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Contemporary challenges of soot build-up in IC engine and their tribological implications

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Abstract

Confronted with the contemporary challenges of maximizing energy efficiency with minimal impact on the environment, the automotive industry has developed various technologies to tackle them. Most of these technologies, however,have wider implications on the tribological performance of the automotive engines due to resultant soot build-up. This paper reviews the effects that attempts by stakeholders to satisfy requirements for reduced fuel consumption, reduced emissions and extended service intervals havehad on increasing soot levels to an extent that can lead to engine component failure.Three areas have been identified that have either not been explored or not widely explored in the study of automotive soot, namely: numerical simulation and modelling of soot wear, soot effects on wear of actual engine components and the wear and friction performance of non-metallic materials used in ICEs. A paper-grading system is also utilised to present an overview of how sooty oil related research covers various areas.

Keywords: *Automotive engine, soot build-up, technological trends, tribological performance, wear, lubrication, friction*

1.0 Introduction

Automotive manufacturers are regularly attempting to extend the service intervals of internal combustion engines (ICEs) [1-7] to reduce both the long-term vehicle maintenance costs and the environmental impact of disposed oil. The clear consequence of this is that lubricating oil will become increasingly contaminated with soot, the effect of which is detrimental to the components in tribological contacts. Exhaust gas recirculation (EGR) is increasingly being used to minimize oxides of nitrogen (NOx) emissions in compliance with emission regulations, and the resulting recirculation of combustion products back into the combustion system further contaminates the oil. The implication of this is that while the EGR is effectively reducing emission of NOx, it is inadvertently increasing soot levels in the lubricating oil; a covert trade-off between NOx and soot [1, 8, 9]. Singh et al. [9] in investigating soot generation and wear of an engine suggested the use of a soot trap along with EGR as the solution to simultaneously control the level of soot and emission of NOx whilst minimising wear. Although, soot is not specifically governed by legislative requirements [10]; its debilitating effect on engine oil lubricity and the wear of engine components have made its control an important focus for automotive manufacturers.

Contemporary challenges of maximizing energy efficiency with minimal impact on the environment have led, the automotive industry and lubricant formulators to show great interest in research that brings about tribological improvements.

The review highlights work undertaken in soot contamination and its effect on engine components. It builds on the Green and Lewis [1] review, and includes work considering soot's tribochemical properties and emphasises the lack of component-based investigations. Potential research areas in the study of automotive soot wear are also identified with a grading map presenting a general overview of areas covered by sooty oil related researches.

2.0 Automotive engine technology trends

Current trends in automotive research that consider soot in the broadest sense can be grouped into those explicitly driven by regulation and those driven by technology development required to measure its presence.

2.1 Regulation-induced

Automotive manufacturers (both OEM and in the supply chain) are introducing many changes to engine design to fulfil current and future requirements of reduced fuel consumption, elongated service intervals and emissions reduction. These include retarded timing, raised piston rings, selective catalytic reduction (SCR) and the use of exhaust gas recirculation (EGR) [11].

Tackling the issue of fuel consumption through downsizing implies an increase in specific power output, accompanied by higher cylinder pressures (increased dynamic load) and oil temperatures (increased thermal load) [12]. Controlling the formation and emission of NOx by reducing combustion chamber temperatures and retarding the fuel injection timing during the combustion cycle, however, traps more soot in the chamber. EGR also assists in controlling the combustion process but also results in soot build-up.

Any design change that increases the soot content is very likely to also increase the viscosity of the lubricating oil, leading to increased oil pump loads and increased fuel consumption. Similarly, interdependencies are seen throughout an engine, for example in the valve and seat insert contact where the legislation for lead-free fuels resulted in the elimination of beneficial tribofilms [13, 14]. Similarly, lubricant additives, such as zinc dialkydithiophosphate (ZDDP), play a major role in protecting the components from wear by forming tribofilms at contact points but as it has been discovered, for example that the lifetime of catalytic converters is shortened by ZDDP breakdown products [15].

The recent aim of the EU Commission [16] to introduce Real Driving Emission (RDE) tests further increases the operating range of the emissions regulations with consequences on the technology to comply. The RDE tests are carried out on the road using Portable Emission Measurement Systems (PEMS) which according to Vlachos [17] have been very effective in vehicle emissions control and a novel approach towards emission abatement with potentialto improve air quality globally.

