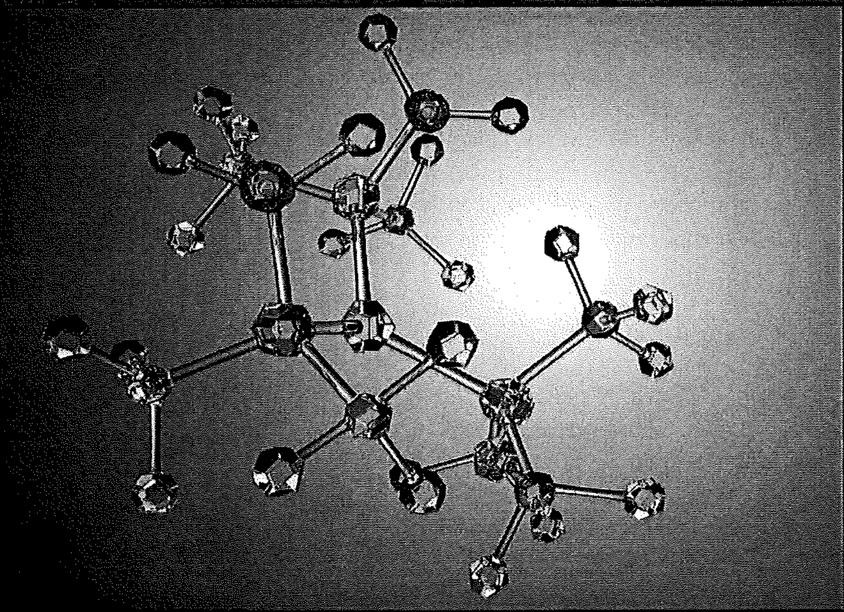
DIAMOND-LIKE CARBON COATINGS

Technologies and Applications



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Diamond-Like Carbon Coatings

Diamond-like carbons (DLCs) display a number of attractive properties that make them versatile coating materials for a variety of applications, including extremely high hardness values, very low friction properties, very low gas permeability, good biocompatibility, and very high electrical resistivity, among others. Further research into this material is required to produce hydrogen-free DLC films and to synthesize it together with other materials, thereby obtaining better film properties. *Diamond-Like Carbon Coatings: Technologies and Applications* examines emerging manufacturing technologies for DLCs with the aim of improving their properties for use in practical applications.

- Discusses DLC coatings used in mechanical, manufacturing, and medical applications
- Details recent developments in the novel synthesis of DLC films
- Covers advances in the understanding of chemical, structural, physical, mechanical, and tribological properties for modern material processing
- Highlights methods to yield longer service life
- Considers prospects for future applications of emerging DLC technologies

This work is aimed at materials science and engineering researchers, advanced students, and industry professionals.

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8.1 INTRODUCTION

Ever increasing environmental legislations for greenhouse gases reduction and the trend towards energy conservation demands environmentally conformable lubrication solutions. It has been estimated that about one-third of the worldwide energy resource is being consumed to overcome frictional losses (Holmberg & Erdemir, 2017). While considering the frictional losses in a typical automotive engine, worldwide, one passenger car uses, on average, 340 liters of fuel per year. This would correspond to an average driving distance of 13,000 km/year (Holmberg et al., 2012).

As huge numbers of reciprocating IC engines are in operation worldwide, even the small improvement in engine efficiency, emissions and reliability can have a significant effect on the global fuel economy and the environment in the long term. Concerning energy consumption within the IC engine, 48% of the energy consumption developed in an engine is due to frictional losses (Tung & McMillan, 2004). This results in millions of tons of CO_2 emission per year (Braun et al., 2014). Modern tribology requires the use of low friction surfaces and improved lubrication to overcome the environmental concerns while meeting the customer requirement of fuel economy and low emissions. From an environmental point of view, low fuel economy is correlated with increased hazardous emissions (Taylor, 1998; Merlo, 2003); thus, there is need for such engine systems which have high fuel economy and lower emissions than before, and this can be accomplished by the wide use of low friction materials, coatings and high-performance lubricants (Erdemir, 2005; Johnson & Diamond, 2001; Beardsley et al., 1999).

Keeping in view the requirement from modern engines mentioned earlier, for high fuel economy, low viscosity engine oils have been adopted. To meet the environmental concerns posed by engine lubricants, dire reductions in sulfur and phosphorous contents of these oils are required (Mubashir Gulzar, 2018). Antiwear (AW)/Extreme Pressure (EP) additives like ZDDP and friction modifier (FM) like Mo-DTC are the sources of sulfur and phosphorous in engine oils. Without such additives, higher friction and wear has been reported in sliding engine parts and components (Al-Jeboori et al., 2018; Konicek et al., 2016; Bahari et al., 2018). Other than AW/EP and FM additive requirements, the conventional engine lubricants are typically additivated by over-based detergents, dispersants, antioxidants, viscosity modifiers and corrosion inhibitors.

The use of all such conventional additives resulted in toxic compounds (M. Gulzar et al., 2017) as shown in Table 8.1.

Though tribologists and lubrication researchers have been working on environmentally friendly lubricant formulations (Zulkifli et al., 2016; M. Gulzar et al., 2015), only commercially available synthetic engine oils are recommended by

TABLE 8.1
Sources of Sulfur and Ash in Conventional Diesel Engine Oil

Component	Sulfur (wt%)	Ash Contribution (wt% of oil)
Detergent	0.05–0.25	0.6–1.3
Zinc dithiophosphate (Antiwear)	0.20–0.25	0.15
Other (Antioxidants, viscosity improvers, friction modifiers)	0.0–0.10	0.0–1.5
Total	0.25–0.60	0.75–1.6
Typical Group II base oil	0.0001–0.003	0.0

automotive manufacturers due to required compatibility, reliability and long drain intervals. With the advent of coating technologies and recent advances in surface engineering, the required performance of engines with low emissions is achieved through the extensive use of low friction engine materials and coatings in combination with adequate lubrication (Dolatabadi et al., 2020; Araujo & Banfield, 2012; Federal-Mogul Corp., 2011). Thus, tailoring the interacting surfaces in accordance with low-viscosity, high-performance lubricants is the way forward to achieve desired clean energy automobiles without compromising the performance, efficiency and durability.

To date, researchers have tested various surface coatings to reduce friction in IC engine parts, and among such surface coatings techniques, diamond-like carbon (DLC) coatings have been found promising for boundary and mixed lubrication regimes applications in internal combustion engines showing low friction, reduced emissions and prolonged component lifetime (Dobrenizki et al., 2016; Kolawole et al., 2020).

8.2 CO_2 EMISSIONS BY TRANSPORT SECTOR

One of the major sources of CO_2 emissions is fuel combustion. More than 24% of CO_2 emissions worldwide from fuel combustion is comes directly from the transport sector (IEA, 2020a).

