Part I

Overture

1

Wear in the Heavy Duty Engine

1.1 Introduction

Stringent standards in different countries for both nitrogen oxides (NO_x) and particulate emissions from diesel engines are becoming unified with national boundaries becoming blurred (Figure 13.1). Emissions increase with engine wear. The easily observable consequences of wear in a diesel engine are the increases in smoke and consumption of fuel and oil. An assured wear life of 8000 hours is expected for a typical off-road engine in the field. Similarly, the vehicles on the road are expected to have an assured wear life of a million kilometres or more. Running many engines in the laboratory or multiple vehicles in the field may help to establish the reliability of the engines and their life. However, it is too late to recognize a problem during these trials. To satisfy reliability, after every failure in the field the engineer is asked to run more vehicles for a geometrically increasing number of testing hours. To prove the engine reliability could take up to three years in the normal course; this is longer than the life of newer emission regimes, and hence it is costly to repeat reliability experiments. In addition, the estimation of life, even by modern reliability methods, is straddled with an error of 50%.

Modern design procedures are detailed and well established against gross failures like fatigue, breaking and loosening. Therefore, only the micron sized failures at the surfaces that result in wear affect the life of an engine. Apart from the basic design aspects that are grounds for 'normal' wear or aging, extreme loads, environments like a dusty atmosphere plus quality of maintenance, fuels and oils bring an earlier end to the life of an engine. If the engine that has lasted its wear life is studied, only less than 0.01% of the total mass of the engine has been wasted away. In other words, more than 99.9% of the mass has survived when the parts are replaced at the end of their wear life. If the normal and abnormal wear is understood early based on the application or design of an engine, it is possible to incorporate features and protections in the design so that the engine is able to complete its expected life with sufficient margin.

1.2 Engine Life

In a diesel engine, the critical parts that wear out are the piston and ring assembly, liners, valve train, valves and bearings. The minimum lives of these parts determine the life of an engine. In other words, the wear life of an engine can be described as the bottom overhaul interval when all the worn parts are changed. The overhaul lives of various engines of different sizes (Chapter 2 references) are plotted in Figure 1.1. The points in the figure are normalized for a common load factor of 0.8 (Chapter 2). Apparently, the life of an engine seems to be a direct function of the power produced by the engine

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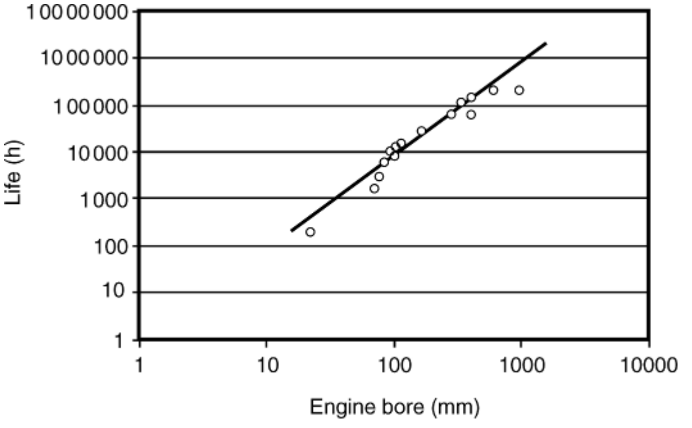

Figure 1.1 Dependency of wear life on engine size

per cylinder, which in turn depends on the size of the engine. The graph shows dependency of life of an engine on its bore.

1.3 Wear in Engines

1.3.1 Natural Aging

At a given load and speed, the pressure and the relative velocity of the pairs of wear parts in an engine vary cyclically undergoing varying degrees of lubrication. All the wear parts in the engine are separated by a thin film of oil. During most of the cycle, the hydrodynamic pressure generated at the wedge shaped interfaces (Figure 1.2) of the pairs of wear parts is sufficient to lift the surfaces beyond their micron sized roughness. However, within a cycle, the thickness of the oil film could drop so low that the pair may come in close contact in some zones. In addition, during starting and stopping in the normal life of an engine,

