

The effects of soot-contaminated engine oil on wear and friction: a review

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Abstract: During the diesel engine combustion process, soot particles are produced and are either exhausted into the atmosphere or absorbed by the engine's lubricant. Soot-contaminated lubricant has been shown to produce significant amounts of engine wear. The main mechanism of soot-related wear is through abrasion, but, at increased levels of soot content in the lubricant, starvation of the contact can occur, which can increase wear further. High concentrations of soot can increase the local acidic level and, around the piston where high temperatures and volatile gases coexist, corrosion may also occur. In this paper, the current understanding of engine wear due to soot contamination and the previous research performed is reviewed. The paper also discusses soot formation and its general effects within the engine (including friction and efficiency), as well as other issues including filtration or removal, effects on the lubricant, engine design and operation, and future industry targets and technologies related to soot contamination.

Keywords: soot, wear, abrasion, starvation, engine, diesel, emissions, particulates, corrosion, lubricant contamination, wear testing, filtration, wear mechanisms

1 INTRODUCTION

Car, engine, and lubricant manufacturers are facing increasing pressure to lengthen service intervals and therefore oil life in order to reduce lifetime vehicle costs for the customer and the overall impact that the vehicles have on the environment, i.e. a reduction in the amount of engine oil discarded. Increasing sump drain intervals, however, means that oil is becoming contaminated with high levels of soot and increasingly more degraded.

On top of this, the use of exhaust gas recirculation (EGR) is increasing; this is where a portion of the exhaust gases are recirculated into the inlet manifold. This acts to reduce the peak combustion temperature and therefore to reduce the nitrogen oxide (NO_x) emissions. EGR also causes combustion products to be recirculated, rather than to pass out of the engine in the exhaust gases, which leads to further oil contamination.

Wear problems are also arising from demands for improved fuel economy and performance, and lower oil consumption, which leads to many component contacts within an engine operating under higher loads with thinner lubricant films.

The problem of increasing soot levels or particulate matter levels less than 10 µm in diameter can be partially solved through further understanding of the formation of soot during fuel combustion and investigating how the amount that is produced can be reduced. This is an area of work that has already attracted much research interest.

The problem has also been investigated from a lubricant viewpoint, in terms of designing lubricants that will disperse particles within the lubricant and keep them in suspension. Vehicle service intervals are currently dictated by the length of time that lubricants can maintain their physical properties, but also, and possibly more importantly, by the length of time that they can hold particles in suspension. The soot particles are contained within the lubricant by dispersant additives. Current lubricant technology, however, has reached a limit on the amount of dispersants that can be added, as too

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much will result in a corrosion problem in the engine due to the free amines associated with the dispersant [1, 2].

A different approach to addressing the problem, which has already received some research interest, is to investigate how engine components and their interfaces are actually affected by soot. This has involved looking at what wear mechanisms occur with soot-contaminated engine oil, and under what conditions they occur, and also investigating how much soot the components can tolerate.

The aim of this paper was to collate all the knowledge to date relating to the soot contamination of automotive lubricants. An explanation is given of what soot is and its formation mechanism in an internal combustion engine. The overriding issues caused by soot are highlighted, as are current and future legislation covering engine emissions. Methods that have been used to test sooty oil are described and the use of soot simulants is assessed. The main causes of engine component wear that have been proposed are outlined and the theories that have been developed over the last 30 years are explained. Potential research areas and opportunities to minimize the effect of soot are also discussed.

1.1 Soot generation

Soot is a microscopic carbonaceous particle that is a product of incomplete combustion of hydrocarbons (in this case, gasoline or diesel fuel) (Fig. 1). It consists of carbon, ash, and unsaturated (unburned) hydrocarbons. The unsaturated hydrocarbons are essentially acetylene and polycyclic aromatic hydrocarbons. These components have particularly

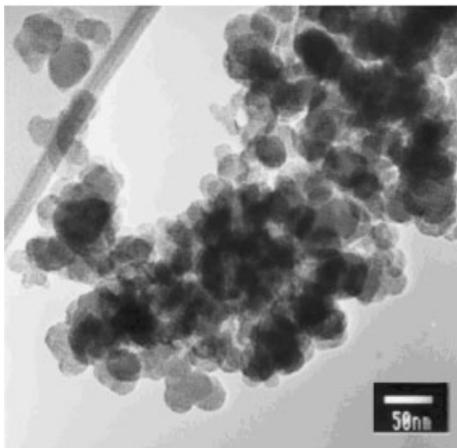


Fig. 1 Image of a typical extracted engine soot agglomeration [3]

high levels of acidity and volatility. Measurements have shown that it typically contains 90 per cent carbon, 4 per cent oxygen, and 3 per cent hydrogen with the remainder consisting of nitrogen, sulphur, and traces of metal [3].

Individual or primary soot particles from diesel combustion have been measured to be approximately 40 nm [3]. Because of soot's colloidal properties, the particles agglomerate up to a maximum of approximately 500 nm, with a mean soot agglomerate size of 200 nm.

Soot particles tend to be more prevalent in diesel engines than in gasoline engines owing to the differences in the combustion mechanisms [4]. Diesel engines are operated at higher air-to-fuel ratios, which tend to produce greater levels of engine soot.

The majority of modern diesel engines operate using direct fuel injection and swirl within the combustion chamber to assist fuel-air mixing. Combustion initiates close to the injection point and occurs very rapidly as a diffusion flame. At this point, the air and fuel mix well, but the mixture is very fuel rich, causing very high levels of soot to be produced. After diffusion burning, the combustion process progresses through the rest of the combustion chamber by pyrolysis burning, which slowly burns the majority of the remaining fuel. This slow burning produces more particulates (soot) and unburned hydrocarbons at the end of the combustion process [5].

Throughout the combustion process, soot particles are produced and destroyed. They are created by the process explained above and destroyed by oxidation. Oxidation is a mechanism that occurs when soot or soot precursors come into contact with various oxidizing species. When this happens, the hydrocarbons that are trapped inside the soot are burned out and the particle size reduces. During the diffusion burning stage of the combustion process, the soot particles produced in the initial phase of the combustion process come into contact with a much higher volume of air compared with fuel, and a large proportion of the soot particles are oxidized.

Further oxidation is required to reduce the amount of soot finally exhausted. When the exhaust valve opens, the combustion products are emitted to the exhaust system, which contains more oxidizing species. Oxidizing catalytic converters are used to reduce further the amount of soot emitted from the tailpipe. The majority of the soot formed is oxidized prior to exhaust. This is possibly why most soot particles are absorbed by the lubricant and relatively little is exhausted [6, 7].

The concentration of the soot particles produced increases with an increasing air-to-fuel ratio. When the air-to-fuel ratio nears stoichiometric (14.5 for diesel fuel) [4], the rate of soot production increases dramatically [8]. This is because near the stoichiometric ratio there is not enough time and oxygen in the cycle to burn all the fuel completely; also, there will be a low proportion of oxidizing species to oxidize the soot. Generally, at values of 20 per cent fuel lean of stoichiometric and higher, which are now being used, excessive amounts of soot are produced from the combustion process [6]. Excess air is required to increase diesel cycle efficiency and to reduce hydrocarbon emissions [6, 9].

Investigations have shown that soot contained in the engine lubricant and soot emitted from the tailpipe are quite different [3]. This may be partly due to the oxidation processes that the combustion products go through. As mentioned above, soot contained in lubricants has a very high carbon content and a low oxygen content. A comparison of approximate content values for engine and exhaust soot can be seen in Table 1.

Soot particles are generally assumed to be extremely hard individually and much softer when agglomerated. The hardnesses of a variety of soots produced during a standard Cummins M-11 engine test were measured by Li *et al.* [2]. They were determined by carbon plasmon energy methods, obtained from the electron energy loss spectra, which were measured using a high-resolution transmission electron microscope. The mean data for each engine operation condition tested are shown in Table 2. It can be seen that soot taken from an engine operating with EGR is slightly harder than soot from an engine without EGR. This increase in hardness is possibly due to the secondary heating and oxidation process that the particles experience.

Table 1 Engine and exhaust soot constituents [3]

Soot constituent	Engine soot content (%)	Exhaust soot content (%)
Carbon	90	>50
Oxygen	4	<30
Volatile content	6	20

Table 2 Soot hardness values [2]

Mode of operation	Vickers hardness (kgf/mm ²)
Direct injection, non-EGR, 300 h	1096
Low injection pressure, non-EGR, 300 h	940
High injection pressure, non-EGR, 300 h	988
Low injection pressure, EGR, 300 h	1235
High injection pressure, EGR, 300 h	1302

1.2 Soot transport and entrainment in component contacts

It has been shown that, of the soot produced within the engine, only 29 per cent reaches the atmosphere through the exhaust pipe [10], with the remainder being deposited on the cylinder walls and piston crown. Of the soot that is retained in the engine (mainly in the lubricant), 3 per cent is attributable to blow-by gases; the remainder results from piston rings scraping away soot deposits in the cylinder, which then end up in the sump [1]. It is then transported around the engine where it can be entrained into component contacts.

Within the valve train, there are many component interfaces, all of differing geometries and motions, as shown in Fig. 2. Sliding, rolling-sliding, and reciprocating contacts exist, some of which are conformal and some non-conformal. Because of the varying motion and loads at each interface, different regimes of lubrication will be apparent. This is further complicated by the mechanisms for lubrication application, which range from contacts where positive lubrication is used, to those where lubricant reaches the contact indirectly by splash lubrication. In some cases, contacts receive little lubrication because of their location, and starvation problems can exist [11]; the presence of soot will further exacerbate this.