It is worth mentioning here that research work related to environmental concerns and air pollution by transportation are mainly focused on land transportation (Van Fan et al., 2018).

Figure 8.1 shows the CO_2 emissions by the transport sector mode in the Sustainable Development Scenario, 2000-2030.

The process of burning fuel is a source of huge volume of CO_2 emissions by vehicles' exhaust pipes every day. Apart from hazardous emissions, which are damaging the ozone layer and resulting in climate change, the transport sector is also responsible for consumption of about 20% of the world's total energy output annually. In the transportation sector, road transport accounted for 80% of the total CO_2 emissions (Cha & Erdemir, 2015). Other than CO_2, emission of gases like NOx and SOx are also responsible for the negative impact on the ecosystem and public health (Faiz, 1990). For a sustainable solution of ever-increasing road transport, the role of modern tribology to reduce frictional losses seems to be the key factor.

8.3 IC ENGINES ENERGY LOSSES AND MAJOR SUBSYSTEMS

The distribution of total energy in a typical fired internal combustion engine is shown in Figure 8.2. Frictional energy losses in the IC engines and transmission resulted in about 28% of the total fuel energy (Cha & Erdemir, 2015). A modern IC engine is composed of thousands of individual components which are grouped as subsystems as per their function and lubrication regime. The major subsystems are the crankshaft assembly, the power cylinder, the valvetrain, and auxiliary systems. Relevant mechanical losses of major subsystems are provided

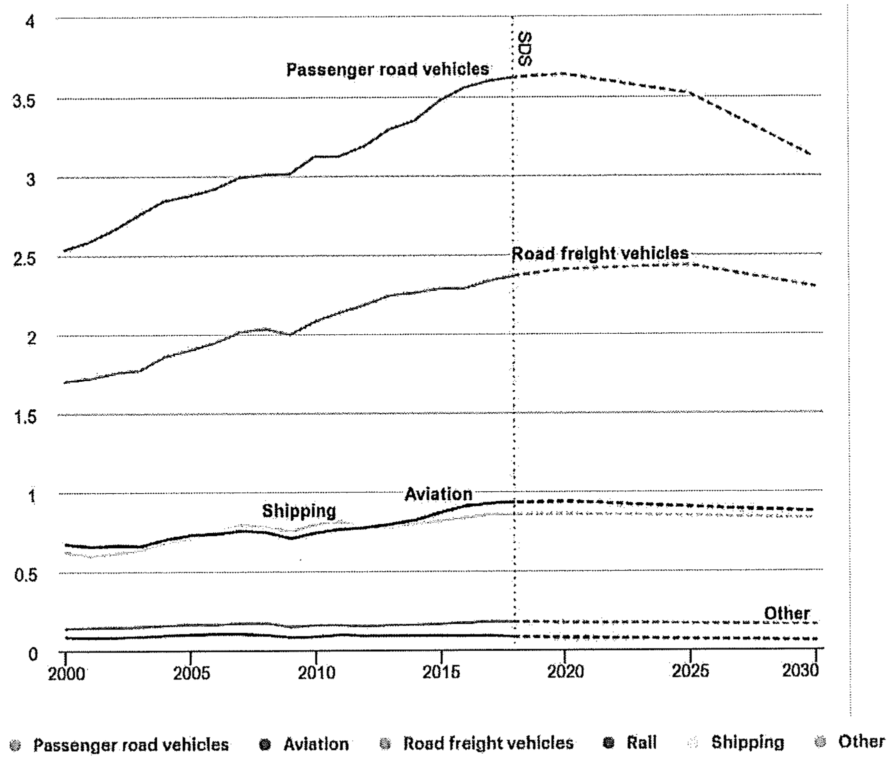

FIGURE 8.1 Transport sector CO_2 emissions by mode in the Sustainable Development Scenario, 2000-2030.

Source: IEA, 2020b.

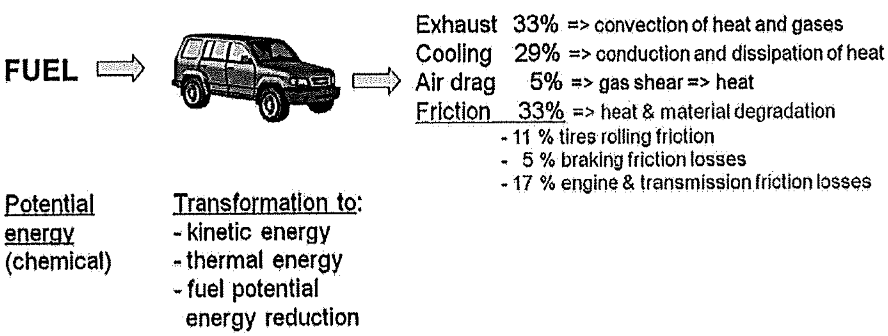

FIGURE 8.2 Fuel energy losses distribution in a passenger car for speed of 60 km/h.

Source: Holmberg et al., 2012.

in Figure 8.3 and Figure 8.4. Excluding the engine auxiliaries, three major subsystems are (a) piston-ring assembly, (b) crankshaft system and (c) valvetrain system (Wong & Tung, 2016). Mechanical friction in the typical IC engine is provided in Figure 8.4. In the next section, the friction and lubrication of these subsystems are discussed.

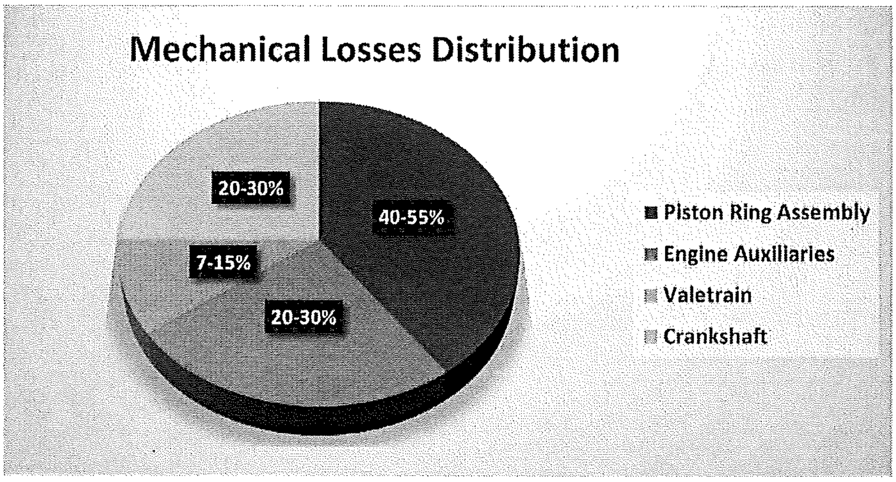

FIGURE 8.3 Mechanical losses distribution in a typical diesel engine.

Source: Wong & Tung, 2016.