The new test is aimed at determining, more accurately, pollutant emissions in real driving conditions. This was consequent upon discovering that the emissions generated by vehicles on the road are substantially higher than in laboratory conditions.

This measure is likely to increase the level of soot generated in the engine as EGR would become more widely used, even by gasoline engines, in order to comply with the new regulations.

More generally, the move towards lower viscosity lubricants (e.g. SAE 0w7, 0w15) to satisfy the quest for more efficient automotive engines, through reduced friction, has significant tribological implications due to the thinner lubricating films formed in the engine contacts [18].

2.2 Soot monitoring and removal

2.2.1 Field-based condition monitoring of soot

The ASTM designed standard for field testing is ASTM D7686 [19] and is designed to measure soot build-up (up to 12%) in diesel crankcases of in-service hydrocarbon-based lubricants using fixed-filter infrared spectroscopy. Absorption intensity measurement is used to determine the soot level after which direct or differential (using a new lubricating oil as reference) trend analysis is used to compare and correlate with the engine performance [20]. Figure 1 shows infrared absorbance spectra for diesel crankcase oils over a range of 4000 to 550 cm^{-1} using FITR spectroscopy. From the baseline offset at 2000 cm^{-1}, the figure indicates the increasing soot loading levels for low to very high (increasing from 1 to 5).

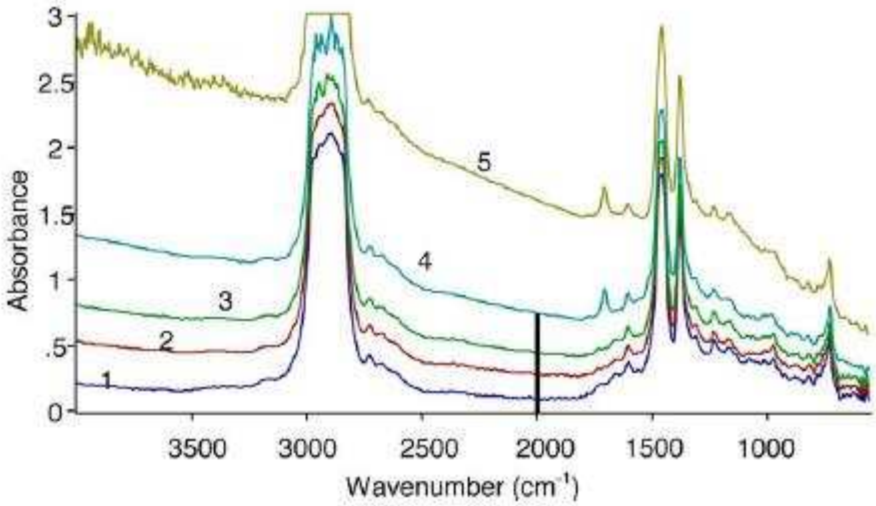


Figure 1: Trend analysis of soot measurements in diesel crankcase oils [20]

Although this standard evaluates only the soot content, ASTM E2412-10 [21] is designed for more complex condition monitoring such as, additive depletion, contaminant build-up and base stocks' oxidation, nitration and sulfation as evidence of degradation. Figure 2 shows the measurement areas for oxidation and nitration (1800 to 1670 and 1650 to 1600 respectively) accumulation monitoring in crankcase oils, and Figure 3 shows measurement area of sulfation.

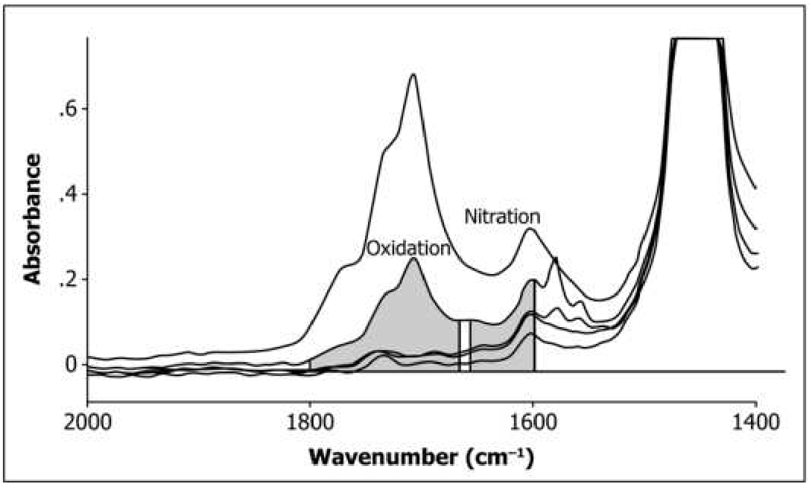


Figure 2: Measurements of Oxidation and Nitration in crankcase oils [21]