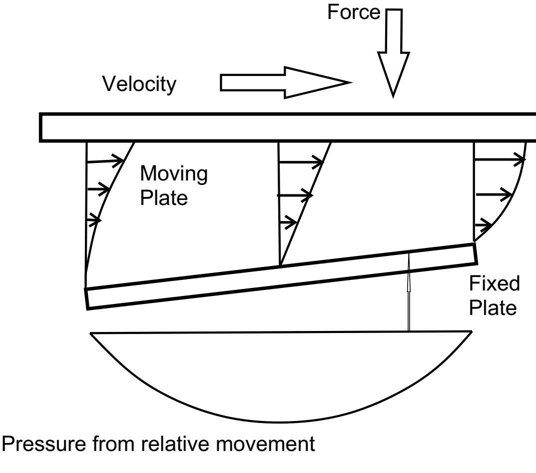

Figure 1.2 Lifting pressure generated by flow of oil in the wedge between relatively moving plates

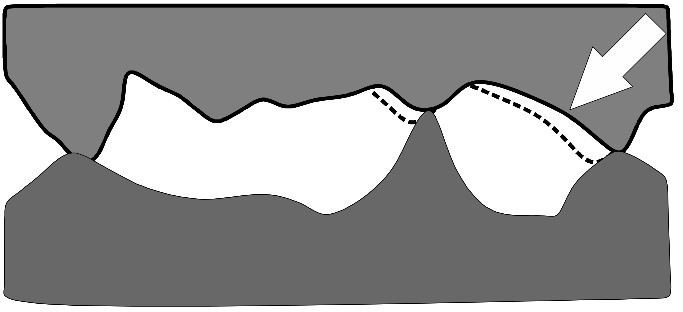

Figure 1.3 Microscopic view of the asperities of bearing surfaces in contact, where the local load is not normal to the nominal surface

the parts run at a relative velocity so small that the asperities of the two wear surfaces come in contact and very high contact pressures are generated at the roughness peaks. Since the peaks are random in occurrence and shape, an element of probability is introduced in their loading and in the direction of loading on the peaks, which is not always normal to the nominal surface (Figure 1.3). The pressure bends the roughness peaks in the local direction of application of load. Even if the local stress is less than the plastic limit of the material, the asperities break away in pieces after many cycles of load, due to fatigue. If there is a special affinity between the metals of the surfaces, it is possible that metal from one surface is transferred to the other surface causing adhesive wear. Such an eventuality is not unusual in the main and connecting rod bearings, which are highly loaded every engine cycle. Therefore, wear takes place when the surfaces separated by a thin oil film come in contact during operating conditions.

1.4 General Wear Model

The wear of a wide range of material combinations has been studied in unlubricated conditions in detail for different loads and relative speeds of wear surfaces (Archard and Hirst,1956). As a broad classification, two contrasting mechanisms of wear have been observed. In nearly all experiments, and for all types of wear mechanism, once equilibrium conditions are established at the surfaces, the wear rate ($kg\,s^{-1}$) is independent of the apparent area of contact. The wear rate is proportional to the load with the same surface conditions. In practice, this simple relation is modified because the surface conditions depend on the load. These rules of wear may be derived, on basic grounds, from the experimental results, or from more detailed theoretical calculations on the different wear parts of an engine.

1.5 Wear of Engine Bearings

The bearing overlay of about 20 microns thickness is an alloy of tin, antimony, copper and lead. This alloy has some important properties, namely, the ability to absorb lubricating oil on the surface and hence provide lubrication when the bearing is starved, the ability to absorb small particles of dirt (embeddability) without increasing the wear of the bearing or crankshaft and seizure resistance, so that it does not weld itself to the crankshaft material even under extreme loads or high speeds. Lastly, it must be able to be run slightly out of alignment without wearing out. Also, the material enables some kind of healing in the event of mild seizure and the material is transferred back to the parent bearing. The parts are heated by friction and also by heat transfer from the hot environment (e.g. hot combustion gases). The copious amount of oil flow between the surfaces enables washing away of both the debris and the heat. These wasted metal particles are found in the oil, sump and the oil filter.

1.6 Wear of Piston Rings and Liners

Usually, today there are three rings in engines that have a swept volume less than three litres per cylinder. Larger engines have four or five rings and they are always above the piston pin. Rings below the piston pin are out-dated, as the arrangement seriously interferes with the supply of oil to the rings above the piston pin and causes excessive wear of the rings and the piston skirt. The three piston rings are nearly always made of three different materials. The oil control ring is the bottom ring and this has significant amounts of lubricant but its job is to limit the lubricant reaching the compression rings above it and this makes life a little difficult for the compression rings. Therefore, the compression rings have to work with very little oil. The lower compression ring is usually an alloy of chrome, while the top ring is usually an alloy of cast iron. In some engines, steel rings are used at the top. Wear is prevented by a thin layer of oil on the surface and oil adsorbed in the surface of the bore and piston rings. The oil film temperature at the top ring is maintained by not only the coolant but, more importantly, also by evaporation of oil trapped in the rough valleys of the liner surface. The reciprocating nature of the piston transfers some lubricant from the cylinder wall to the piston ring and this stops the pistons and rings from seizing in the bore.