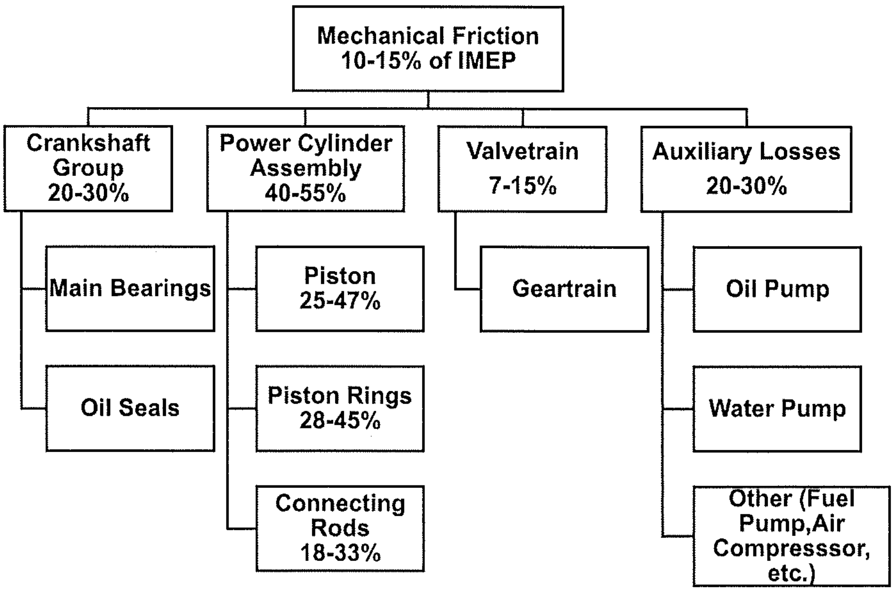

FIGURE 8.4 Mechanical Friction in typical IC engine.

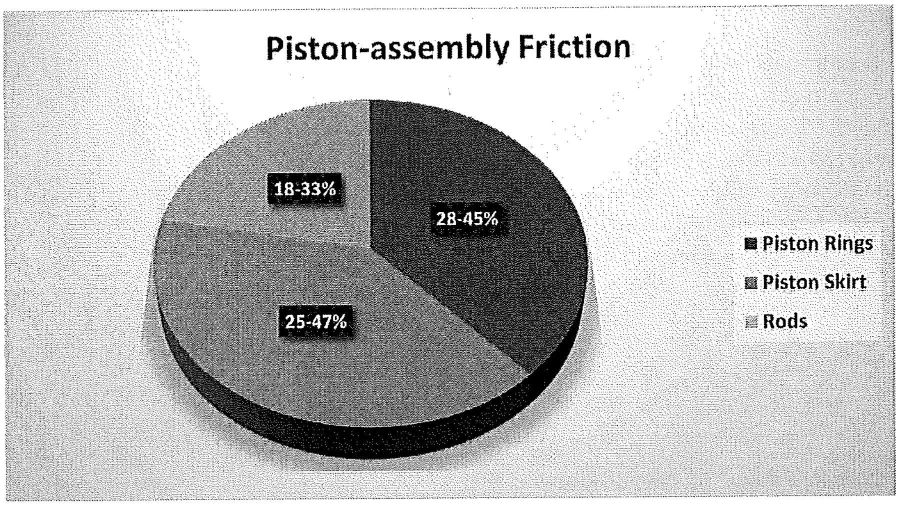

FIGURE 8.5 Piston assembly frictional losses distribution.

Source: Mubashir, 2017.

8.3.1 Piston-Ring Assembly

Engine piston assembly is considered as the heart of IC engines, establishing a link to transform the fuel combustion energy into useful kinetic energy. The piston assembly operates in one of the most arduous environments found in any machine (Mubashir Gulzar, 2018). Here, a thin film of lubricant exists to reduce the friction and wear between the piston ring-cylinder liner conjunctions, thereby ensuring smooth running and satisfactory service life of these engine parts. Significant piston-assembly friction contributed either by (i) piston-skirt/cylinder liner interaction, or (ii) ring-pack/cylinder liner interaction or (iii) rod bearings (see Figure 8.5).

8.3.2 Crankshaft and Bearing System

The crankshaft in the IC engine is responsible for converting the sliding motion of pistons to rotary motion for driving the automotive wheels. The lubrication modes at the various parts of the crankshaft are designed and analyzed as journal-bearing lubrication. There are journal bearings to support the crankshaft at its ends as well as between each connecting rod and piston assembly. In the crankshaft, main bearings are lubricated directly by oil pump to handle high loading conditions.

For the crankshaft, the primary source of friction is the main bearings and attached seals that support it for rotary motion. The crankshaft is supported by an oil layer that exists between the shaft and the outer bearing. The eccentricity of bearing helps in the wedging phenomenon which leads to hydrodynamic pressure generation during rotation. As sufficient oil is available, the bearing surfaces under normal loads, the lubrication at the main bearings is primarily in the hydrodynamic regime.

8.3.3 Valvetrain System

The valvetrain system in an IC engine has components which include the cylinder head, intake and exhaust valves, and the actuation mechanism. For a conventional IC engine, this subsystem would include the camshafts, intake and exhaust poppet valves, rocker arms, valve springs, and cam followers (James, 2012). There are four types of contacts and friction sources in the different configurations of valvetrains (Wong & Tung, 2016). The relevant lubrication regimes include hydrodynamic to boundary lubrication and mixed lubrication. The major contact and friction sources are:

1. The camshaft bearings
2. The cam/follower interface
3. The rocker arm pivot/shaft
4. Linearly oscillatory components

Valvetrain architecture in IC engines can be categorized in five different types. However, two types of valvetrain architectures are mostly used in modern engines including roller finger followers and direct acting mechanical bucket (Gangopadhyay, 2017). Considering the direct-acting mechanical bucket architecture type, the cam lobe-tappet interaction is responsible for major frictional losses. For the roller finger follower type, the cam and tappet interface experiences comparatively very low friction. The reason for low friction is the mixed lubrication regime in which this tribo-pair operates and, thus, offers various options for friction reduction through lubricating oils, surface engineering and low friction coatings.