A study by Chinas-Castillo and Spikes [12] investigated the entrainment of soot particles into a ball-on-flat sliding-rolling contact region, through interferometry and image analysis techniques. Soot particles were found to entrain into an

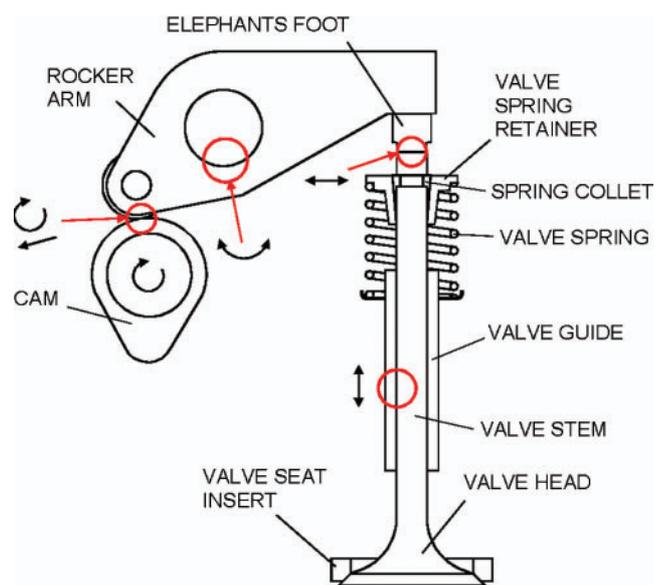


Fig. 2 Sample valve train component contacts

elastohydrodynamic (EHD) lubricated contact, by adhering to surfaces and accumulating until they formed a non-homogeneous boundary layer, influencing the behaviour in the contact particularly at low speeds or high temperatures when the soot primary particle size will be greater than the oil-film thickness. At increased soot concentrations, thicker films were produced and there was a higher probability that soot particles would penetrate the EHD contact.

1.3 Critical soot-affected engine systems

The area in the engine where wear is generally most likely to occur is the valve train. The valve train components require a continuous supply of oil during operation, but, as the valve train is generally located near the top of the engine, they often operate with inadequate lubrication, particularly during a cold start, where the oil pressure will initially be insufficient to pump oil to the top of the engine [6]. Also, many of the valve train component contacts are not positively lubricated.

Figure 3 shows component wear data from engine tests with increasing degrees of EGR (and hence soot) [13]. Clearly, wear rises in the in-cylinder and valve train components, but is worse in the valve train.

1.4 Proposed soot wear mechanisms

Three different wear mechanisms due to soot contamination have been proposed. Rounds [14]

postulated that chemical adsorption of the anti-wear components in the lubricant by the soot reduced the lubricant's ability to protect the surfaces. Other researchers have suggested that soot wear could occur because of starvation of lubricant in the contact. This is where soot agglomerates to dimensions greater than the oil-film thickness and blocks lubricant entry to the contact [15]. The final mechanism proposed suggests that wear of the surfaces occurs by three-body abrasion, where the soot acts as the third body. As agglomerates, soot is reasonably soft, but, as individual particles, soot is thought to be hard enough to wear metal surfaces [16]. There is little work, however, where actual component contacts at realistic operating conditions have been used to verify these theories.

This concludes a brief outline of current thinking; the mechanisms and findings of other researchers will be discussed further in greater detail in later sections.

1.5 Soot removal

Currently, the main removal technique for soot and other particles retained within a lubricant is filtering. The majority of oil filters used for automotive applications are flow-through types, where the oil filter is part of the lubrication system. There are essentially two methods for this type of filtering. First, in full-flow filters, all the oil that is pumped through the engine passes through a filter. Full-flow

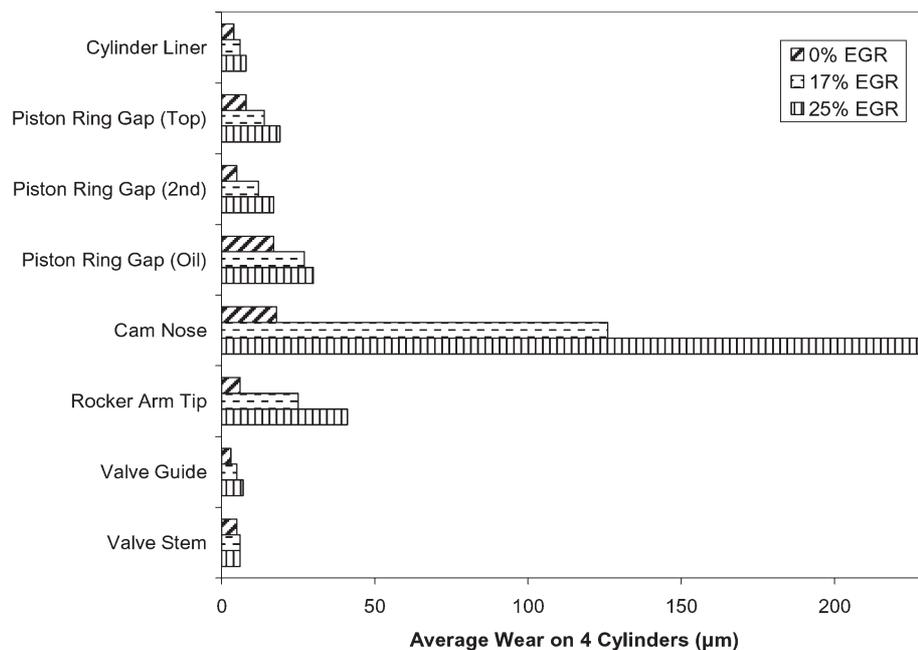


Fig. 3 A reproduction of 4D55T/C engine wear data showing relative component wear levels [13]

filtering generally requires a relatively coarse filter; the dimensions of the filter are governed by the required oil flow volume and particulate retention. Such filters will generally be used for petrol engines.

The second type of filter available is a bypass filter; these take generally less than 10 per cent of the oil flow from the lubricant system. Bypass filters use much finer filtration methods than full-flow systems to remove the finer particles. Filtering with finer grade filters is possible with this method because of the reduced oil flowrate. Other types of filter that can be used with a bypass system include deep-bed filters or centrifuges. Deep-bed filters depend on the residence time of the contaminated lubricant inside the filter, where various levels of filtering can be used to separate suspended particles. Centrifugal filters use chambers rotated at a high speed to separate out the lubricant from the contaminant. There are a number of major issues related to centrifugal filters used for automotive applications, including the required energy to operate, unit size, safety implications, and cost. Bypass filters are generally used for diesel engines.

2 SOOT LEVELS PRESENT AND FUTURE

Currently, typical levels of soot contamination are in the region of 3–5 per cent by mass; such levels are already displaying signs of significant engine wear. Current oil change intervals are up to almost 50 000 km for a passenger car or 120 000 km for trucks. The automotive and lubricants industries are expecting to see soot contamination levels of up to 10 per cent by 2010; the lubricants industry is designing engine oils to cope with such levels, without sig-

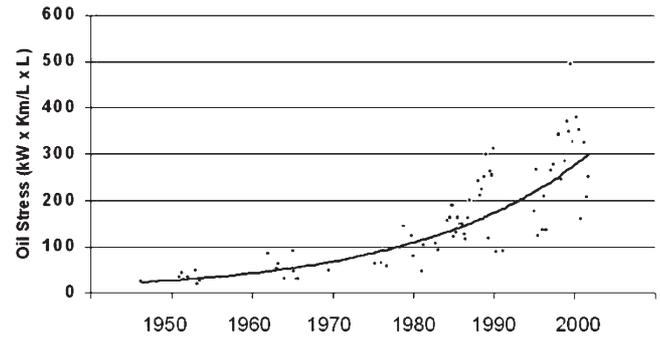


Fig. 4 Graph of oil stress with time [18]

nificant increases in viscosity, and the engine companies are designing engines to minimize the effects of highly contaminated lubricants [17].

Another impact on the quality and ability of the oil to perform its function is the level of stress that it is under, increasing the degradation of the lubricant through shearing and heating. Oil stress has been increasing for the last 50 years and is expected to rise at an increasingly faster rate in the future [18], as shown in Fig. 4. Therefore, significant further development is required to help to maintain lubricant performance under these expected conditions.

The current and future levels of soot contamination of engine lubricants are partially due to the legislation for tailpipe emissions. The European vehicle emissions legislation for heavy-duty diesel vehicles relating to NO_x and particulates is shown in Fig. 5. It can be seen that both types of vehicle emission have been vastly reduced in recent years with the forthcoming Euro 5 target for 2008 – and this will continue [17].