1.7 Wear of Valves and Valve Guides

Valves and valve guides, especially the exhaust valve and guide, survive in the harshest environment in an engine. They operate at temperatures ranging from below freezing to as high as 1000 °C. At the valve guide, the gas is at a pressure in excess of 0.3 MPa. The gas flow coats the inside of the guide with deposits of carbon. The guide and the valve seat conduct heat away from the valve into the water jacket to prevent it from melting. The guides are sometimes made of porous sintered metals which absorb oil to lubricate and cool the valve stems.

1.8 Reduction in Wear Life of Critical Parts Due to Contaminants in Oil

In a normal engine, the natural wear is far less than the wear due to contaminants in the oil, such as the metal debris, soot contributed by combustion and the dust from environment in which the engine is working. There are almost no roller or ball bearings inside an engine of a swept volume less than three litres per cylinder because they are more susceptible to damage by contamination as well as quite noisy and expensive to produce.

The combustion gases contain acid, soot and heat. At the walls of the liner, the oil is kept relatively cool by the coolant but it faces the intense heat of combustion protected only by flame quench distances and the flow boundary layer along the wall. At very abnormal conditions like knocking, the boundary layer can be torn and penetrated by the high temperature gases instantaneously (Heywood, 1988), and the oil can become over heated. Also, the soot of combustion in diesel engines disperses in the oil. In engines using exhaust gas recirculation (EGR) and late post injection to aid regeneration of diesel particulate filters, the problem is accentuated. Contamination of lubricating oil by diesel soot is one of the major causes of increased engine wear (Totten, Westbrook and Shah, 2003), especially with EGR technology used to curb nitrogen oxides (NO_x) emissions. The dispersion of the soot in oil is increased by additive packages containing zinc dithiophosphate (ZDP) for these engines (Sam, Balla and Gautam, 2007). Otherwise, in normal conditions, the oil degrades slowly by oxidation and sludge forms. The strong acids formed during combustion in the presence of water vapour dissolve in the oil and the acidity of the oil increases. The oil contains alkaline compounds to neutralize these acids. However, all the weak acids formed under heat in the oil are not neutralized, and hence oil in use is both acidic and basic at the same time. The acids cause corrosive wear. In addition, the air taken in by the engine contains dust particles of different sizes and only about 99.9% of it is filtered at the air filters. As the filter accumulates dust, its efficiency improves at the cost of increased loss in pressure across the filter element. Thus, in a new filter, 0.1% of the dust enters the engine and a small part of it is retained on the wet walls of the liner to be washed by the oil on the liner to the oil sump. The higher the concentration of the dust in the air entering the filter, the higher is the quantity of dust entering the engine as the percentage filtration remains the same for a given air filter. Excessive soot, dust and acid cause abrasive and corrosive wear of critical parts of an engine.

1.8.1 Oil Analysis

The periodic analysis of wear metals in the oil, therefore, diagnoses various parts that are wearing out in the engine and at what rate. It enables the user to take the right action in time. A comprehensive list of sources of wear metals in oil is given in Table 1.1 (Bentley Tribology Services, 2010; Totten, Westbrook and Shah, 2003).

