hard powder in Cu–Sn–Pb alloy (Enomoto and Yamamoto 1998).

Surface engineering

The recent trends in IC engine include the improvement in surface structures with suitable coatings instead of earlier trend of using monolithic materials to minimize frictional losses. The friction between the sliding pairs can be significantly reduced by surface texturing such as dimple, grove and mesh pattern textures. The different surface texturing techniques are mechanical milling or shot blasting, photolithography, etching, laser beam processing, pellet pressing etc. (Yan-qing et al. 2009). Initially, the concept of lubrication mechanism is nothing but providing reserved oil in different surface textures. Hence, the inside of the cylinders of combustion engines was designed with cross-hatch pattern by honing process for not less than 60 years. The micro-irregularities help in achieving improved hydrodynamic pressure that increases the load carrying capacity of the surfaces (Yan et al. 2010). Yu et al. (2011) studied the effect of dimples of different shapes, viz. circle, square and ellipse, on the tribological performance of surface texture and found that the elliptical dimples showed the best friction reduction effect.

Studies revealed that a large amount of heat generated in the combustion chamber of IC engine is absorbed by piston and the walls of the combustion chamber that reduces its performance. This situation can be overcome by using thermal barrier coating that reduces the heat loss which in turn helps in burning the un-burnt gases to reduce pollution in exhaust gases (Dhomne and Mahalle 2018). Titanium alloys can be a competent light weight material for automotive applications due to its high strength, low density and excellent corrosion resistance. But at high temperatures, the engine components are subjected to oxidation, creep and thermal fatigue. Especially, the engine valves frequently strike the seat inserts, at hot environment of combustion gases ~500 °C, that are subjected to short distance sliding contact leading to localized wear. The development of tribolayer is expected to reduce the intensity of wear. The weight of Ti alloy valves is 45% less than the stainless steel valves that increases the engine speed and reduces vibration and noise. Instead of great importance of Ti alloy such as Ti–6Al–4V in automobile industry, it is subjected to oxidational wear at low sliding speed and metallic wear at high sliding speed. Hence, various surface engineering methods like physical vapour deposition of Ti alloy coating, chemical vapour deposition of carbon based polycrystalline diamond coating, ion implantation with nitrogen and oxygen and thermal oxidation. Amongst these techniques, the thermal oxidation method can be implemented at a lower cost for mass production (Lou and Alpas 2019). Some of the hard antiwear coatings are diamond-like carbon (DLC), boron nitride (BN), silicon carbide (SiC), titanium nitride (TiN), tungsten carbide (WC), etc. (Zhmud 2011). Mutafov et al. (2014) observed that tungsten doped DLC coating on laboratory samples and valve lifter possess good adhesion and hardness nearly 15 GPa. The coating showed excellent wear resistance in pin-on-disc and engine testing due to the formation of thin solid tribolayer of 2–4 nm on the coating surface.

Lubrication and additive technology

The engine lubricants are basically used to make the engine more durable, to improve fuel economy and to reduce emission level. In order to increase engine's durability, the lubricant must prevent wear through hydrodynamic lubrication or by using anti-wear additives and inhibit corrosion formed by oil degradation or its contamination by combustion gases and unburnt fuel (Howard 2014). The introduction of nanoparticles to engine oils improves the tribological behavior of IC engine due to rolling, mending and polishing effect and formation of protective film as shown in Fig. 16.3. The spherical nano particles act as rollers for the two sliding surfaces as well interacts with the friction surfaces to form a protective film between them. Also, the nanoparticles form physical tribo-film by depositing on the friction surfaces to reduce mass loss and reduce the roughness of the rubbing surfaces by their abrasiveness property (Ali and Xianjun 2015). Darminesh et al. (2017) reviewed the present status of biodegradable nanolubricant possessing improved properties. Several surface-active anti-wear additives like zinc dialkyldithiophosphate (ZDDP), antiscuff phosphorus and sulphur improves the friction and wear behavior due to chemical reactions with the surfaces forming cohesive anti wear tribochemical films. The regeneracy and stability of a tribofilm at high loads and temperatures are the key factors in determining its efficiency and persistence (Komvopoulos 2003).