The NO_x target (as shown in Fig. 5) requires the use of EGR, which (as mentioned previously) causes an increase in the amount of soot returned into the

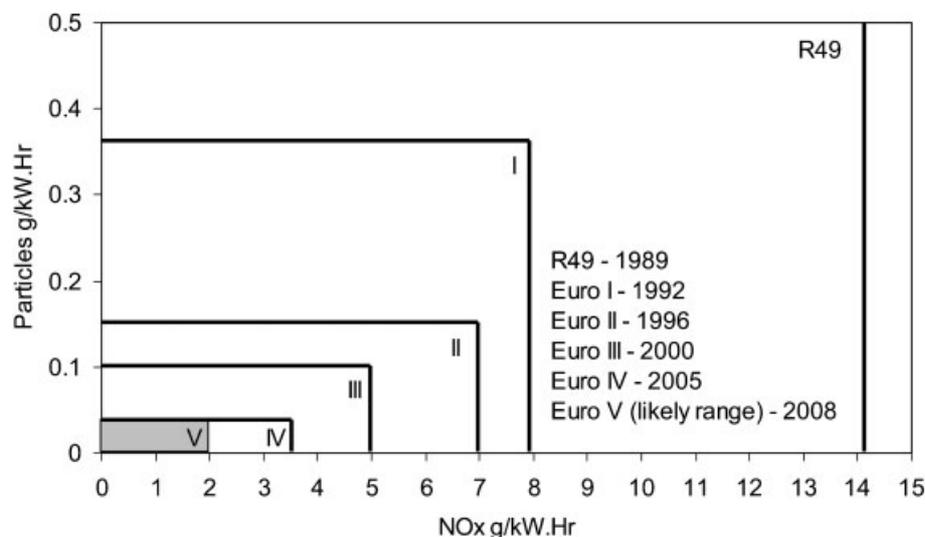


Fig. 5 European heavy-duty vehicle emissions [17]

engine. The restriction on the amount of particulates emitted introduces the need for exhaust particulate filters to be fitted, with the result that soot particles are contained onboard the vehicle. Particulate filters may, however, have an effect on the efficiency of the engine, as they gradually trap increasing amounts of exhaust soot, and the engine's back pressure will be detrimentally affected [18]. The results of such targets may lead towards an increased level of servicing, but technological advances are required to overcome such issues and to continue the trend of reduced vehicle servicing.

Some of the most stringent tailpipe emissions targets are produced by the Environmental Protection Agency in the USA with their latest Tier 2 legislation, where reductions in carbon dioxide, carbon monoxide, unburned hydrocarbons, NO_x , and particulate matter are required [19]. The US tailpipe legislative targets for NO_x and particulate matter are shown in Fig. 6 [20].

2.1 Other fuels

With an aim of reducing the amount of carbon dioxide emitted into the atmosphere by internal combustion engines because of the global concern that increased levels of greenhouse gases in the atmosphere accelerate the rate of global warming, new fuels are being investigated. These fuels include modified diesel, i.e. water–diesel fuel emulsions, synthetic fuels produced through advanced gas-to-liquid conversion technologies, biofuels, and hydrogen technology, to name but a few.

Additive-modified diesel fuels and water–diesel fuel emulsions have been tested and shown to be potential substitutes for current diesel fuels [21, 22], as have synthetic diesel fuels produced through the Fischer–Tropsch gas-to-liquid fuel production method [23, 24]. However, there have been findings from various researchers demonstrating reductions in particulate matter emitted during engine test using biofuels, in particular rapeseed oil [25, 26], palm oil [27, 28], and soybean oil [29, 30].

3 TESTING METHODS

Tribological testing can be carried out at a number of different levels. Figure 7 illustrates this for engine components. Clearly, the complexity decreases with the move down from field testing to specimen tests and greater control of the test parameters can be achieved. The tests are also more repeatable and the statistical significance of the results is greater. However, as the complexity is decreased, exact simulation of the component dynamics and loading conditions is more difficult to achieve. A compromise is needed, usually based on cost and time restrictions that allow generation of results appropriate to the particular application.

With testing involving contaminants, it is essential that a good representation of the contact motion, loading, and geometry is achieved if bench testing is to be used. Entrainment of the contaminants will be directly affected by these and is key to determining which wear process may occur. This means that the

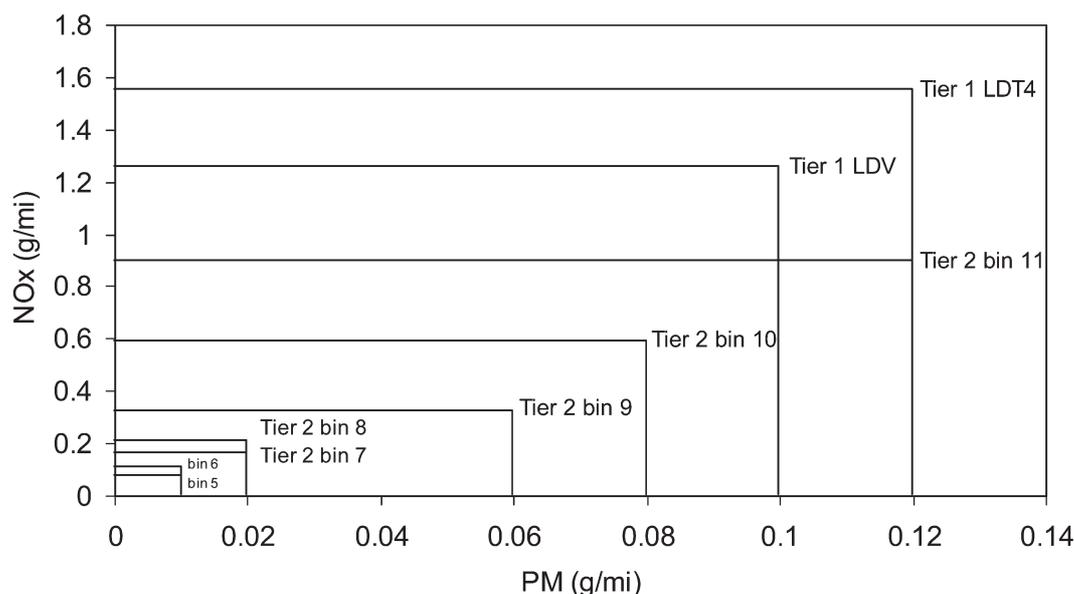


Fig. 6 US Tier 1 light-duty diesel and Tier 2 full useful life exhaust [20]

Field Test (actual vehicle)	Complex	Good	Difficult	Easy	Poor	Poor	Expensive
System Test (e.g. engine dyno-test)	TEST CONDITIONS ↑ ↓	PARAMETER INJECTION ↑ ↓	INTERPRETATION OF RESULTS ↑ ↓	UTILISATION OF RESULTS ↑ ↓	REPEATABILITY OF TESTS ↑ ↓	STATISTICAL SIGNIFICANCE OF RESULTS ↑ ↓	COST OF TEST METHOD ↑ ↓
Sub-System Rig Test (e.g. motorised cylinder-head)							
Component Bench Test							
Specimen Bench Test							
	Simple	Poor	Easy	Difficult	Good	Good	Cheap

Fig. 7 Levels of simulation in engine component tribological testing

best approach would probably be to use actual components.

Engine tests are always problematical. It is difficult to control many of the test parameters and to provide good wear measurements. However, standard engine test cycles designed to promote soot production have been defined, as will be outlined in a later section, that allow soot wear studies to be carried out.

3.1 Test apparatus

In early work on soot wear, the most popular test method was the four-ball approach [14] in which various soot-contaminated lubricant formulations were tested in a standard four-ball wear tester. High-frequency reciprocating rigs [31], pin-on-disc [32], and ball-on-flat rolling sliding apparatus [33] have also been used in more recent times.

These methods have their limitations, as recognized by Bell [34], who stated that it was necessary to test the levels of wear using test equipment that was designed to replicate the engine components in question, rather than generic wear testers. Tests have been carried out since then using test conditions related to actual components [31], as well as some with actual components [35]. Engine tests have also been used to study soot-related wear, usually through industry standard engine tests.

The measurement of wear data to assess the effects of soot contamination is generally carried out through imaging of the wear scar produced after each test [31]. This involves the use of optical microscopy or, for a

more detailed analysis of the wear surface, scanning electron microscopy (SEM) [36].

3.2 Testing standards

Engine testing standards are followed when carrying out engine tests to ensure that the data obtained can be reproduced if necessary in later tests, either on the same equipment or elsewhere in the world. This also means that, when operating parameters are changed (within the parameters of the testing standard), data from various tests can be compared against each other to develop conclusions. Standard tests are defined for Europe (European Automobile Manufacturers Association (ACEA)–Co-ordinating European Council (CEC) tests) and the USA (American Petroleum Institute (API) tests). The main engine tests for assessing the effects of soot are outlined below.

The API CI-4 Cummins M-11 EGR engine test (also known as the Cummins M-11 cross-head wear test) is used to investigate engine wear under high-soot and high-load operating conditions. This is carried out by running the engine fuel rich to create the high load in conjunction with operating retarded injection timing to generate the high levels of soot [37, 38]. It determines the effectiveness of lubricating oils in reducing soot-related wear of valve train components in engines with EGR, through reduction in filter pressure drop, excessive viscosity increase, sliding valve train wear, bearing corrosion, and sludge deposits. The Cummins ISM test is also used to assess soot-induced wear.

Two tests defined by Mack also investigate the effects of soot build-up. They are the Mack T-8E (ASTM D 5967), where the fuel injection timing is adjusted to achieve a target level of soot in the bulk lubricant; it evaluates an oil's ability to prevent excessive viscosity increase and filter plugging. The second Mack test is the Mack T-9 (ASTM D 6483), again generating an increased soot level in the bulk lubricant through adjusted injection timing to investigate ring and liner wear in a high-output diesel engine. This evaluates the amount of corrosion due to loss of total base number in the oil as it degrades [37, 38].