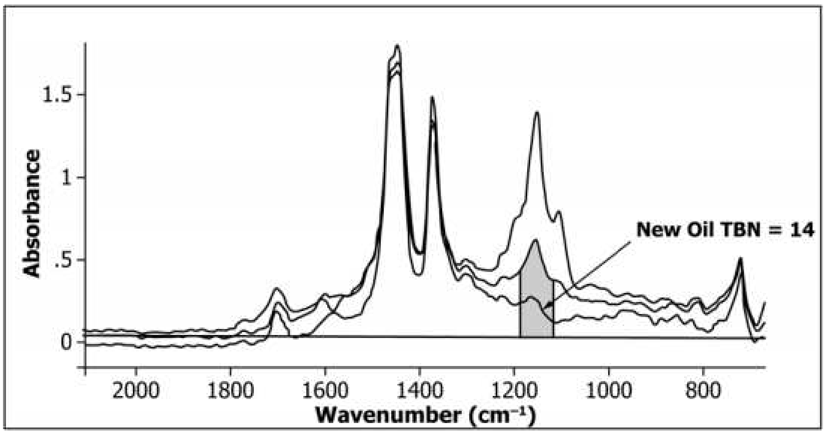


Figure 3: Measurement Sulfation in crankcase oils [21]

Oxidation occurs as a result of oil reaction with oxygen which is usually accelerated by high temperature, water and acids. While nitration is a degradation of oil resulting from a reaction with NOx, sulfation results from the reaction of oxygen, heat, water and sulfur from diesel fuel or base oil additives. Each of these causes premature oil thickening which increases oil viscosity, deposits of varnish and sludge.

2.2.2 Removal of soot

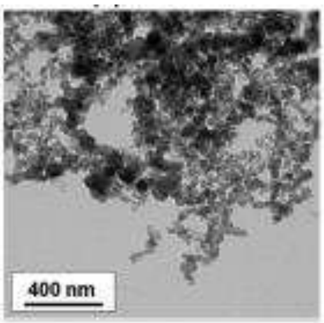
Effective and efficient soot removal from the lubricant can help achieve the desired engine performance and durability and prolong oil drain intervals, a significant current trend driven by users [22].

The two main removal approaches to date have been through mechanical filtration and centrifugal filtration. Mechanical filtration involves efficient single-pass filtering using coarse filter (mainly used for petrol engines) and/or by-pass filtering with a finer filter (mainly used for diesel engines). Centrifugal filtration involves the use of high speed rotating chambers to separate the contaminating particulates from the lubricant [1]. Cheekala et al. [22] used a new approach involving the utilization of electric field on the soot particles to stabilize the weakly bound soot cake. This method achieved appreciably higher filtration efficiency as compared to mechanical and centrifugal filtration.

3.0 Soot formation

Soot is microscopic hard amorphous carbon particles, the concentration of which can be as high as 8%in automotive lubricants [23]. As elemental particles, soot presents as small but hard spherical particles of 20-50nm; however, they can aggregate into secondary particles which are ‘soft’ and ‘slippery’ due to their agglomerated structure with sizes 50-500nm. Soot clusters can build up to thousands of spherules. Each spherule comprises hydrocarbon material and inorganic material (mostly sulfates), which are responsible for the abrasive behaviour of soot [24]. Figure 4 shows soot in its various forms as elemental particles and sticking together to form an agglomerate in a chain-like structure; while, Figure 5 shows the transmission electron microscopy (TEM) images for diesel soot in both two-dimension and three-dimension.

Figure 4: The depictions of: (a) Soot as elemental particles and (b) a chain agglomerate of soot particles



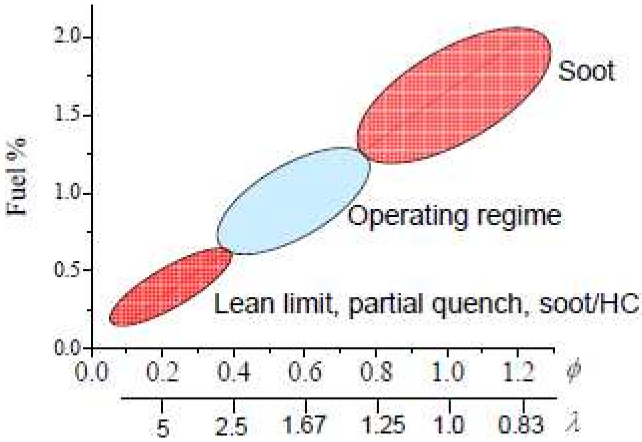
(a)

(b)

Figure 5: Transmission electron microscopy (TEM) images of diesel soot (a) in two-dimension [25] and (b) three-dimension visualisation [26].