In addition, the lubricant must possess low viscosity to minimize power loss due to viscous drag and hence increase efficiency. Tormos et al. (2017) made a comparative fuel consumption test of low viscosity engine oil (LVEO) on an urban compressed natural gas buses fleet and tribometers. They found reduced fuel consumption in fleet test and reduced friction in tribometers due to the application of LVEO. The fuel economy can be improved by using friction modifier additives that are long molecules with polar head groups that attach to the metal surface to make the surface more slippery in boundary lubrication. The engine efficiency can be increased by better handling of oxidation and contaminants with lubricants to maintain a viscosity profile which provides the required film strength for protection. The use of

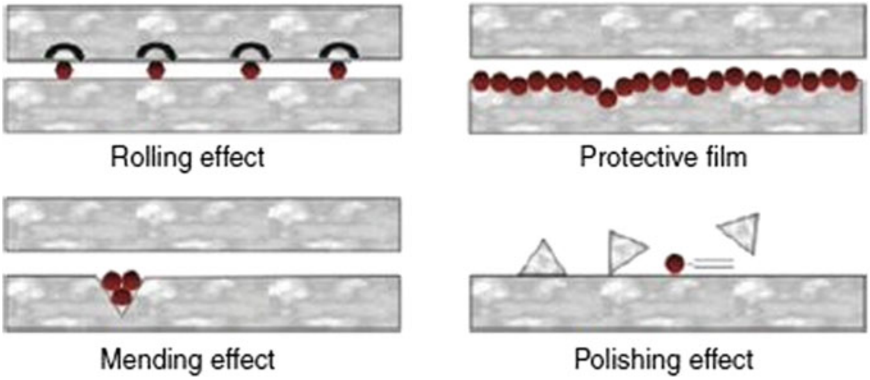

Fig. 16.3 Mechanism of lubrication of nanolubricants (Ali and Xianjun 2015)

anti-oxidant additives in lubricants can reduce oxidation and dispersants within the additives reduce contamination. Engine's good emission performance is possible due to lubricant's ability to prevent wear and deposits along with several after treatment methods, viz. particulate filters, NO_x adsorbers and selective catalytic reduction (SCR) systems (Howard 2014).

16.4.2 Hybridization and Engine Downsizing

Engine downsizing means employing smaller engines in a vehicle that provides the same power as that of larger engines using recent technologies. It involves the reduction of engine size by reducing the number of cylinders and the displacement. It is one of the viable methods to improve fuel economy and combustion by reducing friction and automobile weight. In spite of having advantageous properties, engine downsizing can have certain drawbacks like poor acceleration, lowered maximum speed and smaller internal space. Nozawa et al. (1994) performed a numerical simulation to assess the consequences of engine downsizing on the frictional losses and fuel ingestion of automobiles by making use of simplified models for friction and combustion. They observed an improvement in fuel economy and an existence of optimal engine displacement due to engine downsizing.

Engines are said to be downsized when they possess high load levels. Hence, downsized engine possesses high power density and/or high full load mean pressures and specific full load torque. The engine power density Pe/VH is given by (Golloch and Merker 2005):