The Mitsubishi 4D34T4 test increases the soot level within the lubricant to 4.5 per cent, through high-speed operation and 10 per cent over-fuelling, to analyse the lubricant's protection performance of soot-related valve train wear, essentially through a decrease in the cam lobe diameter [37, 38].

The Caterpillar 1R (and 1P-API CH-4) test runs a Caterpillar 1Y3700 single-cylinder oil test engine for 504 h at fully rated speed and load to evaluate the performance of lubricants for direct injection high-speed engines operating on low sulphur fuels. Analysis of the piston deposits and oil consumption, pistons, piston rings, and cylinder liner is carried out to evaluate performance [37, 38].

The roller follower wear test (ASTM D 5966) defined by GM is a useful method for directly understanding an oil's ability to prevent valve train wear with ageing oil. Analysis is carried out via the valve lifters, which are replaced between each test [37, 38].

Of the above tests, the Cummins M-11 EGR test appears to provide the most useful, standard, soot-induced wear engine test as it focuses on the main areas of potential wear and gives more opportunities for analysing and understanding the effect of soot. This is also the test that appears to be most commonly used in industry.

Standard tests are also available for specimen testing. One of the most common specimen tests is the reciprocating ball-on-flat test, as detailed in ASTM G133-05 [39]; this method was followed by Green *et al.* [31]. ASTM G133-05 is essentially only applied to fresh oil, but work is in progress to create ASTM standards that account for contaminants in the test lubricant, focusing on testing between a piston ring and cylinder liner [40].

3.3 Soot simulants

To investigate soot wear, there are essentially three options to choose from regarding the test particles. These are as follows:

- (a) used engine oil;
- (b) extracted engine soot mixed with fresh engine oil;
- (c) carbon black mixed with fresh engine oil.

Used engine oil is the most realistic option, but adds complications as the oil will contain other contaminants and wear debris, all of which will affect wear results. An extra complication of testing with used oils is that they are naturally degraded, but this is extremely dependent on use. Test oils would each need to be produced in an identical manner in an attempt to degrade the lubricant consistently by the same amount each time, as used engine oils will be mixed together to produce the required soot content for testing purposes. However, even this will not allow full control over the final amount of soot produced, which will vary from batch to batch. Laboratory techniques exist for ageing engine oils outside of an engine (without producing soot) [41]. This is quite an unpredictable process, however, and would add further complications to the process. The process of producing used engine oils is expensive and time consuming.

The second method of extracting engine soot alone from a used lubricant allows for the assessment of the effect of soot alone on wear without any other contaminants or lubricant degradation issues. Using this method the extracted soot is simply mixed in with the desired test lubricant. This method is less time consuming and expensive than the first method and reasonably practical for experimental purposes.

The final method of using carbon black has for many years been the standard method for assessing the wear level due to soot contamination. This method is quick and inexpensive. The major drawbacks of this method are that carbon black, although very similar to engine soot, is not engine soot, and produces results that industry has argued may be relative to tests with soot from used engine oil, but not directly comparable.

Investigations by Clague *et al.* [3], however, have shown that carbon black particles do have the capability of mimicking the behaviour of soot from engine oils. Findings showed that, when looking at primary soot particles (30–50 nm) using electron microscopy techniques, there is very little difference between engine soot and carbon black. There was a great deal of similarity in particle size and structure, confirming that the two are essentially the same on a nanometre scale. When investigating agglomerated soot and carbon black particles (up to 500 nm), carbon black was again found to be similar to engine soot, although a slight difference was discovered.

The carbon black particles disperse in a similar fashion, but create a larger agglomerate diameter than extracted engine soot, greater by approximately 50 nm. Chemical analysis of soot and carbon black particles showed that carbon black particles display higher carbon contents and lower ash and volatile contents. Oxygen and hydrogen were shown to concentrate on the surface of the carbon black, creating a relatively polar surface, meaning it will tend to have a greater tendency to interact with other polar species, i.e. other carbon black particles. Prior to extraction from its lubricant, the engine soot displays a higher polar surface than carbon black, but, once the soot has been extracted from the lubricant, it becomes less polar than carbon black. This explains why (as mentioned above) carbon black particles created a larger-diameter agglomerate than extracted engine soot.

Rounds [42], however, has described a method of heat treating carbon black particles in oil and air which produced soots that had different pro-wear properties relating to real engine soots experiencing low or high engine loadings. This is very time consuming, however.

Investigations by Wedlock *et al.* [43] into soot particle aggregation demonstrated that, when carbon black particles are mixed in a lubricant, particularly by ultrasonic means, the particle structures formed are essentially similar to those formed by engine soot. This work demonstrated that soot aggregate structures are fractal bodies, meaning that they create chaotic complex formations when they agglomerate. This was investigated through transmission electron microscopy analysis and was shown to be reproduced in various engine soot and carbon black lubricant mixtures.

4 WEAR MECHANISMS

Initial investigations (*circa* 1970s) were carried out from a purely chemistry point of view, as soot was known to be one of the contributing factors to long-term oil degradation. Observations showed that, as the oil degraded, the amount of engine component wear increased. As very little was known at the time about engine soot, lubricant scientists assumed that the soot must have been degrading the lubricant's anti-wear additives. However, even in the presence of soot, the elements required to produce the anti-wear function of the lubricant remained. Therefore, the wear seen in many engines with soot-contaminated lubricants must have been due to more fundamental mechanisms, such as abrasion.

Research has developed in more recent years to investigate the physical and mechanical actions of particles in lubricants. Studies have highlighted wear mechanisms such as polishing on a macroscopic level, microscopic abrasion, and lubricant contact starvation due to the soot contained within the lubricating oil. Consensus appears to be difficult to achieve, however, but in recent years (2000 onwards) many studies are obtaining similar findings, leading to greater acceptance of the theories by lubricant and engine manufacturers. This is largely due to an increasingly broad scope of investigations involving different lubricants, soot (and soot surrogate) types, other contaminant particles, and specimen, component, and engine testing methods. This is all discussed in greater detail below.

4.1 Breakdown of anti-wear layers

The earliest investigations into soot wear were performed by Rounds [14, 42], in which tests were performed with a four-ball wear test machine, using base oils with various additives, mixed with carbon black and centrifuged engine soot. The wear tests demonstrated an increase in specimen wear with increasing contamination level. Rounds proposed that increasing wear was due to the carbon black and soot particles preferentially adsorbing anti-wear species within the lubricant, e.g. zinc dialkyldithiophosphate (ZDDP).

A study by Hosonuma *et al.* [44] using a Japanese valve train wear test showed that, during engine tests, ZDDP decomposes quickly initially, but the lubricants still retained their anti-wear properties. Analysis of diesel soot showed that it adsorbs compounds containing zinc, but very few compounds containing phosphorus, with the phosphorus compounds being retained within the lubricating oil, maintaining the oil's performance. This study agrees with the Rounds theory, but dismisses the suggestion that the performance of the lubricant is degraded because of this.

Nagai [13] suggested that the soot acts to strip off the anti-wear film on the surface of the metal surface, leaving it exposed, which results in increased wear. This study proposes that the anti-wear film is removed through abrasion and not adsorption, as analysis of the centrifuged oils show very little sign of zinc and phosphorus depletion, as would be expected if the ZDDP had been adsorbed.

Recent work carried out by Torrance [45] has backed this up and added another possible mechanism to the mix. The results from this work suggested

that the addition of ZDDP to a lubricant containing carbon black can actually aggravate wear, with corrosion being the most likely cause. It is suggested that the carbon black abrades the anti-wear reaction film, therefore continuously exposing a fresh reaction surface.

4.2 Abrasion

During the 1980s, research into soot wear of engine components increased; the general trend of the findings tended to disprove the early work by Rounds where it was suggested that the soot adsorbed the anti-wear additives in the lubricant and favoured abrasion as the major factor in soot-induced wear [46, 47]).

Early research into the abrasion of surfaces due to soot suggested that polishing mechanisms prevailed. Berbezier *et al.* [47] discovered that the size of the carbon black particle was very important. They found that carbon black particles with a 20 nm diameter produced a lower wear rate than particles of diameter 300 nm by a factor of approximately 60 per cent. The term 'polishing wear' was used at the time as wear scars from tests with carbon black and other similar abrasive particles, including silica and aluminium, produced apparently featureless surfaces on a micrometre scale, but with apparently minor wear features in the range of tens to a few hundreds of nanometres, as discovered by Ryason *et al.* [48].

A recent investigation by Green *et al.* [31] demonstrated that using base oil and carbon black mixtures

produced significant increases in wear volume using ball-on-flat high-frequency reciprocating (HFR) tests designed to replicate an elephant's foot-valve tip contact (see Fig. 2), as shown in Fig. 8. Tests with a 5 per cent carbon black (by weight) contamination level showed an increase of over 800 per cent in wear volume at a test temperature of 100 °C.