Soot, though undesirable because of its harmful effects, is an inevitable combustion product of partially combusted fuelin an internal combustion engine (especially diesel) [27]. Soot is formed mainly in the fuel-rich regions of the combustion chamber at elevated temperatures. It can also be formed to some extent at lean combustion when some unburned oxygen passes through the flame. This normally occurs during cold starting, low speed engine and other circumstances, such as deceleration and acceleration, mostly common especially in urban traffic.

For diesel engines, the complex combustion process is further aggravated by the non-uniformity of fuel distribution and air-fuel mixing process [28]. This combustion initiates close to the injection point around the top dead centre (TDC) when the mixture is fully compressed and occurs very rapidly and spontaneously as a diffusion flame. Since the mixture (air-fuel) is very fuel-rich, this results in the production of high level of soot. Figure 6 shows how air-fuel ratio influences the formation of soot in a diesel engine.



$\phi = Equivalent\ ratio$

$\lambda = Air - fuel\ ratio;\ \lambda = \frac{1}{\phi}$

Figure 6: Soot formation process in a diesel engine (The University of Sheffield)

Obviously, it can be seen from Figure 6 that:

$\phi < 1$, $\lambda > 1$ when there is fuel lean mixture,

$\phi = 1$, $\lambda = 1$ for stoichiometric mixture and

$\phi > 1$, $\lambda < 1$ when there is fuel rich mixture [29].

4.0 Overview of soot effects on automotive engines

The damaging effects of lubricating oil contamination by soot particles have long been recognized. Research has clearly shown that soot plays a major role in the wear of various specimen/components subjected to different laboratory/components experimental investigations [1-8].

Soot effects on ICEs are multi-dimensional and the mechanism of soot-induced wear is thought to be either one or combination of some of the following elements:

1) Soot can either directly entrain into the contact between two components and with its hard particles abrade or scratch the surfaces in three body abrasion [1-3] or block oil entrance into the contact zone of rubbing components when its size, through agglomeration, is larger than the oil film thickness or indirectly degrades the oil through alteration of its chemical properties thus rendering it ineffective [30].

2) Soot acts as an abrasive on the anti-wear solid film, comprising calcium, oxygen, phosphorus and sulphur, formed by the oil on the metal surface [31-33]. The idea of preferential adsorption and chemisorption of anti-wear additives in the lubricants by the soot [34-36] still subsists.

3) Soot contaminants produce large increases in oil viscosity [5, 8, 37-40] and thus hinder the effectiveness of the oil pump which consequently affects the rate and amount of lubricant getting into tribological contacts when required.

4.1 Soot microstructure and tribochemical activity

It is also thought that the microstructure of the soot has an effect on its chemical reactivity due to the arrangement of carbon structure influencing its oxidation resistance. Thermal ageing transforms soot structure from disordered amorphous carbon to more orderly polyaromatics with higher oxidation resistance [41]. Ivleva et al. [42], in a study of soot samples from gasoline and diesel engines, observed that theircarbon structures, amorphous and graphitized respectively, have an impact on their chemical reactivity during the process of oxidation and gasification, with well-graphitized diesel soot oxidizing less readily.

The temperature at which soot forms also influences its properties (chemical composition, surface area and morphology) and hence its reactivity behaviour [43]. The higher the temperature of formation, the more ordered and less reactive are the soot samples.

Antusch et al. [34] studied the tribochemical action of various sooty oil mixtures from diesel engine, gasoline engine and laboratory produced carbon black, and reached a conclusion that soot particulate concentration is not solely responsible for wear properties with soot morphology, surface chemistry, and reactivity play more significant roles. They also proposed a new wear model specifically for sooty oil from gasoline engines (Figure 7); where the unpaired reactive electrons (dangling bonds) of the highly disordered soot particle surface compete with anti-wear additives for the metal surface. The soot particulates, being more polar, have a more likely chance of reacting with the metal surface first and also attract the polar additives to itself, thereby increasing wear. This was corroborated by Uy et al. [44] in their comparison of samples of soot from gasoline and diesel engines, concluding that the more amorphous structure of the gasoline engine is responsible for its high level of polarity and reactivity with metal surface and other polar additives in the lubricating oil.