$$\frac{P_e}{V_H} = i.n.P_{me} = 2\pi.n.\frac{M}{V_H} \tag{16.1}$$

where V_H is the piston displacement, n is the engine speed, P_{me} is the engine's effective pressure, i is the number of cycles per crankshaft rotation and M is the torque. The power density can be increased by increasing n or P_{me}. Engines use high load concepts through effective charging systems and other measures to show high mean effective pressures and specific powers (Golloch and Merker 2005). The engine downsizing process involves increased performance by using turbochargers, superchargers and twin charging. These methods alone cannot have high efficiencies and can be coupled with new techniques, viz. direct fuel injection (DI), advanced exhaust gas recirculation (EGR) and variable valve timing (VVT). Turbocharging is used to provide the required amount of air in the combustion chamber to burn additional fuel for efficient and clean combustion. A hybrid turbocharger is used to obtain high electrical efficiency due to absence of mechanical linkage between the turbine and the compressor. The hybrid turbocharger consists of a series of hybrid setup where compressor speed and power are independent from turbine speed and power that improves turbine and compressor efficiency. The supercharger compresses air to increase its pressure and density with the help of mechanical power of the engine. Twin charger is an amalgamation of an exhaust-driven turbocharger and an engine-driven supercharger that work together to give maximum work output. Downsizing will be a great boon for petrol and diesel engines in future containing just two cylinders and lower displacement that provides the required torque and power and reduces the amount of pollutants (Patil et al. 2017).

The emergence of various innovative vehicle technologies like electric vehicles (EVs), hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs) leads to the improvement of fuel economy and reduced emissions. So far, the HEVs are the most cost-effective feasible choice as they use smaller battery pack and are similar to conventional vehicles. The different automobile industries are developing solutions to the standardization of electric systems to the extent that the hybridization factors, viz. bus voltage, motor size and the relative size of the motor to IC engine, are concerned. Lukic and Emadi (2004) showed that hybridization improves fuel economy and vehicle performance up to a critical optimum point. Beyond that, the performance did not improve satisfactorily on increasing the capacity of electric propulsion system. Besides, there was a considerable benefit of fuel economy when fitted with small electric motors. Katrašnik (2007) proposed combined simulation and analytical approach to accurately determine the energy distribution and losses in the individual components of the hybrid powertrain. They showed that the utmost necessity to enhance fuel economy by hybridization and downsizing involves the determination of optimum hybridization factor.

16.4.3 New Combustion Concepts

The present scenario of engine combustion and its related emissions is very complex that leads to rigorous research in the field of new combustion concepts. There is no significant distinction associated with gasoline and diesel fuel use in SI and CI engine respectively, homogeneous or non-homogeneous and stoichiometric or lean mixtures. The new combustion concept in traditional stoichiometric homogeneous SI engine for better fuel economy includes lean burn combustion and stratified gasoline combustion. In lean burn combustion, a homogeneous mixture of low air-fuel ratio is used to improve fuel efficiency. However, the after-treatment process becomes complicated as the conventional three-way catalyst cannot reduce NO_x with excess oxygen. In stratified gasoline combustion, the stratification of cylinder charge is done with high pressure in-cylinder injection of the fuel that prepares a near stoichiometric mix in the vicinity of the spark plug (Payri et al. 2014).

The efficient diesel engines having the problems of harmful emission can be improved using high pressure injection, lower compression ratio through advanced valve timing, lean burning and advanced after treatment techniques and renewable energy sources. Direct use of biofuels or biogas as a fuel, along with use of hydrogen fuel, synthetic fuel and electricity for electric vehicles produced from wind, hydro or wave energy can reduce the emissions to a large extent (Olander 2018). The NO_x and particulates are in a trade-off position in diesel engines. The NO_x can be reduced by lowering the combustion temperature using techniques like EGR, timing retard, low swirl, pilot injection etc. Whereas, particulate matter can be reduced by air-fuel mixture using high pressure fuel injection, low sulphur fuel, HC reduction and a decrease in lubrication oil consumption (Odajima 1994). Igartua et al. (2011) developed a new generation lubricating oil for two-stroke engines that is compatible with Bioethanol E85 having the properties like low friction, good wear and scuffing protection, no residual ash, low carbon soot or existence of deposits. Penchaliah et al. (2011) examined the effect of four contaminants viz. soot, oxidation, moisture and sulphuric acid, and observed that they reduce the conductivity of oil. The sulphuric acid and soot influenced the wear rate in the form of abrasion and polishing wear whereas sulphuric acid and moisture produced corrosive wear. On the other hand, all contaminants and their levels increased the coefficient of friction.