Table 1.1 Sources of wear metals in oil

Metals	Wear Metal Source
Iron	cylinder liners, piston rings, valve train, crankshaft, rocker arms, spring gears, lock washers, nuts, pins, connecting rods, engine blocks, oil pump, gears, pinions, case hardened teeth, pump, motor, vanes, pump housing, cylinder bores and rods, pistons, bearings, cylinders, housing, shafts, piping
Copper	valve train bushing, wrist pin bushing, cam bushings, oil cooler core, thrust washers, governor, connecting rods bearings, valve gear train thrust buttons, oil cooler baffles, plates, thrust washers, bearings, wear plates, thrust washers, oil pump, thermostats, separator filters
Tin	valve train bushing, wrist pin bushing, cam bushings, oil cooler core, thrust washers, governor, connecting rods bearings, valve gear train thrust buttons, journal bearing pads (babbit), bearings, separator filters
Aluminium	engine blocks, pistons, blowers, oil pump bushings, bearings (some) cam bushings, oil coolers, pistons, aluminium complex grease contaminant, coolers, baffles, plates, housing, bearings, cylinder guides, wear plates, thrust washers, residue from synthetic media (alumina) filters
Chrome	rings, liners, exhaust valves, zinc chromate from cooling system inhibitor, shaft coatings, some special gears are chrome plated, cylinder liners, cooler tubes, baffles, plates, bearings, cylinder guides, wear plates, thrust washers, bearings, oil pump, oil coolers
Lead	main bearings, connecting rod bearings, red lead paint flakes
Silicon	engine blocks (alloying element with aluminium parts), ingested dirt from breathers, external sources, defoaming additive in lubricant, elastomeric seals, oil coolers, cooler tubes, baffles, plates, ingested dirt, silicone sealant, bearings, cooler (alloyed with aluminium)
Silver	valves, valve guides, cylinder liners, bearings, heavy alloying element for tool steel gears
Metallic additives	
Sodium	corrosion inhibitor additive, also indicates coolant leak into oil, can also be road salt, sea water, ingested dirt
Boron	corrosion inhibitor additive, anti-wear/antioxidant additive, coolant leak, grease contamination
Magnesium	detergent/dispersive additive, can also be alloying element in steels
Calcium	detergent/dispersant additive, alkaline reserve additive for high sulfur fuelled engines, can be grease contamination
Molybdenum	solid/liquid anti-wear additive, alloy in bearing and piston rings
Barium	corrosion inhibitors, detergents, rust inhibitors
Zinc	anti-wear corrosion inhibitors, anti-oxidants, alloying element for bearings, thrust washers, galvanized cases
Phosphorus	anti-wear corrosion inhibitors, antioxidant additives
Titanium	wear metal for aircraft engines, bearings, paint (titanium dioxide)
Vanadium	fuel contaminant, can also be alloying element for steel

1.9 Oils for New Generation Engines with Longer Drain Intervals

Oil is a part of the engine build like the connecting rod or the piston, unlike fuel and air which are consumables. The life of the oil is defined as the oil drain interval. The main driving force since 1990 for the development of API grades of oil is the concern over the environmental impact of diesel engine emissions. To further control emissions, lower limits on diesel fuel sulfur are set (reduction from 500 ppm sulfur to 15 ppm) (EPA, 2000). Demand for longer lasting oils as well as the concern over increased temperatures of the engine and oil sump due to current and future engine designs to meet these emissions standards have further driven the development of new engine oil service categories.

1.9.1 Engine Oil Developments and Trends

Selective catalytic reduction using ammonia from urea solution in conjunction with high pressure fuel injection enables achievement of very low nitric oxide and particulates levels along with the improved fuel efficiency by up to 10%. This technique is popular among most of the (truck, marine and electric power generation) engine designers in the world. Nevertheless, wary of handling urea solution, some engines are designed using a combination of cooled exhaust gas recirculation (EGR) at higher rates (30–35%) and exhaust after-treatment devices, such as catalytic diesel particulate filters and oxidation catalysts. There are some engines (Griffith, 2007) that use EGR gases drawn after the particulate filter and the clean gas does not induce engine wear. However, EGR engines commonly allow only unclean gases that cause wear. Therefore, the new generation of engine oils and diesel fuels are developed to provide durability of emission control systems, prevent catalyst poisoning and particulate filter blocking, while still offering optimum protection for control of piston deposits, oxidative thickening, oil consumption, high temperature stability, soot handling properties, foaming and viscosity loss due to shearing (Ludwig, 2007).

The diesel particulate filters are expected to operate for at least 240 000 km before they need cleaning. Engine emissions must comply for 696 000 km. The particulate filters are kept from clogging by active regeneration using electric or diesel heating or by passive regeneration using a catalyst (DECSE, 2000). The remaining residue and ash is blown against the exhaust flow and into a trap for disposal.

The new generation EGR engines generate more soot and experience higher peak cylinder temperatures due to the higher levels of EGR. This requires engine oil with improved oxidation resistance. A small amount of engine oil enters the combustion chamber and burns; its ash-like residue can lead to rubbing wear on the cylinder liner, causing the piston rings to not operate freely and, hence, higher oil consumption. In addition, metal oxide particles (ash) can be carried downstream with the exhaust to clog the diesel particulate filter.