Hence, the level of disorder in the soot microstructure is proportional to their chemical reactivity.

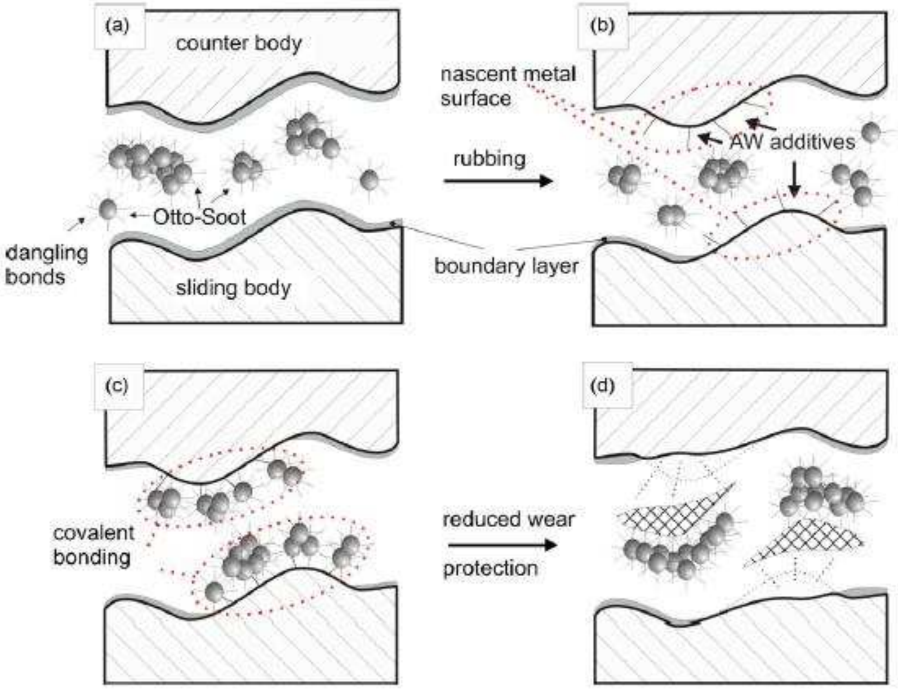


Figure7: New wear model for gasoline soot [34]

Another soot-induced wear mechanism attributable to the high wear under boundary lubrication conditions is corrosive-abrasive mechanism [45, 46]. This mechanism results from concurrent formation and removal of tribofilms by carbon black (CB) particles. While the CB content influences the level of removal of tribofilms, its formation rate is determined by the temperature [45].

All these ideas should be seen as complementary rather than contradictory as each comes to strengthen our understanding of the behaviour of soot in an automotive engine.

4.2 Soot effects on wear and friction of ferrous metals

The detrimental effects of lubricant contamination cannot be overemphasized; apart from causing wear of engine components, it also adds to frictional losses in the contacts of the engine moving relative to each other (rubbing surfaces). Soot contributes significantly to the wear of engine components; the most vulnerable being components in tribological contacts, such as: cylinder liners, piston rings, valve train system, bearings. Many researchers [1-8] have shown that the infiltration of soot particles into contacts between these components is largely responsible for increased wear of rubbing surfaces. In some cases, soot like any other detached abrasive material, embeds in the softer body at the point of contact with the harder body and then scratches the harder body while serving as protective layer for the softer body.

Extensive research in this area has investigated various lubricants, soot types (including varying composition of surrogates) and numerous testing methods ranging from specimen, components to engine and has built confidence and a high level of acceptance of these theories by automotive stakeholders (engine manufacturers and lubricant formulators).

Nagai et al. [33] presented the results of the engine component tests where increasing the EGR efficiency level aggravates the level of wear of the tribologicalcomponents correspondingly (Figure 8) and is attributed to progressive soot build up as EGR level increases. Findings from other researchers [8, 32, 47] corroborate this with the assertion that life span of an engine may be shortened by EGR as a result of rapid oil contamination and degradation from exhaust products.