16.5 Summary

The review shows the contribution of different components of IC engine to the total frictional losses and the minimization of these losses through various techniques. In order to increase the efficiency and durability and to reduce emissions of IC engine, it is important to design the major frictional components based on the knowledge of tribology. The importance of improved lubrication, surface profiles and surface finish has been focused. The automobile engineers, material engineers and tribologists must work together to eliminate the difficulties of engine tribology.

Despite the threats of strict pollution legislation, globalization and variable fuel quality, the IC engine will continue as a title role in the next decades with significant improvement in technologies. Technologies that are already available in the market includes stop-start, EGR and VVT systems, advanced after-treatment systems to deal with lean combustion. Some emerging technologies may include low temperature combustion concept and modified operating cycles. The widely used efficiency enhancing technologies in current automotive engines is engine downsizing due to which engines are able to increase their rated power. Different boosting technologies are being investigated so as to decrease turbo-lag and to broaden turbocharger operation range, limited by surge and overspeed. Some of the active fields of research may involve accurate engine control in system integration level, management of subsystem requirements, operational limits and their interaction, providing a systematic calibration procedure and adapting the control system to variations in the environment and to engine ageing.

References

Adams DR (2010) Tribological considerations in internal combustion engines. In: Tribology and dynamics of engine and powertrain, pp 251–283

Ali MKA, Xianjun H (2015) Improving the tribological behavior of internal combustion engines via the addition of nanoparticles to engine oils. Nanotechnol Rev 4(4). https://doi.org/10.1515/ntrev-2015-0031

Andersson BS (1991) Company perspectives in vehicle tribology-Volvo. In: 17th Leeds-Lyon symposium on tribology—vehicle tribology, vol 18, pp 503–506

Becker EP (2004) Trends in tribological materials and engine technology. Tribol Int 37:569–575

Bompos DA, Nikolakopoulos PG (2016) Tribological design of a multistep journal bearing. Simul Model Pract Theory 68:18–32

Cakir M, Akcay IH (2011) An investigation on correlation between engine performance and piston ring-cylinder friction in internal combustion engines. J Tech Sci 16(2)

Chiu Y (1992) Lubrication and slippage in roller finger follower systems in engine valve trains. Tribol Trans 35(2):261–268

Darminesh SP, Sidik NAC, Najafi G, Mamat R, Ken TL, Asako Y (2017) Recent development on biodegradable nanolubricant: a review. Int Commun Heat Mass Transfer 86:159–165. https://doi.org/10.1016/j.icheatmasstransfer.2017.0

Dienwiebel M, Pohlmann K, Scherge M (2007) Origins of the wear resistance of AlSi cylinder bore surfaces studies by surface analytical tools. Tribol Int 40:1597–1602

Dhomne S, Mahalle AM (2018) Thermal barrier coating materials for SI engine. J Mater Res Technol. https://doi.org/10.1016/j.jmrt.2018.08.002

Dyson A, Naylor H (1960) Application of the flash temperature concept to cam and tappet wear problems. Proc Inst Mech Eng Autom Div 14(1):255–280

Enomoto Y, Yamamoto T (1998) New materials in automotive tribology. Tribol Lett 5(1):13–24

Fenske G (2014) Engine friction reduction technologies. Argonne National Laboratory. https://www.energy.gov/sites/prod/files/2014/07/f17/ft012_fenske_2014_p.pdf. Accessed on 03/05/2019

Friedrich K (2018) Polymer composites for tribological applications. Adv Ind Eng Polym Res. https://doi.org/10.1016/j.aiepr.2018.05.001

Ghorbanian J, Ahmadi M, Soltani R (2011) Design predictive tool and optimization of journal bearing using neural network model and multi-objective genetic algorithm. Sci Iranica B 18(5):1095–1105