8.3.4 Modern Tribology for Improved Fuel Efficiency

With the advancement of low friction materials, coating technologies and low viscosity synthetic lubricating oils, modern engine are desired to be more fuel efficient and durable (Holmberg & Erdemir, 2017; Holmberg et al., 2012; Konicek et al., 2016; Zhmud, 2011). Recent research has shown that coatings, along with suitable additives, are able to provide friction coefficients in the superlubric sliding regimes, i.e., less than 0.01 (Jozwiak et al., 2020; Vinoth et al., 2019). The relevant wear rate was also reported to be lower than those of conventional materials (Li & Hsu, 2019; Erdemir & Martin, 2018). Figure 8.6 shows typical values of Coefficient of friction (CoF) for various coatings being used. Figure 8.7 shows typical CoF and wear loss values of engine piston ring segments for sliding wear when coated with such emerging engineering materials. Various studies have investigated and have shown the effectiveness of such modern materials in the presence of lubricating oils and suitable additives (Jozwiak et al., 2020; Elagouz et al., 2019). As a result, it has been observed that the use such materials in combination of liquid lubricants is a must for internal engine applications for achieving low friction and wear. Thus, tribologists and lubrication engineers are also focusing on the intense R&D efforts for effective lubricant with environmentally conformable additives and long drain intervals. Such efforts are expected to provide enhanced lubrication behavior and long-part life despite severe engine operating conditions. In this regard, it is worth mentioning that lubricious coatings have been widely used on specific engine parts where high-load

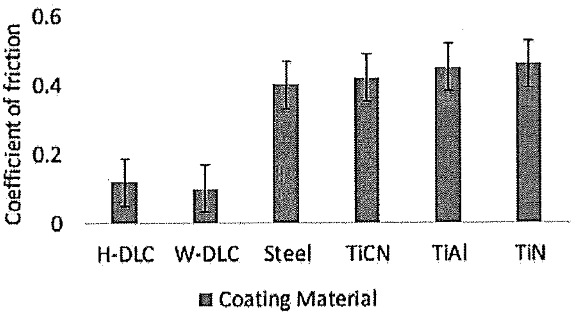

FIGURE 8.6 CoF for different coating materials.

Source: Banerji et al., 2014.

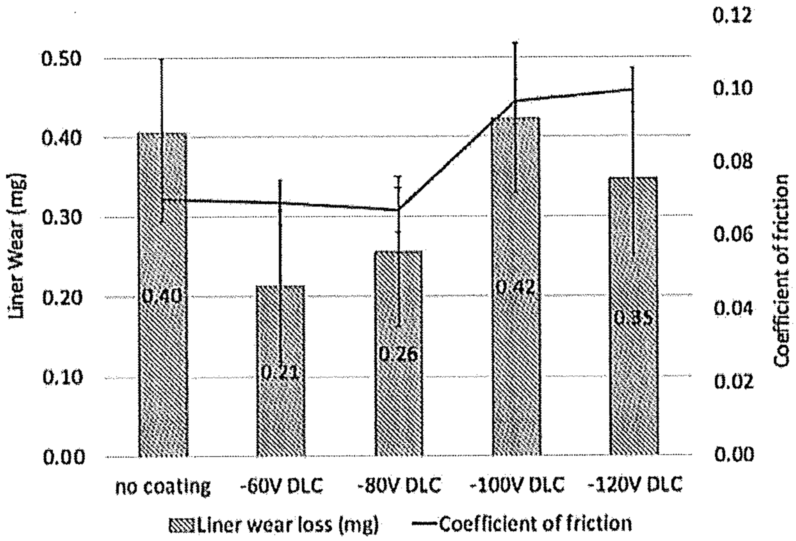

FIGURE 8.7 Friction and liner sliding wear for different coated ring segment.

Source: Li & Hsu, 2019.

carrying capacity and boundary lubrication regimes are expected. For boundary-lubricated sliding conditions, the enhancement of surfaces has been carried out in terms of material hardness and shearing. The effectiveness of coating technology is also witnessed for elasto-hydrodynamic and hydrodynamic lubrication regimes (M Kalin & Velkavrh, 2013).

8.4 SMART SURFACES AND COATING TECHNOLOGIES

Advances in materials technology have made revolutionary changes in surface engineering. Various studies have shown the promising results for friction reduction when tribo-pairs were coated with modern thin films. In vehicles tribology, the surface engineering and coatings have shown improved lubrication performance. The relevant advances helped in the development of such engine mechanical parts, transmissions, as well as inner and outer parts, which are durable and possess low frictional behavior.

At the initial stages of coating films development, there had been issues related to adhesion between substrate and coating layers. At present such adhesion shortcomings have been eliminated by the advancement in PVD technologies like use of high-power impulse sputtering, pulse DC and arc-PVD. Additionally, the improvements in interface engineering helped in the decision for selection of inter layers at the coating/surface interface for durability as well as thermal and residual stress resistance under the cycling loading conditions. Finite element analysis based numerical simulation methods and other modelling and simulation techniques have also been developed to predict coating efficiency and life under specific loading (Holmberg et al., 2008; Dhinesh et al., 2018). As coating film deposition on the interacting surfaces is an expensive procedure, such modelling and simulation techniques help in finding out the optimized solution for coating material and tribo surfaces and thereby ensure high life of coated surfaces.

Various research studies have shown that the use of low friction and hard coatings improved the fatigue life of gears and roller bearings (Sinha et al., 2020). An increase of seven times in the anti-wear behavior has been reported for the gears and relevant improvement of threefold in gear life time was observed (Doll, 2011). For roller bearings, the increased fatigue life was also witnessed with the use of hard coatings (Zhong-Yu et al., 2020). For coated gears, as high as seven-time high wear protection has been witnessed, resulting in longer gear life. The use of multi-layered coatings (Cr/CrN- & CrN/ZrCrN) on gear surfaces developed high load carrying ability among tribo-pairs even in the saline-based corrosive environment (Seabra et al., 2011). DLC and other low-friction coatings such as MoS_2 can reduce friction of dry sliding contacts by more than 90%. As DLC is harder coating than that of MoS_2, it is widely used to coat engine components (Cha & Erdemir, 2015). The value addition by such coating was provided between the injected fuel and the injector surfaces in terms of lower friction (Neuville & Matthews, 2007). Similarly, in other recent research for fuel injectors coated with SiO-DLC, the result shows higher injector durability than those of non-coated injectors. It was observed that coated parts were at least 100% more durable than non-coated parts, i.e. typical life enhancement of 20 years or 320,000 km (Cha et al., 2020). Moreover, this coated injector was found suitable for protection against corrosions. In addition to the coating films mentioned earlier, engine parts have also been coated with some other coating including hard chrome, CrN, CrN/GLC, WC/Co, AlTiN, TiAlN, AlTiN, AlCrN, W-C:H, AlMgB14-TiB2 and a variety of coatings applied by various different processes (Biberger et al., 2017; Singh et al., 2019; Wan et al., 2017; Jojith et al., 2020; Özkan et al., 2018; Hui et al., 2019; Javdošňák et al., 2019).