Studies of the resulting wear scars using optical microscopy (Fig. 9) indicated that wear mechanisms probably vary with increasing carbon black content. With low levels of soot (below 2 per cent), very little of the increase in wear was due to the soot content and the contact mainly experienced lubricated metal-to-metal sliding. Higher carbon black content levels saw more abrasive wear (as indicated by the linear scratch marks) because an increased level of carbon black particles were entrained into the contact region. Tests with carbon black contamination levels greater than approximately 4 per cent demonstrate a transition from abrasive wear to starvation of the contact as the carbon black particles block the inlet to the contact region. The wear scar features visible in the images with high soot contamination levels included heavy grooving and galling. A schematic diagram indicating the wear mechanisms that occur during a reciprocating stroke of a ball-on-flat contact with a high level of contamination is shown in Fig. 10.

Gautam [16, 49, 50] and Sato *et al.* [51] also showed that increasing the soot concentration increased wear, using a three-body pin-on-disc tester and fall ball tester, respectively. They also attributed the

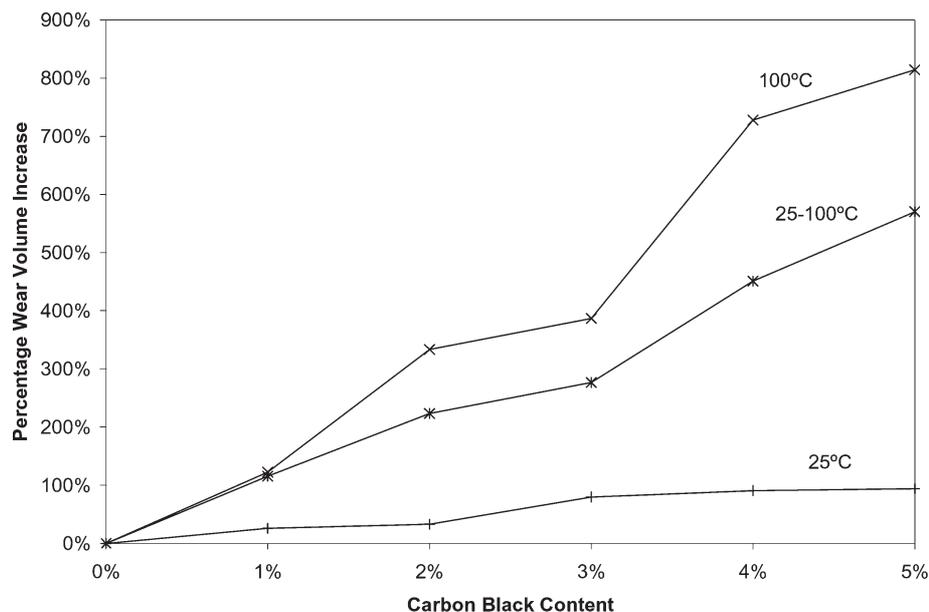


Fig. 8 Results from ball-on-flat testing relative to 0 per cent carbon black content tested at 25 °C, ramped heating, and 100 °C (base oil at 0.36 m/s) [31]

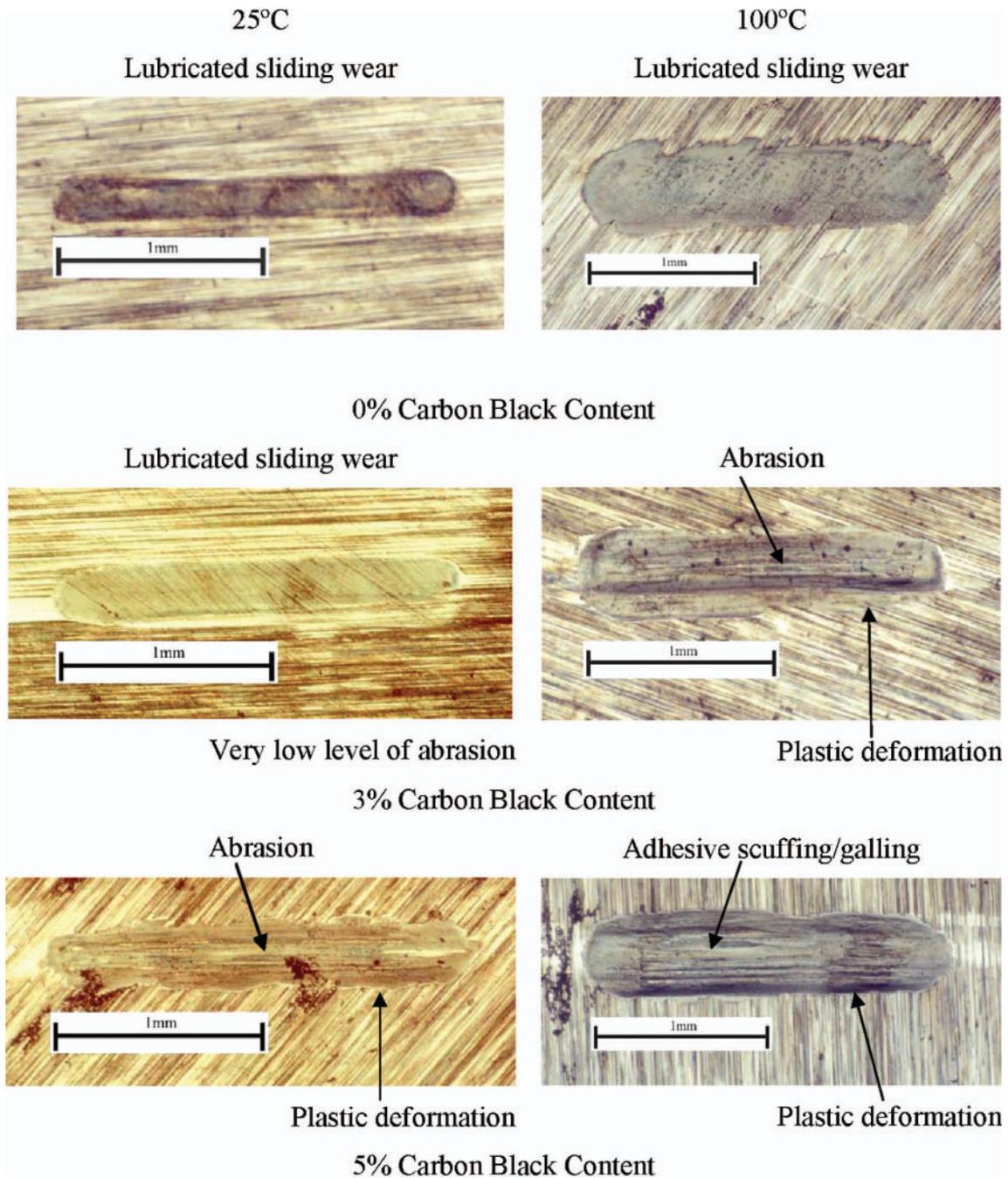


Fig. 9 Images of wear scars for 1 per cent, 3 per cent, and 5 per cent carbon black contents at 25 °C and 100 °C [31]

wear to abrasion and confirmed this with SEM images showing fine streaks on the surface of the material, which were thought to be caused by primary soot particles, therefore again highlighting abrasion as one of the main contributing factors to wear.

Mainwaring [52] and Chinas-Castillo and Spikes [12] have shown that the primary soot particle dimension affects the amount of wear produced

using Mack T-8E and Cummins M-11 engine tests and an EHD test rig, respectively. Mainwaring also showed that good soot dispersant control can promote lower wear levels, but it does not guarantee satisfactory wear control. Good wear control with soot present was found to be dependent on viscous and oil-film-forming compounds in the lubricant.

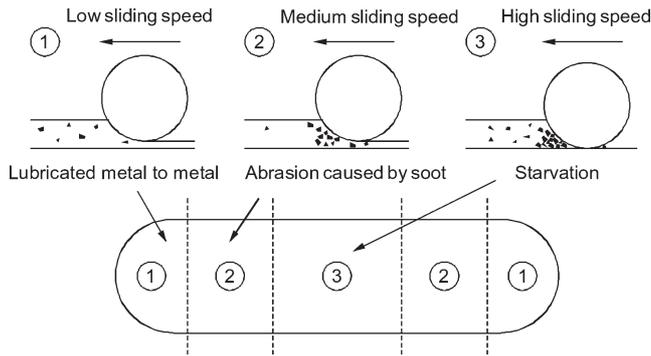


Fig. 10 A schematic diagram of the wear mechanisms at a high carbon black contamination level [31]

4.3 Starvation

Starvation wear is caused by a blockage in or of the lubrication inlet to a contact. In the case of diesel engines, it is thought that soot agglomeration at critical zones could cause a blockage capable of restricting the flow of lubrication enough to starve the contact zone, therefore resulting in unlubricated sliding wear.

The proposal by Green *et al.* [31] suggesting that, at high contamination levels, severe wear is caused by this process is supported by work carried out by Sato *et al.* [51], who, after carrying out four-ball tests, suggested that, when soot particles aggregate within the lubricant, starvation may occur as the diameter of soot agglomerates is much larger than the oil-film thickness. In an actual engine, some contacts receive little lubricant because they are not lubricated positively and rely on splash from other lubricant supplies [11], and so starvation is even more likely to occur with soot present.

4.4 In-cylinder wear mechanisms

The main focus of soot-related wear of engine components has been on the valve train, but some research has shown that the in-cylinder region around the piston rings to cylinder wall contact suffer from soot-related wear.