Golloch R, Merker GP (2005) Internal combustion engine downsizing. MTZ Worldwide 66(2):20–22. https://doi.org/10.1007/bf03227737

Hirani H, Athre K, Biswas S (1999) Comprehensive design methodology for an engine journal bearing. Proc Inst Mech Eng Part J 214:401–412

Howard K (2014) Advanced engine oils to improve the performance of modern internal combustion engines. In: Alternative fuels and advanced vehicle technologies for improved environmental performance, pp 138–164. https://doi.org/10.1533/9780857097422.1.138

Igartua A, Nevshupa R, Fernandez X, Conte M, Zabala R, Bernaola J, Zabala P, Luther R, Rausch J (2011) Alternative eco-friendly lubes for clean two-stroke engines. Tribol Int 44(6):727–736. https://doi.org/10.1016/j.triboint.2010.01.019

Ji F, Taylor C (1998) A tribological study of roller follower valve trains. Part 1: a theoretical study with a numerical lubrication model considering possible sliding. Tribology series, vol 34, pp 489–499

Katrašnik T (2007) Hybridization of powertrain and downsizing of IC engine—a way to reduce fuel consumption and pollutant emissions—part 1. Energy Convers Manage 48(5):1411–1423. https://doi.org/10.1016/j.enconman.2006.12.004

Khurram M, Mufti RA, Bhutta MU, Afzal N, Abdullah MU, ur Rahman S, ur Rehman S, Zahid R, Mahmood K, Ashfaq M, Umar M (2019) Roller sliding in engine valve train: effect of oil film thickness considering lubricant composition. Tribol Int. https://doi.org/10.1016/j.triboint.2019.06.022

Komvopoulos K (2003) Adhesion and friction forces in microelectromechanical systems: mechanisms, measurement, surface modification techniques, and adhesion theory. J Adhes Sci Technol 17:477–517

Komvopoulos K, Do V, Yamaguchi ES, Ryason PR (2003) Effect of sulfur- and phosphorus-containing additives and metal deactivator on the tribological properties of boundary-lubricated steel surfaces. Tribol Trans 46(3):315–325

Kumar V, Sinha SK, Agarwal AK (2018) Tribological studies of an internal combustion engine. Energy, environment, and sustainability, pp 237–253. https://doi.org/10.1007/978-981-13-3275-3_12

Kumar V, Sinha SK, Agarwal AK (2019) Wear evaluation of engine piston rings coated with dual layer hard and soft coatings. J Tribol 141:1–10

Lou M, Alpas AT (2019) High temperature wear mechanisms in thermally oxidized titanium alloys for engine valve applications. Wear 426–427:443–453

Lukic SM, Emadi A (2004) Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles. IEEE Trans Veh Technol 53(2):385–389. https://doi.org/10.1109/tvt.2004.823525

Martin FA (1983) Developments in engine bearing design. Tribol Int 16(3):147–164

Mishra PC, Rahnejat H, King PD (2009) Tribology of the ring-bore conjunction subject to a mixed regime of lubrication. Proc Inst Mech Eng C J Mech Eng Sci 223(4):987–998

Mutafov P, Lanigan J, Neville A, Cavaleiro A, Polcar T (2014) DLC-W coatings tested in combustion engine—frictional and wear analysis. Surf Coat Technol 260:284–289

Nakada M (1994) Trends in engine technology and tribology. Tribol Int 27(1):3–8

Nozawa R, Morita Y, Shimizu M (1994) Effects of engine downsizing on friction losses and fuel economy. Tribol Int 27(1):31–37. https://doi.org/10.1016/0301-679x(94)90060-4

Odajima M (1994) Trends in diesel exhaust gas control and engineers' expectations from tribology. Tribol Int 27(1):9–15. https://doi.org/10.1016/0301-679x(94)90057-4