For the coatings mentioned earlier, robust adhesion to substrate materials is required to ensure longer life and functionality. In IC engine operating conditions, most of the parts undergo severe cyclic loading conditions as well as high temperatures; therefore, interface adhesion is required to be strong enough to avoid premature delamination and wear. Based upon their performance under different lubrication condition for coating on engine parts, it is evident that PVD and CVD techniques are providing much superior chemical and structural qualities, leading to long part life and high friction resistance. In addition to coatings, different surface engineering solutions are being investigated to improve the lubrication. In this regard, surface texturing has attracted the greatest attention during the last decade. Conventional honing on the cylinder liner surfaces has been a common feature, which was also considered as well-controlled texturing practice. The significant variation in tribological behavior has been witnessed for laser surface texturing (LST). It has been reported that partial LST piston rings exhibited up to 4% lower fuel consumption (Akbarzadeh & Khonsari, 2018; Liang et al., 2020). The LST appeared in the form of dimples of various shapes, depth, density and other geometric features which have different effects on lubrication regimes (Galda et al., 2009). They serve as micro-reservoirs to overcome starved lubrication conditions, micro-traps for wear debris and micro-hydrodynamic bearings for hydrodynamic as well as mixed lubrication. (Stark et al., 2019). Based upon results of research studies, it can be claimed that the modern engine tribology demands adequate lubrication in the presence of optimized surfaces. For optimized surfaces, the combination of surface texturing and coating may be far more effective (Koszela et al., 2018; Mishra & Penchaliah, 2020; Meng et al., 2018; Ferreira et al., 2020; Kim et al., 2017). Thin hard coating on the interacting surfaces is associated with reduction of friction and wear losses, and surface texturing helps in improved hydrodynamic support (Ferreira et al., 2020; Ala'A et al., 2014).

8.4.1 DLC Coatings

As highlighted earlier, the material properties and variety of chemical and structural design of DLCs made them popular among all functional coatings for IC engine applications. Typical structure, mechanical and tribological properties of DLC and ta-C films are shown in Table 8.2. There are various techniques

TABLE 8.2
Structure, Mechanical and Tribological Properties of Diamond and ta-C Films

Classification	Grain size (nm)	Typical RMS surface roughness (nm)	Hardness (GPa)	CoF in humid air
Natural Dimond	large single crystals	Atomically smooth	100	0.01–0.05
Microcrystalline Diamond	1000–10,000	100–1000	90–100	<0.6
Nanocrystalline Diamond	10–100	20–50	80–90	0.05–0.1
Ultrananocrystalline Diamond	3–10	3–20	90–100	0.01–0.03
ta-C	Amorphous	5–10	70–90	0.01–0.05

Source: Erdemir & Martin, 2018.

to deposit DLCs on the substrate surface including ion beam, chemical vapor deposition and physical vapor deposition. Additionally, there are various types of DLCs including amorphous, hydrogenated, hydrogen-free, doped with elements like silicon, boron, tungsten, etc. Each of these types of DLCs is used to enhance material as well as tribological characteristics of the rubbing surfaces, like hardness, toughness, and corrosion resistance, high temperature resistance, wear protection and friction reduction. As compared to other alternatives, DLCs can provide super low friction and wear coefficients together with corrosion protection and resistance to oxidation, which makes them desirable to be used for various applications including engine parts, magnetic hard disk applications, high precision ball bearing applications and aerospace mechanisms (Jeng et al., 2017). DLC is typically a mix of graphitic and diamond-like phases with or without hydrogen, which are doped with specific elements for various performances, e.g., W-doped DLC for high thermal stability (Cha & Erdemir, 2015). Simple structured DLCs with a monolithic phase have been used vastly having a single layer. To improve and modify the mechanical, thermal and tribological behaviour of DLCs, a few alloying elements like silicon, tungsten, and chromium are included. In this regard, the effective coatings for engine parts consist of a various of DLCs and CrN. Specifically, for IC engine applications, lowest values of wear rate and CoF have been reported for DLC-coated surfaces (Bhowmick et al., 2018; Kolawole et al., 2020).

The adoption of DLCs helped in achieving about one-tenth of CoF as compared to that of the best known lubricants and promised results for wear protection. To address different loading conditions and lubrications requirements, in addition to tetrahedral amorphous carbon (ta-C), doped DLCs have also been vastly used for automotive applications. Particularly, Si-DLC films have been successfully tested in several engine parts, and significant tribological improvements have been demonstrated for sliding contacts (Elagouz et al., 2019; M. Zhang et al., 2018; Vinoth et al., 2019). M. Arshad et. al. reported that tungsten-doped diamond-like-carbon (WDLC) coatings in the presence of ionic liquids reduce boundary friction significantly (Arshad et al., 2020). Recently Boron Doped DLC (BDLC) have been emerged as suitable option for low friction for engine applications (Mori et al., 2017; Ren et al., 2019). In another study, WC/C-coated gears show high durability and increased efficiency (Barbieri et al., 2020). For engine applications involving high thermal stresses, the selection of coating is an important decision. DLCs, particularly the hydrogenated ones, are not suitable to be used at high temperatures and have a tendency to wear out during the long run. For such condition, the choices include ta-C and silicon, chromium and titanium doped DLCs. He et al. reported that combination of DLCs with textured surface has shown significant reduction in friction and wear as compared to DLCs alone. The textured DLCs with micro-dimples densities of 39%, 52% and 58% were tested for friction and liquid lubrication conditions (He et al., 2020). The results for lubricated textured DLCs have shown as much as 52% reduction in friction (Figure 8.8). The relevant lubrication mechanism was also elaborated and shown in Figure 8.9.

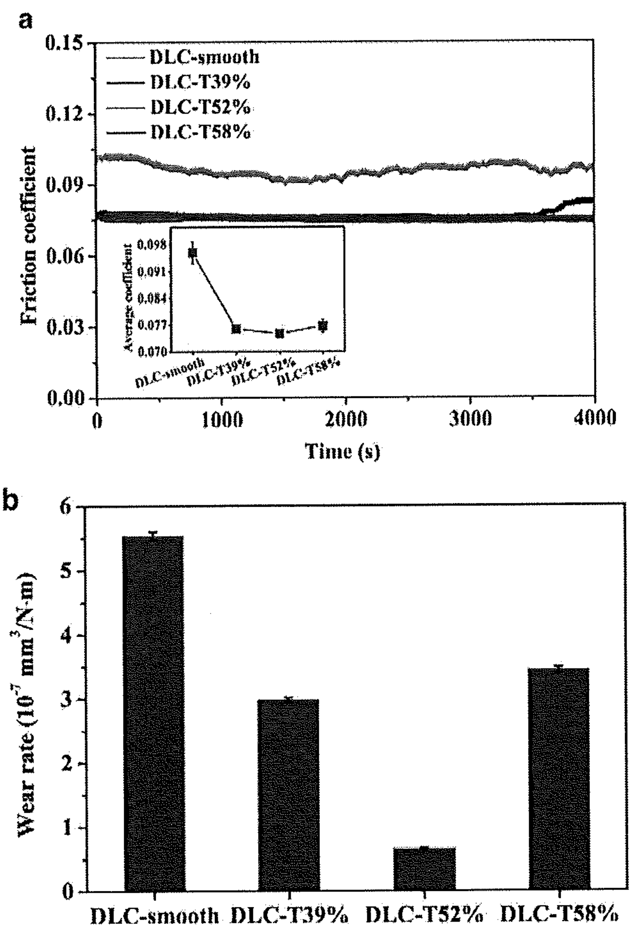

FIGURE 8.8 (a) CoF; (b) wear rate for lubricated textured and untextured DLCs.