Investigations by Devlin *et al.* [53] demonstrated that carbonaceous materials, aromatic species, and oxygenated carbon, all of which are combustion products, were deposited on piston land regions. Testing using a single-cylinder diesel engine by Ishiki *et al.* [54] demonstrated that, with the application of EGR, top piston ring wear increased. They also suggested that the wear was due to abrasion from the soot particles. Similar engine testing by Dennis *et al.* [1] showed again that, with

the application of EGR, wear on the piston ring and the cylinder wall–liner increased, but only under high-load conditions. It was also suggested that corrosion-induced wear could possibly occur within the in-cylinder region of the engine, depending on the composition of fuel and lubricant used. It is understood that sulphur used in fuels and lubricants is a corrosion inhibitor; therefore, current legislation to reduce the amount of sulphur in fuels and lubricants could lead to the occurrence of corrosion, especially as such a region in the engine contains high levels of acid products post combustion. Lubricants therefore need to have a sufficient neutralizing ability in that region to prevent the occurrence of corrosion. Yahagi [55] demonstrated that corrosion wear of the cylinder bore in diesel engines is aggravated by changes to the combustion conditions, mainly through the use of EGR. Under such conditions, high levels of sulphuric acid and soot are produced. The presence of sulphuric acid leads to corrosive wear.

Engine testing on a Cummins M-11/EGR test engine by Li *et al.* [2] with soot contamination levels of 6 per cent and 9 per cent produced very high wear levels on both the piston ring faces and the cylinder wall–liner. As previously demonstrated, high levels of wear were due to abrasion due to the soot particles acting as a third body within the contact, but also significant signs of corrosion.

Tests were carried out by Masuko *et al.* [56] to understand the anti-wear performance of simulated used engine oil, using base oil, ZDDP (an anti-wear additive), and carbon black in a four-ball wear tester. The test lubricants were degraded and the results showed corrosive wear on the test balls due to the compounds present in the degraded oils.

4.5 Link between laboratory and engine testing

It is key that a link is made between laboratory observations and the actual systems and components that soot affects in the field.

To this end, Green *et al.* [35] have carried out tests using the same HFR rig described above using actual elephant's feet and valve tips. These were run at a sinusoidal mean sliding speed of 0.24 m/s (a frequency of 45 Hz). The test was designed to simulate the oil-film thicknesses produced by the contact at a realistic engine operating speed (4000 r/min). Rather than perform a direct comparison, this testing builds on previous investigations to compare specimen testing with engine components under similar conditions. The resulting wear scars are shown in

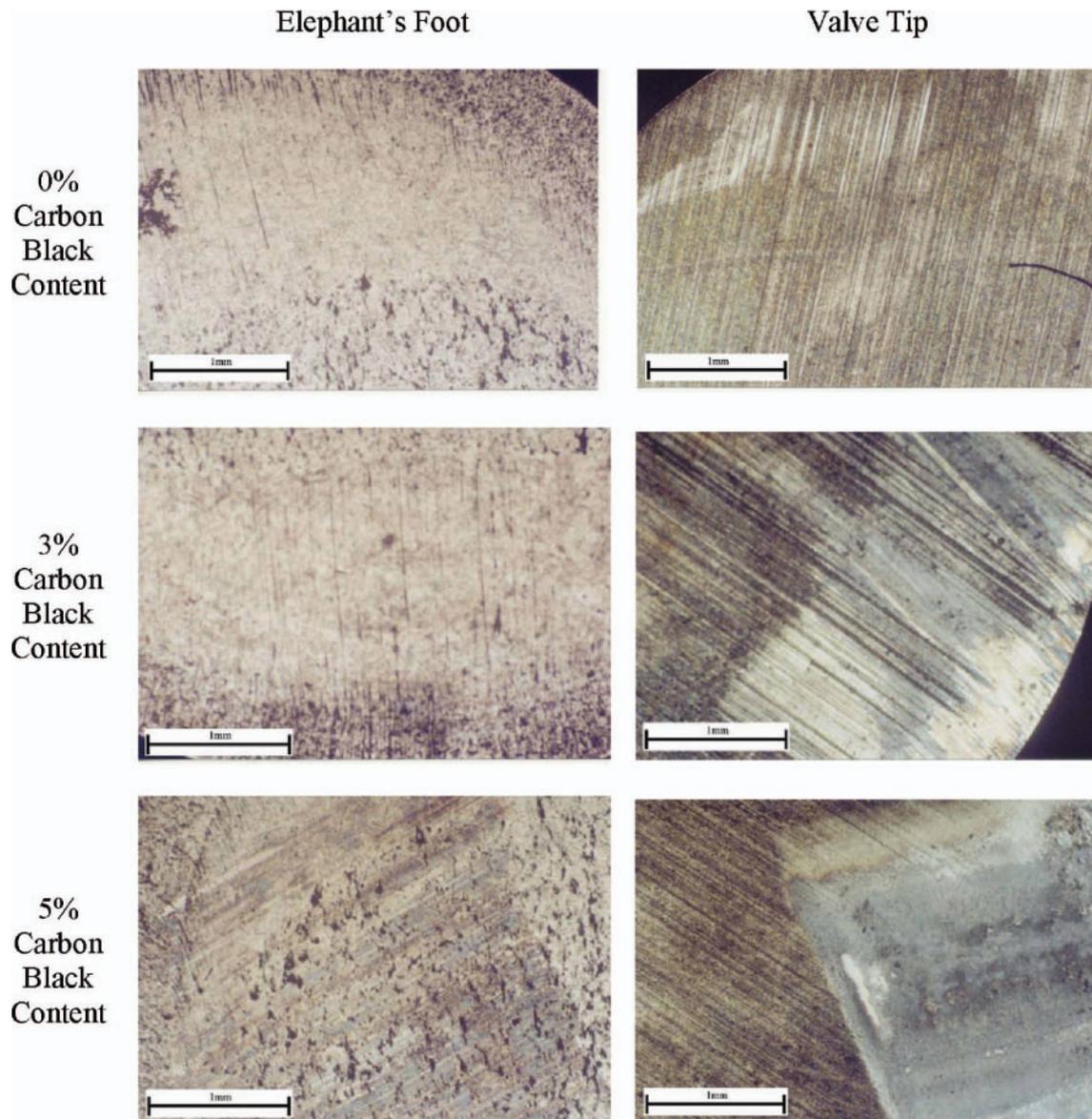


Fig. 11 Images of component reciprocating tests performed at 100 °C [35]

Fig. 11. The results compared favourably with previous specimen tests and wear scar images clearly highlighted the wear mechanisms that were expected.

A study by Kuo *et al.* [36] used the Cummins M-11 engine test to investigate engine wear under various operating conditions, where the soot level reached 5 per cent content by weight. After testing for 200 h, the cross-head components of the engine valve train were examined using SEM imaging. The components were shown to have heavily worn surfaces similar to those seen in the work by Green *et al.* [35]. The wearing process progressed from lubricated wear, where the oil-film thickness is greater than the primary soot particles present because of oil

thickening, to abrasive three-body wear. In addition to the abrasive wear, fatigue cracking and micropalling of the component surface were visible. Li *et al.* [2] carried out M-11 EGR engine tests; cylinder liners, valve train cross-heads, and top ring faces were shown to be key areas where wear occurred, owing to soot abrasion.

Cam experiments were performed on a follower test rig by Soejima *et al.* [57], with a fresh engine lubricant and another identical lubricant that had been used. Findings showed that the soot dispersed in the oil caused the wear rate to increase over that of the fresh lubricant. Engine tests were performed by Kim *et al.* [58] on a 6.2 l GM diesel engine; these showed that a correlation was evident between

engine testing and four-ball wear testing. Wear in both cases increased with increasing soot concentration.

5 EFFECT OF SOOT ON FRICTION

Soot will also affect friction in contacts as well as wear. Little work has been carried out to study how friction varies with soot and conflicting results have been presented.

Through cylinder-on-disc reciprocating testing, Liu *et al.* [59] measured the variation in friction coefficient of different diesel lubricants with various soot contamination levels (using soot produced in a fired engine). While there was some scatter, results showed that the friction coefficient decreased with soot present in the lubricant. It is suggested that the soot particles acted as friction modifiers. However, pin-on-disc measurements by Ramkumar *et al.* [32] demonstrated that, with diesel engine soot mixed with a model diesel lubricant at different contamination levels, the friction coefficient increased. Green and Lewis [60] found similar trends using increasing levels of carbon black contamination in a Plint TE77 reciprocating ball-on-flat test rig (Fig. 12).

Soot size relative to the oil-film thickness [12] also produced oil degradation [61, 62], which may help to explain the differences in the results seen. EHD oil-film thickness measurement by Chinas-Castillo and Spikes [12] indicated that soot contamination of a lubricant affected the oil film produced (this is discussed further in the next section), and therefore influenced the frictional characteristics of the contact, especially when the primary soot particle diameter was greater than the film thickness.

6 EFFECTS OF SOOT ON LUBRICANTS

Various studies have been carried out to attempt to understand the properties of soot-contaminated lubricants. Early work carried out by Ryason and Hansen [63] investigated the shear rate rheometry of used oils; the study showed that soot contamination of oil increases the viscosity and therefore reduces its ability to perform its function, particularly at lower operating temperatures. One investigation has shown that, below 1 per cent (by weight) soot concentration in the lubricant, the viscosity increase is linear. However, above 1 per cent, the viscosity rose rapidly. The work also suggests that soot suspended in oil is thixotropic, meaning a contaminated

lubricant's properties are dependent on their shear histories.