Olander P (2018) Tribology for greener combustion engines. Scuffing in marine engines and a lubricating boric acid fuel additive. https://uu.diva-portal.org/smash/get/diva2:1161025/FULLTEXT01.pdf. Accessed on 29/05/2019

Patil C, Varade S, Wadkar S (2017) A review of engine downsizing and its effects. Int J Curr Eng Technol. https://inpressco.com/wp-content/uploads/2017/06/Paper75319-324.pdf. Accessed on 28/05/19

Payri F, Luján J, Guardiola C, Pla B (2014) A challenging future for the IC engine: new technologies and the control role. Oil Gas Sci Technol Rev d'IFP Energies Nouvelles 70(1):15–30. https://doi.org/10.2516/ogst/2014002

Penchaliah R, Harvey TJ, Wood RJK, Nelson K, Powrie HEG (2011) The effects of diesel contaminants on tribological performance on sliding steel on steel contacts. Proc Inst Mech Eng Part J J Eng Tribol 225(8):779–797. https://doi.org/10.1177/1350650111409825

Priest M, Taylor C (2000) Automobile engine tribology—approaching the surface. Wear 241(2):193–203. https://doi.org/10.1016/s0043-1648(00)00375-6

Rosenberg RC (1981) General friction considerations for engine design. SAE paper 821576, pp 59–70

Sander DE, Allmaier H, Priebsch HH (2016) Friction and wear in automotive journal bearings operating in today's severe conditions. In: Advances in tribology, pp 143–172. https://cdn.intechopen.com/pdfs/51522.pdf. Accesses on 19/06/2019

Scherge M, Martin JM, Pohlmann K (2006) Characterization of wear debris of systems operated under low wear-rate conditions. Wear 260:458–461

Shakhvorostov D, Pohlmann M, Scherge M (2006) Structure and mechanical properties of tribologically induced nanolayers. Wear 260:433–437

Siczek KJ (2016) Valve train tribology. In: Tribological processes in the valve train systems with lightweight valves, pp 85–180

Taylor CM (1993) Lubrication regimes and the internal combustion engine. Engine tribology, pp 75–87. https://doi.org/10.1016/s0167-8922(08)70008-7

Taylor CM (1998) Automobile engine tribology—design considerations for efficiency and durability. Wear 221:1–8

Teodorescu M (2010) A multi-scale approach to analysis of valve train systems. In: Tribology and dynamics of engine and powertrain, pp 567–587. https://doi.org/10.1533/9781845699932.2.567

Tormos B, Ramírez L, Johansson J, Björling M, Larsson R (2017) Fuel consumption and friction benefits of low viscosity engine oils for heavy duty applications. Tribol Int 110:23–34. https://doi.org/10.1016/j.triboint.2017.02.007

Vencl A, Rac A (2014) Diesel engine crankshaft journal bearings failures colon Case study. Eng Fail Anal 44:217–228

Willermet PA (1989) Tribological design—the automotive industry. Tribology series, pp 33–39. https://doi.org/10.1016/s0167-8922(08)70178-0

Wong VW, Tung SC (2016) Overview of automotive engine friction and reduction trends—effects of surface, material, and lubricant-additive technologies. Friction 4(1):1–28

Yan-qing W, Gao-feng W, Qing-gong H, Liang F, Shi-rong G (2009) Tribological properties of surface dimple-textured by pellet-pressing. Procedia Earth Planet Sci 1:1513–1518

Yan D, Qu N, Li H, Wang X (2010) Significance of dimple parameters on the friction of sliding surfaces investigated by orthogonal experiments. Tribol Trans 53(5):703–712

Yu H, Deng H, Huang W, Wang X (2011) The effect of dimple shapes on friction of parallel surfaces. Proc Inst Mech Eng Part J J Eng Tribol 225(8):693–703

Zhmud B (2011) Developing energy efficient lubricants for auto applications. Tribology and Lubrication Technology, pp 42–49. www.stle.org. Accessed on 25/05/19