Source: He et al., 2020.

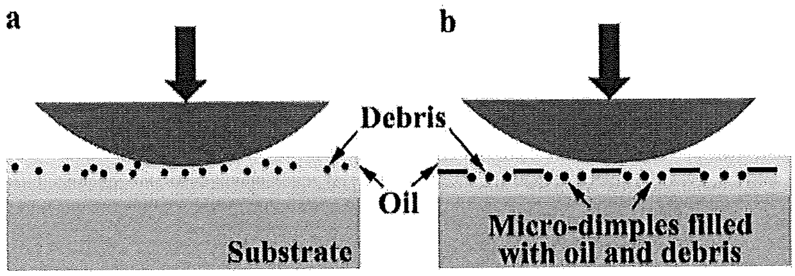

FIGURE 8.9 Lubrication mechanism for (a) untextured DLC (b) textured DLC.

Source: He et al., 2020.

8.4.2 Engine Tribology and DLCs

Different coatings were used and tested for different automotive parts about 25 years ago, mainly in racing cars. Such coating films are applied on engine parts using physical vapor deposition (PVD) and chemical vapor deposition (CVD) approaches nowadays. Modern PVD and CVD systems can be utilized for coating thousands of parts on every deposition cycle, which is cost effective as well (Hosenfeldt et al., 2015). In this regard, DLCs have increased popularity in the recent era, and this coating material is being used for hundreds of millions of engine parts each year (Bewilogua & Hofmann, 2014). In recent years, ta-C coatings are commonly deposited in engine components like cam and followers, piston rings and piston pins in huge quantities (Kano et al., 2017; Götze et al., 2014).

As engine interacting parts undergo different lubrication conditions and regimes, different types of DLCs have been tested which have shown high performance in different conditions. Under boundary-lubricated conditions, where direct surfaces contacts occur, specific DLC coatings (like ta-C) have appeared to surprisingly reduce friction and safeguard surfaces against wear. Similarly, in case of slip-rolling contact geometry and high loadings, it has been observed that ta-C coatings outperformed the other types of DLCs (Woydt et al., 2012). For high-load carrying capacity requirement, the mechanical properties of DLC coatings play a significant role, and it has been noticed that DLCs with sufficient hardness could survive. For low-loading conditions, a high-level of sp2-bonded carbon played an important role in decreasing in wear for boundary regime (Ciarsolo et al., 2014). For mixed and hydrodynamic lubrication phenomenon, the effect of DLCs could be marginal, but for the oleophobic DLC, reduction of shear forces may be achieved. Thus, functions of DLCs include high lubrication performance, strong anticorrosive behaviour and their safe trend towards human beings. The findings about superior tribological performance of such coatings prompted their vast use for IC engine parts. Therefore, DLCs have been vastly applied to the sliding interacting tribo-pairs of IC engines, such as pistons, piston rings, cam-tappets and fuel injectors for required performance in serve operating conditions. The aluminium alloy piston of motorbike coated with DLC is shown in Figure 8.10. As environmental concerns and relevant legislations are also a key factor in developing a lubrication system, researchers and tribologists are also focusing on a combination of DLCs with an environmentally friendly lubricant (Arslan et al., 2018; Abdul, 2018). Over the years, the application of DLCs is applied to variety of parts. Table 8.3 shows the details of such applications of DLCs to automotive components.

For the coupling clutch application, the results of using Si-doped hydrogenated carbon coating include high wear protection, resulting in an improved clutch system (Kano, 2015). Similarly, in another application for gears, WC/a-C:H coating was used for high wear protection. For motorcycles, the (a-C:H) coating was applied to the front fork to reduce friction (Kano, 2015). The application also includes the tribo-pair in a suspension system on luxury vehicles (Sadaaki et al., 2007). The PVD method is being used for deposition of tetrahedral amorphous carbon (ta-C) coating, for valve lifters and piston rings of mass-produced IC engines. In addition to tribo-testing in the laboratory testing, the tribological performance of DLC coating

FIGURE 8.10 Wear Protection of DLC coated piston.

Source: Kano, 2014.

TABLE 8.3
Application of DLC Coating for Vehicle Parts

Parts	DLC	Coating	Tribological Properties
SUV 4WD coupling clutch	a-C:H-Si	PECVD	Excellent friction reduction and wear protection
SUV differential gear	WC/a-C:H	PECVD	High wear protection
Motor bike front fork	a-C:H	PECVD	High wear resistance
Fuel injector, Pump	a-C:H	PECVD	High wear protection
Motorcycle engine piston ring	WC/a-C:H	PECVD	High wear resistance
Engine valve lifters	ta-C	PVD	Ultra-low friction and high wear protection
Engine piston rings	ta-C	PVD	Ultra-low friction and high wear resistance

Source: Kano, 2014.

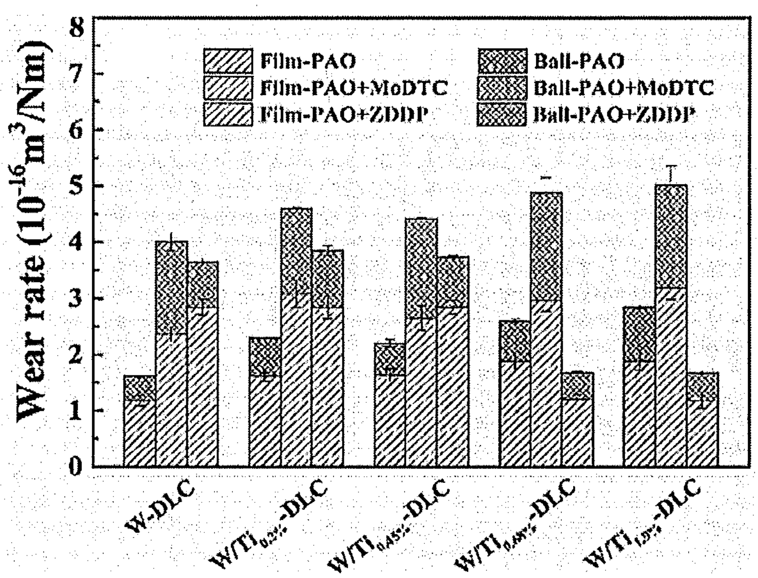

FIGURE 8.11 Wear rate for different doped DLCs using different lubricants combinations.