Investigations by Batko *et al.* [64] looked at the increase in the viscosities of oils from the field, specifically passenger cars equipped with 2.7l DOHC V6 engines operating under 'taxi-cab' conditions, including 'stop and go' and idling situations (which would promote soot production). Oil sampling and testing was performed at 4000 km operating periods, up to 16 000 km. At the end of the tests, viscosities had risen to between 300 and 350 cS (mm^2/s) from an initial viscosity of approximately 60 cS. Unfortunately, no data are available on the soot contamination levels of the test lubricants. An investigation by Zeidan *et al.* [65] into the simulation of aggregation of soot-laden lubricants demonstrated that a strong relationship was to be found between the soot level and the aggregate morphology. This demonstrated that higher soot loading rates lead to a much lower fractal dimension and a higher degree of aggregate dispersion, producing an increased lubricant viscosity.

This trend of increasing viscosity has also been seen in measurements by Green and Lewis [60] using formulated oil mixed with carbon black up to a contamination level of 7 per cent by weight, as shown in Fig. 13.

Investigations into the real effects of lubricant viscosity increase have shown that, in hydrodynamically lubricated engine contacts, friction is roughly proportional to the square root of the lubricant's dynamic viscosity [18]. This clearly demonstrates that increasing levels of soot contamination will have a detrimental effect on fuel consumption and tailpipe emissions.

7 DISCUSSION

7.1 Testing

Although full-scale engine testing is preferred because of the more realistic results achieved, bench specimen test data are displaying significant similarities, allowing cost-effective and reliable testing to be carried out to gain an understanding of an extremely difficult issue that has many influencing factors. A large variety of test rigs have been used to try to understand the wear created by soot-contaminated lubricants. This approach has led to confusion of many issues and does not allow for results to be compared against each other. In order to allow for comparisons, standards need to be established to provide consistency.

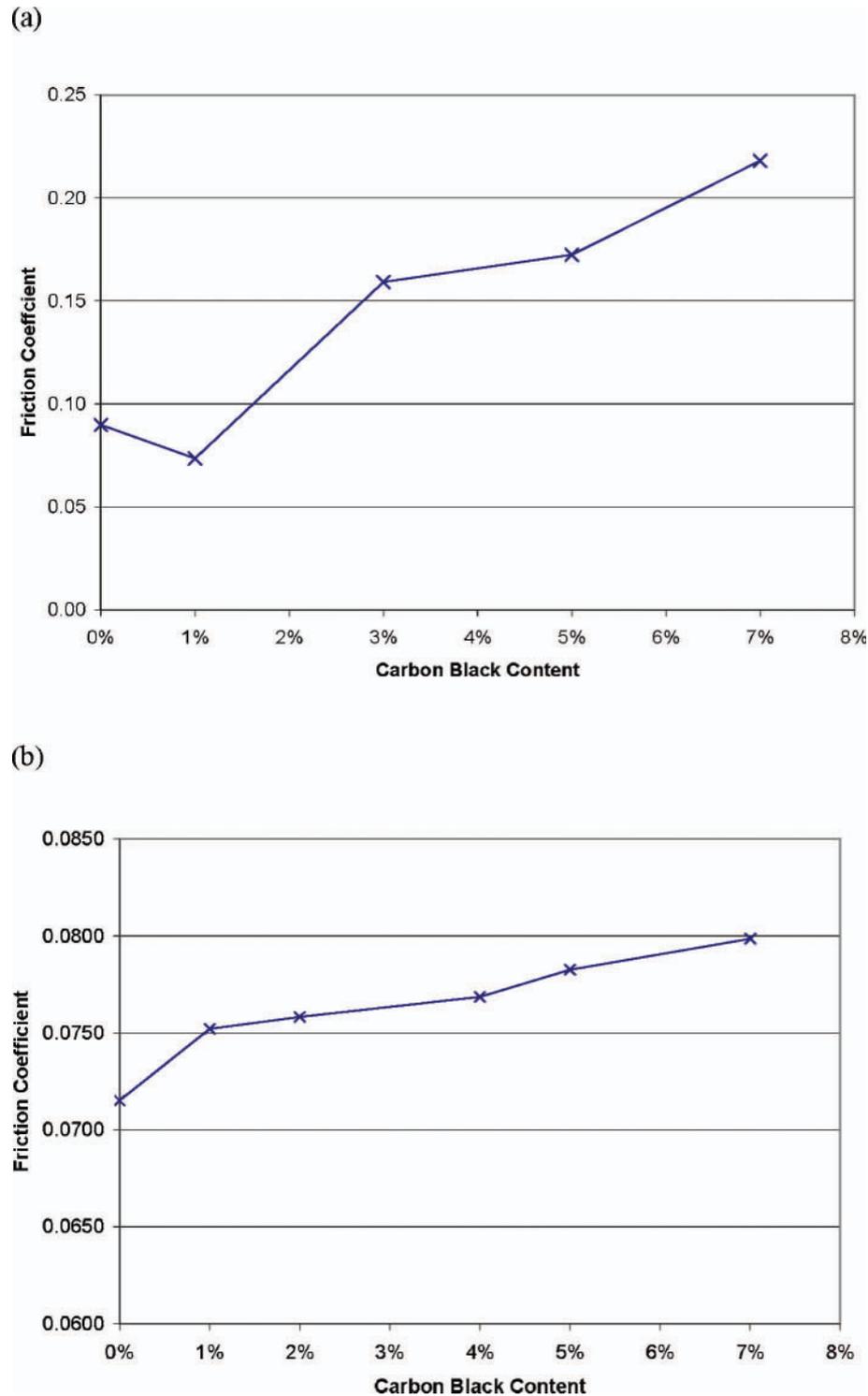


Fig. 12 Reciprocating ball-on-flat friction measurements [60] with (a) base oil and (b) formulated oil

The main issues to be considered when creating a test standard for investigating soot wear include the contaminated oil mixture method, test specimen preparation, test method and procedure, and wear analysis. When considering the contaminated oil

mixture itself, the elements used are important. The lubricant should be selected depending on the aims of the testing: base oil should be used to demonstrate wear that occurs when there are no anti-wear additives present (with base oil, a dispersant is

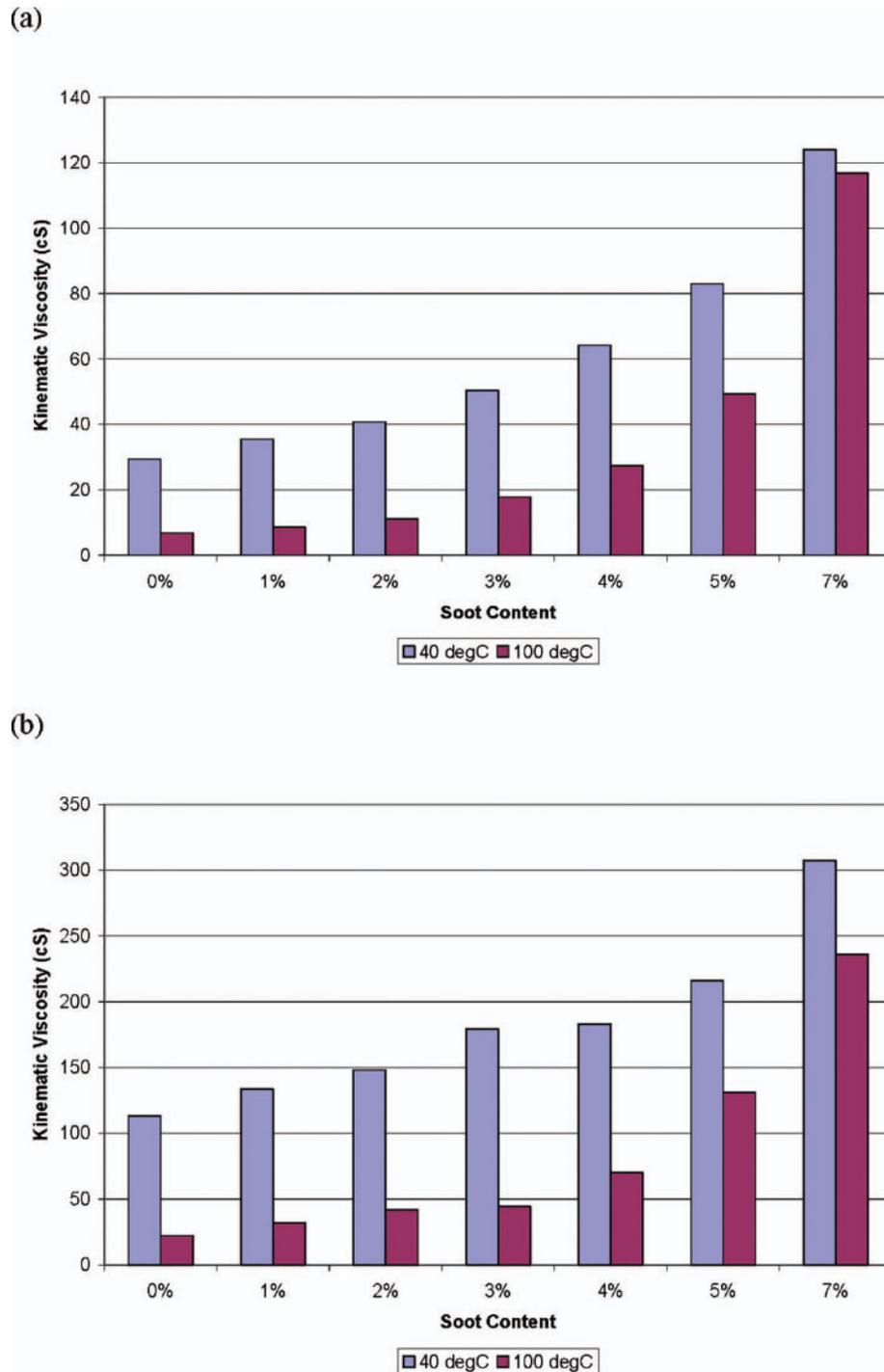


Fig. 13 Kinematic viscosity measurements [60] with (a) base oil and (b) formulated oil