In the exhaust stream, sulfur inhibits the effectiveness of the particulate filters by poisoning, and desensitizes the oxidation catalyst and the filter. It increases the conversion of sulfur oxides to sulfates, hence increases particulate emission and clogging of the filter. This can lead to reduced engine performance, due to increased backpressure and ultimately failure of the particulate trap.

Phosphorus in heavy duty diesel engine oils comes from the anti-wear agent zinc dithiophosphate (ZDP), corrosion inhibitors, friction modifiers and antioxidants. It can deactivate and damage the noble metal catalysts by coating on the active catalyst sites. As a result, harmful emissions, such as nitrogen oxides, carbon monoxide and hydrocarbons, increase.

To protect the after-treatment devices, the engine oil will have to contain lower sulfated ash, sulfur and phosphorus (SAPS), while still offering protection to the wear surfaces. SAPS are found in or derived from additives and base oils which help to extend oil drain intervals, base number (BN) retention, and protect against wear, oxidation, corrosion and piston deposits. However, lower sulfur in the new fuels is a blessing in disguise. Because of the use of ultra low sulfur diesel fuel in on-road applications, the metallic additives needed to maintain the required basicity (BN) of the oil will be correspondingly less, and thus the exhaust will have slightly lower ash content.

Considering all the points described above, API CJ-4 is developed to ensure protection of the after-treatment devices with chemical limits targeting the SAPS set for the first time ever for heavy duty diesel engine oils.

1.9.2 Shift in Engine Oil Technology

The low ash levels and the reduction in sulfur levels of the base oil and additives require replacing conventional metal-containing additives with alternatives low in metal content and sulfur, and in some cases ash-less. The use of these alternative additive chemistries has reduced the required basicity number from 10. For on-road diesel engines, this reduction in BN does not affect current oil life (drain interval) because of the use of ultra low sulfur diesel fuel (15 ppm maximum). Nonetheless, it can reduce oil drain intervals in diesel engines that will still be allowed to use 500 ppm sulfur fuels, for example, off road (Ludwig, 2007, Chapter 13).

The reduction in sulfur and volatility limits and the need for increased oxidation stability due to the increased thermal stress placed on the engine oil by the use of heavy EGR rates and after treatment resulted in an increased use of Group II, Group III and Group IV base stocks. The likely additional after-treatment devices, for example lean NO_x catalysts, lean NO_x traps, will further limit the chemistry of the oils to ensure compatibility of the catalyst and hence a number of severe tests are carried out to study the wear behaviour of critical parts (Whitcare, 2000) like cylinder liner, bearings, pistons and valve train.

1.10 Filters

Abrasive wear, pertaining to the internal combustion engine, has been the subject of numerous technical investigations, papers and articles. The majority of these presentations are in the area of filtration and the prevention of excessive or abnormal wear. Maintenance men must learn to determine if abrasive wear is present and then take corrective measures (Kolbe, 1969).

The contaminants from atmospheric air, combustion and degradation of oil are the most important in reducing the wear life of critical parts of a diesel engine. It is absolutely necessary to have improved filtration for air and oil filters to reduce engine wear (Fodor, 1979, 1982). The oil is operated by monitoring the contaminants within safe limits. Oil is one of the engine critical parts whose drain life must be very large. Therefore, filters play the most important role in maintaining the concentration of contaminants in the oil at a tolerable or economic level, as too large and fine a filter will be costly and unwieldy. The oil life is estimated when the acidity reaches the basicity or when the wear debris in the oil reaches set limits and the oil is ready for draining.

1.10.1 Air Filter

Airborne dust (quartz) is very abrasive and the most common cause of high wear of critical parts in engines. Studies have shown that engine life is a function of cleanliness of the air taken in (Sherburn, 1969). Concentrations and sizes of dust taken in by the engine determine wear life of an engine. Engine wear is produced by particles in the size range 1–40 μm and the most harmful particles are in the range 1–20 μm (Needleman and Madhavan, 1988; Treuhaft, 1993). Even in small amounts it can significantly increase the wear on piston rings and cylinder walls. By using high efficiency air and oil filters, engine wear can be significantly reduced (Jones and Eleftherakis, 1995). A part of the dust ingested by the engine eventually ends up in the oil. Silica in the oil should less than 25 ppm to limit its harmful effect. A new filter in modern engines has an efficiency of 99.8% and after about 20 000 km on the road this reaches 99.95%. In other words, the wear rate decreases fourfold, sometime after the new air filter element is placed.