Source: S. Zhang et al., 2019.

was also found promising in actual engine cam and tappet interaction of valve train systems (Zahid et al., 2018). Lanigan reported, that for piston ring-cylinder interaction, ultra-low wear rate was observed for ta-C coating (Lanigan, 2015). Similarly, doped DLCs have different wear rates for different lubrication conditions. The wear rate comparison for W-DLC and W/Ti-DLC is shown in Figure 8.11.

Besides deposition on hardened steel, applications of DLC coatings on low weight metals have also been reported. Such applications include a titanium-based lightweight valve lifter and a valve spring retainer of an aluminium alloy (Doi & Kurita, 2013; Ahn et al., 2007). In another study for DLC in engine application, a DLC coating was deposited on the slider pad to make it more compact (Schultheis et al., 2012). Thus, using the lightweight materials along with coating technology was found effective to improve automobile fuel efficiency. It is anticipated that such lightweight materials with DLCs will be a promising solution for energy efficiency and a way towards eco-friendly efficient vehicles.

8.5 DLC FOR ENGINE SUBSYSTEMS

High wear protection and significant reduction in frictional energy losses have been achieved by DLCs for various tribo-pair in laboratory-based simulations as well as for actual operating conditions. The understanding of various lubrication regimes during actual engine operating conditions is essential to comprehend the suitability and compatibility of surface coatings for various engine parts. Figure 8.12 shows

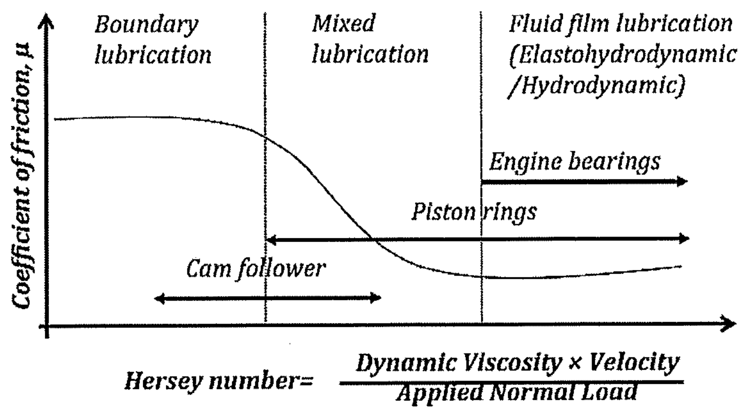

FIGURE 8.12 Stribeck curve for engine lubrication.

Source: Chong et al., 2019.

a Stribeck curve for engine parts lubrication, where it can be observed that the engine interacting parts operate in various lubrication regimes. The overlapping of lubrication regimes can be observed for the engine lubrication system. Based on the variation in the speed, various engine components undergo different lubricating oil regimes. The cam/tappet interface in the valvetrain system mainly work in the boundary and mixed lubrication regime. While engine bearings operate predominantly in elastohydrodynamic and hydrodynamic regime. The piston assembly (piston ring, piston skirt) operates in mixed lubrication, elastohydrodynamic and hydrodynamic regimes. In fully flooded conditions, metal-to-metal contact is avoided and surfaces are separated by lubrication film; thus, application of a surface coating may not be effective for lubrication performance. However, significant effectiveness of such coatings has been witnessed for boundary and mixed lubrication regimes. In such regimes, use of DLC coating helped in enhancing tribological performances by controlling the wear rate and friction due to direct contact between surface asperities. The subsequent section will highlight the individual sub system of IC engine and effect of DLCs on these subsystems.

The present CVD and PVD methods are providing appreciable chemical and morphological characteristics to coated surfaces resulting in long life and reduced CoF, even under minimal lubricated reciprocating test conditions (Erdemir & Voevodin, 2010). Low friction coatings like MoS_2 and DLC are tribologically suitable due to their inherent nature making them capable of reducing friction of dry sliding contacts. However, due to its soft coating nature, MoS_2 is not used as a primary coating for engine parts. For this reason, DLC is broadly used as an overcoating in various engine parts due to its superior hardness than that of MoS_2 and its hardness can be modified as well for specific requirements. DLCs have gained the utmost attention in recent years due to their variants and flexibility in structural and chemical behavior as compared to existing counterparts. Furthermore, DLCs have shown enhanced tribological behavior under both lubricated and dry conditions when compared to other coatings (Sulaiman et al., 2019; Kovacı et al., 2018). According to a systematic study done by Kano et al. (Kano, 2014), DLCs can help reduce boundary friction by approximately 90% in the existence of some polar additives. In fact, by using different kinds of additives in combination with low-friction coatings like DLC, it seems possible to obtain much lower friction. The combination of additives like glycerol monooleate and a poly-alpha-olefin oil resulted in a CoF of 0.05 in reciprocating testing conditions with ta-C. On the other hand, the same combination when lubricated by pure glycerol resulted in a friction coefficient as low as 0.005 (de Barros Bouchet et al., 2009; Martin et al., 2010), which is one-tenth of what is being attained with available lubricating oil packages. At present, DLC coatings are being applied in an enormous amount for automotive components, operating under lubricated conditions and high temperature conditions, efficiently decreasing the friction coefficient (e.g. valve-train parts). Moreover, DLC coatings are used as wear protection (e.g. piston pins) (Choleridis et al., 2018). Other than ta-C, doped DLCs have also gained popularity for engine parts applications. Specifically, silicon doped DLCs have been attempted for various engine components, and substantial advancements in wear and friction have been observed for boundary lubrication. M Kalin et al. reported 50% more wear reduction using Ti-doped DLC as compared to W-doped DLC coatings (M Kalin et al., 2010). In addition to coatings, numerous surface engineering methods are used to regulate engine wear and friction. Among others, surface texturing has garnered the utmost attention in recent years. Honing is a well-controlled texturing practice for ring-liner assemblies, which has been used by the industry for many years. Using surface texturing, a substantial reduction in wear and low specific fuel consumption of an IC engine by 2.5% were found after DLC coating of cylinder liners than those of uncoated ones (Koszela et al., 2018). Such textured surfaces are having dimples, which help in wear reduction by efficiently trapping the wear debris or foreign particles produced at reciprocating surfaces. Thus, improved fuel efficiency as well as enhanced parts life can be expected by incorporating surface texturing on engine and valvetrain parts.