required to suspend the test particles); formulated oil should be used to test the wear resistance of new lubricants and for comparison between different finished lubricants. Ideally, extracted engine soot mixed into a fresh test lubricant is the best soot stimulant, but there are variability issues with such particles. To avoid such variability, carbon black particles are the next best option. A variety of mixing

methods have been applied, but heating and ultrasonic agitation of the mixture has been proven by many to be the most appropriate method. Test contacts should replicate the real engine conditions: an example of this can be seen in work by Green *et al.* [31], where an elephant's foot reciprocating valve train contact was replicated in a reciprocating test rig. Ideally, the specimens should be similar in terms

of material composition and dimension to real engine contacts, experiencing a realistic contact pressure. The duration for the tests should be long enough to produce wear data that are unaffected by a running-in period, but short enough to be a practical laboratory test (in terms of minutes, and not hours). Current analysis techniques using wear scar imaging (using microscopy and SEM) and surface profilometry are providing extremely useful information. The latest advanced techniques, such as scanning interferometry, may provide much more detailed information on the wear features produced.

Standard techniques are being investigated and used, such as the ASTM G133-05 for a reciprocating ball-on-flat wear, but specific standards are required to incorporate all the issues above for soot-contaminated oil wear testing. Such a standard is currently being developed for piston ring on cylinder liner specimens with contaminated oil [40].

Testing with contaminated lubricants provides many complex and contentious issues. One main issue relates to the real dispersion of particles within the test lubricant. Practically, it is known that in any mixture of contaminated oil there is a significant amount of residue in the bottom of the receptacle containing the mixture. In many cases, further analysis is required to assess the contamination level in the sample rather than bulk test mixture.

7.2 Wear and friction

It has been clearly shown that a significant majority of research does not demonstrate that soot particles reduce the performance of the anti-wear additives in lubricants, but that abrasion is the major wear mechanism that occurs with soot-related engine wear. Various workers have referred to such wear as either abrasion or polishing; also, the automotive industry generally refers to soot-related wear as polishing.

As the levels of contamination used have been increased, the amount of wear produced has also increased and the wear mechanisms witnessed have also changed to that of contact starvation of lubricant. As lubricants are expected to retain up to 10 per cent soot by 2010, further investigations are required to investigate the wear levels produced with modern lubricants containing this level of contamination. It is expected that the starvation wear mechanism will dominate at this level unless lubricants can be developed to operate without causing starvation. Starvation is obviously an extremely detrimental wear mechanism regime to operate in as engine failure due to excessive

component wear, overheating, and localized welding is extremely likely. These high soot retention levels (within the lubricant) are a serious issue for engine efficiency too, causing the engine to burn an increased amount of fuel and therefore to emit an increased amount of carbon dioxide.

As the transition between wear mechanisms is dependent on the amount of soot in the lubricant, the oil-film thickness produced, and the size of the soot particles in the lubricant, future research is required to develop lubricants that increase oil-film thicknesses without a significant detrimental effect on engine efficiency.

One main area of testing that has attracted very little attention is that of visualization of soot entrainment into a contact. Visualization techniques could vastly improve the understanding of how soot enters the contact (if it does) and how it forms around the contact to starve it of lubricant. Such research would complement wear and friction testing and assist with the understanding of the motion of soot around contacts.

Engine valve trains have been shown to be the most susceptible to soot-related wear because the type of motion (generally reciprocating) creates interrupted oil films, low lubricant flowrates, and related design issues. The effect of soot contamination around the piston has also proven to create significant wear. Abrasive wear occurs to a lesser degree as the reciprocating motion in that region of the engine is more effective in creating oil films, but, owing to the extreme temperatures, volatile gases, and the presence of oxygen, corrosive wear is highly likely to occur.

7.3 Wear modelling

Currently, no modelling of soot-related wear has been performed, other than to produce Archard wear coefficient graphs [31]. Modelling has been performed, however, on the related issues of soot production through combustion, soot adsorption, and agglomeration within lubricants. Similar models are required to complement the above models and to make significant use of the testing that has been performed and the wear mechanisms that have been proposed to simulate wear due to soot in a variety of engine contacts in various operating conditions.

7.4 Soot removal

Current flow-through filtering is expected to be used in the near future as there is no alternative available

with the ability to match it in terms of both performance and cost. Bypass filters with increasingly finer-grade filters and deep-bed filters are expected to continue to perform this function.

Possible future lubricant filtering techniques can draw inspiration from various other industries; such techniques may include magnetic [66, 67], ultrasonic [68–71], and electrostatic [69, 72–74] means. Chemical and biological treatment of the contaminated lubricant may also be a possibility in the future [75, 76].

Another approach to take in relation to the problem of lubricant contamination is possibly not to retain the contaminant in the lubricant at all. With this process, the particles would be flushed through the engine and into the sump. This process would be extremely dependent on detailed engine design to ensure that all the particles travel through the engine to the sump and are not retained within the main body of the engine and, therefore, entering any critical contacts to cause wear. In the sump, the particles could be filtered through a deep-bed filter, to ensure good retention of particles, to avoid recontamination of the lubricant. If this method were to be applied, the life of a lubricant would not be determined by its particulate contamination level, but by its natural degradation through use, possibly leading to extended engine oil drain periods.

The detection of soot in a contact or in the lubricant alone is also important as it increases understanding of the transportation of soot around the engine and also the amount of soot in the lubricant at that point or as a bulk quantity. It is thought that this may be possible with various removal techniques.

7.5 Other fuels and lubricants

Alternative fuels, such as modified diesel, synthetic diesel, and biofuels, in tests have been shown to reduce the amount of particulate matter produced [21–30]. Some biofuels produce no more wear than conventional diesel fuel [27]. Such testing needs to be continued as these fuels will reduce both the amount of carbon dioxide emitted and the level of soot-related wear in engines, while allowing the trend of increasing service interval to continue.

Increasingly, synthetic lubricants are being used in engines and are a requirement for high-performance engines. The use of synthetic lubricants over mineral-based lubricants are that they can be very carefully controlled to provide the properties required. They also have a very high viscosity index,

meaning that their viscosity is not highly dependent on temperature changes. This is important in the role of controlling the oil-film thickness produced at high engine operating temperatures to reduce the wear effects of soot-related wear issues.

8 CONCLUSIONS

This review paper has brought together a significant amount of information and research in the field of soot-contaminated lubricants and the associated engine wear problem. It has been shown essentially that, in fuel-rich and high-load engine operating conditions, soot production increases dramatically; the primary soot particles of approximately 40 nm diameter are either transported to the exhaust system or absorbed by the lubricant. When absorbed by the lubricant, the soot particles tend to agglomerate into clumps of an approximate mean diameter of 200 nm. If EGR (a technique used to reduce NO_x emissions) is fitted to the engine, then some of the exhausted air is reintroduced into the engine, increasing the soot loading in the lubricant.

Soot-contaminated lubricants have been shown to increase the wear of many engine components. An engine's valve train has proven to be the most seriously affected because of the thin oil-film thicknesses experienced in many of its reciprocating contacts. The film thicknesses produced in such contacts have been shown to be less than the diameter of the soot particles contained within the lubricant.

To understand the degree to which soot in a lubricant increases component wear and, more importantly, the wear mechanisms that cause the wear, various tests have been performed. The tests have included a laboratory bench test all the way through to full engine tests. Each type of test provides more information to add to the increasing knowledge on the subject. The dominant wear mechanism that has been discovered is abrasion, but the more serious starvation wear mechanism, which occurs at very high soot contamination levels, could lead to engine failure as contacts may end up operating unlubricated.

Soot contamination has also been shown to affect adversely the properties of lubricants, in particular increasing the viscosity, which in turn increases contact friction, leading to a reduction in engine efficiency. This will increase fuel consumption and, therefore, tailpipe carbon dioxide emissions.

Many future research opportunities are possible in this area as it adversely affects operating costs to the

customer, wear of the engine, and exhaust emissions. Further testing to confirm the wear mechanism theories is required, especially with different materials and contact conditions. From such testing, wear prediction models can be produced to predict how wear will occur in new engine contact designs and how to minimize the wear effects of soot contaminants. Investigations are required into the actual removal of the particles from the lubricant, to attempt to reduce the potential that wear occurs.

A reduction in the amount of soot produced through the combustion process can be achieved through development of current diesel fuels and through the introduction of synthetic diesel fuels where tighter component control is possible owing to the nature of the production process. Biofuels are also showing promise as they naturally tend to produce less combustion soot than current diesel fuels. Finally, improvements in lubricant technology can assist in the retention of soot particles and anti-wear performance through additive improvements. Also, increased wear protection can be achieved through the very high viscosity indices possible with modern synthetic lubricants.

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