1.10.2 Oil Filter

Similar to the air filter, the oil filter is a percentage filter, and hence a fraction of the dirt, soot and sludge inevitably passes through the filter to the bearing surfaces along with the oil. These particles initiate three-body wear and may result in seizure when caught in the small bearing gap but for the embeddability property of the overlay.

To enhance the wear life of the engine and the oil drain life, high capacity fine filters and bypass filters are helpful. A filter is considered nominally efficient at a certain micron level if it can remove 50% of particles of that size. In other words, a filter that will consistently remove 50% of particles 20 microns or larger is nominally efficient at 20 microns. Three times the reduction in the contaminants could be observed by using a ten micron bypass filter in conjunction with a main filter rated at 40 micron (Land, Shadday and Philips, 1979). Abrasive engine wear can be substantially reduced with an increase in filter efficiency. Compared to a 40 micron filter, engine wear was reduced by 50% with 30 micron filtration. Likewise, wear was reduced by 70% with 15 micron filtration (Staley, 1988). A filter is considered to achieve absolute filtration efficiency at a certain micron level if it can remove 98.7% of particles that size. Today, it is usual to have a 15–20 micron full flow filter with a tighter bypass filter. It was also reported by Staley (1988) that for the same oil quality, the wear of the main bearing was proportional to the contaminants and that improving the filtering improved the wear rate of main and connecting rod bearings by better than 95% and of the piston ring wear rate by 90%. In other words, if the contaminants are completely eliminated from the oil, the wear life of engine parts would enhance substantially.

1.10.3 Water Filter

Scale is formed in the coolant circuit and also there is precipitation of hard salts in the water. These are abrasive and wear out the seal in the water pump. Also, where the velocity of water flow is less and the passages are narrow, build up of debris could obstruct the coolant flow and cause heating up of the engine and oil film locally. Boundary lubrication related wear could be the consequence. A bypass filter in the water circuit solves these problems satisfactorily.

1.10.4 Fuel Filter

Advanced emission norms require higher injection pressures. However, higher injection pressures are obtained with very tight clearances between the metallic parts in the fuel injection pump and the injector so that the leakage through the clearances is kept low, even at higher fuel pressures. Correspondingly, the demand on the fuel filters for higher efficiency to limit small particles is high.

1.11 Types of Wear of Critical Parts in a Highly Loaded Diesel Engine

The book focuses on the life of the critical parts namely liner, piston, piston rings, bearings and components in the valve train affected by the adhesive, abrasive, corrosive and fretting wear.

1.11.1 Adhesive Wear

This form of wear occurs when two smooth bodies slide over each other or one surface adheres to the other. The strong adhesive forces arise out of intimate interaction at molecular level. In this process, the wear particles are pulled off from the softer surface and become welded to the harder surface. For example, cylinder bores will wear at the top ring reversal zone due to the adhesive action of piston rings under gaseous load.

1.11.2 Abrasive Wear

Abrasive wear occurs when a rough surface slides against hard particles, causing a series of scratches on the smoother surface, and the material from the softer surface is displaced in the form of wear particles. For example, a diesel engine running on heavy furnace oil undergoes wear of the piston grooves due to abrasive action of hard carbon particles produced by combustion.

1.11.3 Fretting Wear

Fretting wear arises when contacting surfaces undergo oscillatory tangential displacement of small amplitude. It is a type of wear because of the cyclic motion that produces a displacement (under high contact pressure) that is so small that it may be difficult to anticipate a large volume of wear debris. The wear of the inlet valve seat due to micron-scale displacement under highly loaded conditions illustrates fretting mode of wear in diesel engines.

1.11.4 Corrosive Wear

Virtually all materials except noble metals like gold or platinum corrode in the normal environment. The most common form of corrosion is oxidation. Most metals react with oxygen in air or water to form oxides. Abusive conditions, for example low or high temperatures, increase the rate of chemical reactions and the corrosive wear increases abruptly, leading to mechanical destruction of the surface layer due to sliding or rolling contact of two mating bodies. Typically, the greyish lapped appearance of liner surfaces under cold running condition is an example of corrosive wear.

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