8.5.1 DLC for Valvetrain

In the valvetrain subsystem of an IC engine, the cam/tappet tribo-pair experiences the peak loads, and relevant frictional loss is about 85% of the whole valve train (Lyu et al., 2020). Therefore, various studies have considered the tribological improvement for DLC coated cam and follower contact in valvetrain assembly (Al-Jeboori et al., 2018; H Okubo et al., 2020). Due to their small size as compared to camshafts, the deposition of DLC is economical. For the cylindrical surface of a steel tappet, no coating is required; however, the top surface of tappet is coated for wear protection and to avoid friction. Ratamero and Ventura reported that the fuel consumption of a light passenger vehicle with tappets coated with DLC was different than the fuel consumption of the same vehicle having noncoated tappets (Ratamero & Ventura, 2018). An improvement of 0.5% fuel economy was observed for DLC coated case. For the cam/tappet interface, variants of DLC coatings showed improved friction reduction (Broda & Bethke, 2009; Marian et al., 2019). Apart from tribological behavior improvement, additional benefit in terms of surface protection was observed for DLC

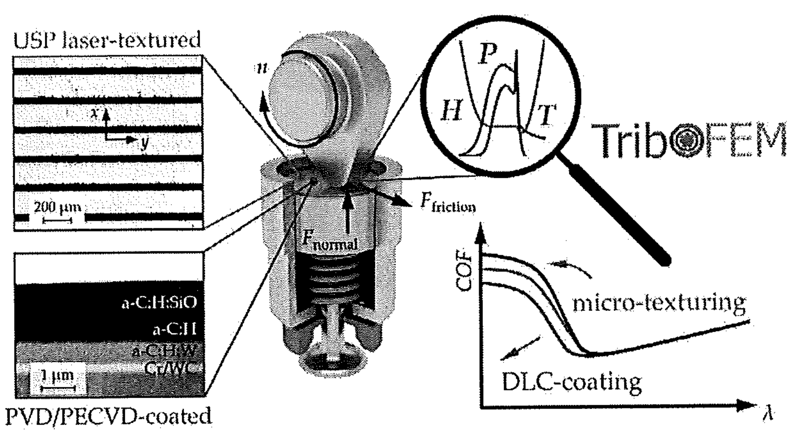

FIGURE 8.13 Friction Reduction in the DLC coated Cam/Tappet-Contact.

Source: Marian et al., 2019.

coated cam-tappet tribo-pair (Dobrenizki et al., 2016). In another study, a hydrogen-free DLC as an amorphous carbon film (a-C) was applied to an engine valve lifter to reduce mechanical losses (Mabuchi et al., 2007). Though DLC variants showed improved friction-reduction ability in the presence of friction modifiers, the use of DLCs in combination with a friction modifier for friction reduction was not found useful in some cases (Okuda et al., 2007). In a recent study, valvetrain cam/bucket tappet interaction was investigated to analyze the friction behaviour of microtextures and PVD/PECVD deposited silicon-doped hydrogenated amorphous DLCs (Marian et al., 2019). The results showed, a significant friction reduction of up to 30% by use of the DLC variant mentioned. The graphical abstract of this study is given as follows in Figure 8.13.

8.5.2 DLC for Piston Assembly

Various parts of piston assembly undergo different lubrication regimes depending upon the operating conditions. In this regard, piston rings mainly operate under boundary and mixed lubrication regimes at low speed, but at high speed, hydrodynamic regime may be observed. As piston rings operate under boundary as well as mixed lubrication regime, there is an opportunity to enhance tribological behavior of such surfaces with the help of DLCs. The details of such studies are relevant results for parts of piston assembly and are discussed in the following section.

8.5.2.1 DLC Coated Piston Rings

For the case of DLC coated piston rings, in addition to tribological performance, the improvement in material properties of surfaces was also considered. Vinoth et al. reported that DLCs can be applied to automobile components, particularly piston rings, for high lubrication performance and appreciable micro-hardness. The surface polishing effect after deposition of DLC coating on the piston ring surface helps in reducing the relevant shear, thus reducing frictional losses. (Vinoth et al., 2019). In another study, the top compression ring coated by DLC resulted in significant reduction of the wear rates and CoF (Tas et al., 2017). It was observed that the DLC coated piston rings protected the cylinder liner from scuffing up to 600 N normal load. The reported lubrication mechanism was attributed to the formation of a mixed tribolayer on the liner surfaces that existed in all tested loads. It was observed that, for low friction, the suitable condition is a DLC coating deposited to a smooth ring surface (mirror-polish finish). Higuchi et al. reported that an H-free DLC coated top ring reduced friction by 10%. The friction reduction effect of H-free DLC deposited on an oil ring was comparatively low. It is also important to highlight that low frictional losses were observed when lower viscosity engine oil was used (Higuchi et al., 2017).

The increased hardness by DLCs is expected, which may cause abrasive wear when interacting with a softer surface. However, the piston ring-cylinder liner contact must be designed tribologically in such a way that the improvement of one sliding part will not cause the damage of the other one.

With the advances in surface texturing techniques, a combination of surface texturing and DLC was found suitable in specific testing condition. A combination of the texturing and coating showed 12.5% improvement in the frictional behavior (Akbarzadeh & Khonsari, 2018). The relevant friction results for considered surfaces are shown in Figure 8.14.

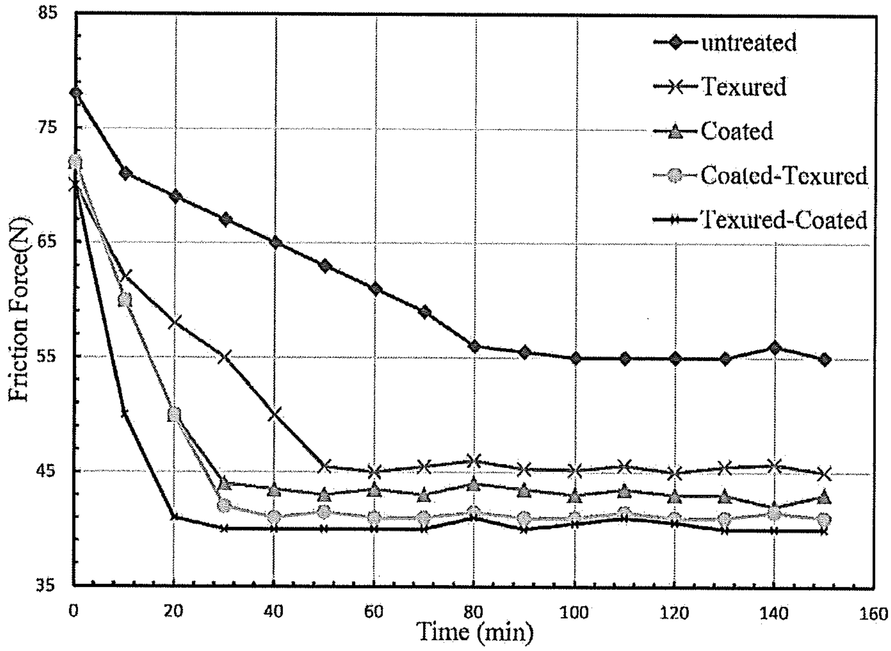

FIGURE 8.14 Frictional force of piston ring for various surface treatments.

Source: Akbarzadeh & Khonsari, 2018.