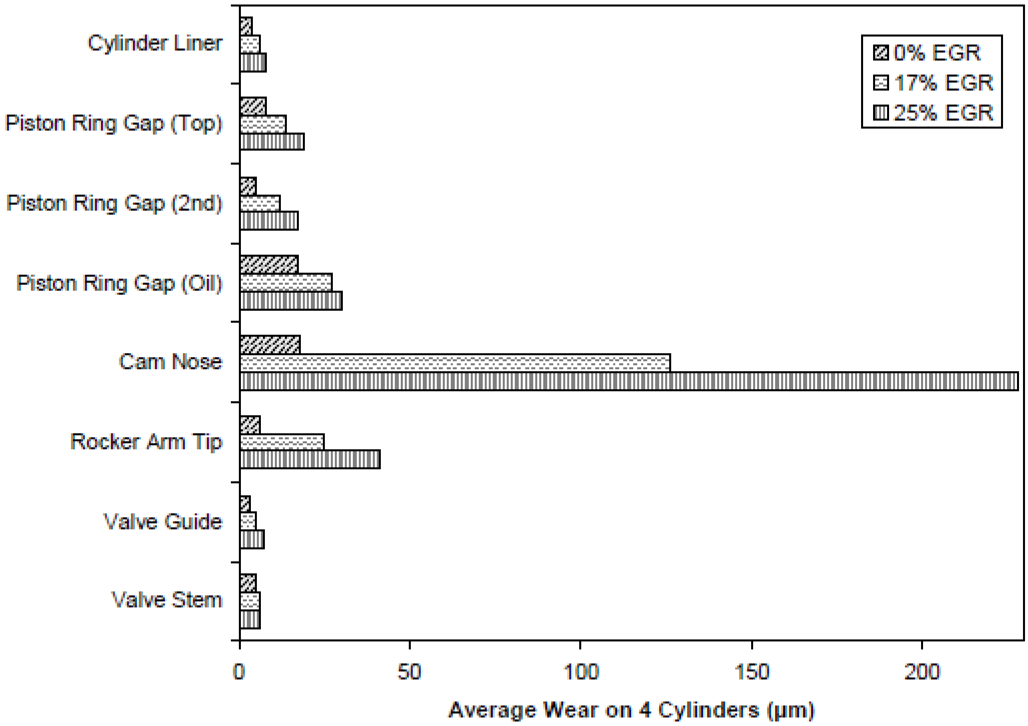


Figure8: A depiction of the influence of EGR on the wear of tribological components in a 4-cylinder engine [33]

A number ofstudies have been carried out to understand the effects of soot on ferrous materials such as steel and cast iron that are commonly used in engine components [5, 6, 31, 34, 39, 40, 53]. It is known that the presence of soot causes high wear and also affect friction in contacts.

Soot is known to also affect friction in contacts. Through a four-ball-tribometer, Georgeet al. [35] discovered that the average friction coefficient increases proportionally with carbon black concentration. Hu et al. [48] observed the same trend in a similar experiment using CD SAE 15W40 lubricating oil, especially for carbon black content above 2wt%.They attributed the reduction in the coefficient of friction at 2wt% to the fact that the carbon black particles are well-dispersed in the mineral oil. Green and Lewis [1], using a reciprocating ball-on-flat test rig,found that increasing levels of carbon black in engine oil increases the friction coefficient. Similar work also has shown that friction fluctuates and increases in case of contaminated oil with soot[31]. Other studies have reported that the presence of soot decreases the coefficient of friction. Aldajah et al. [8] discovered that friction reduces when tested in used engine oil, but the wear volume is higher. While Antusch et al. [34] found that high soot concentration decreases the friction in a pin-on-disc (PoD) tribometer. These conflicting reports on the effects of soot on friction suggestfurther investigations are required.

Most of the work considering soot wear of ferrous metals shows that all specimens (arbitrary or real components) tested have shown signs of abrasive wear starting from low percentage of soot/carbon black in the lubricant with evidence of lubricant starvation at higher concentrations [3, 5, 34, 48, 49]. Using data from three-body wear tests, Gautam et al. [32, 50] discovered that soot contaminated lubricants produced higher wear than uncontaminated oils. It was also found that the wear increase was due to an abrasion wear mechanism. Green et al. [3] had observed from a ball-on-flat disc test that the wear mechanism of lubricated metal-to-metal sliding wear showed signs of abrasion due to carbon black particles in the contact and starvation of lubricant from the contact as shown in Fig. 9.

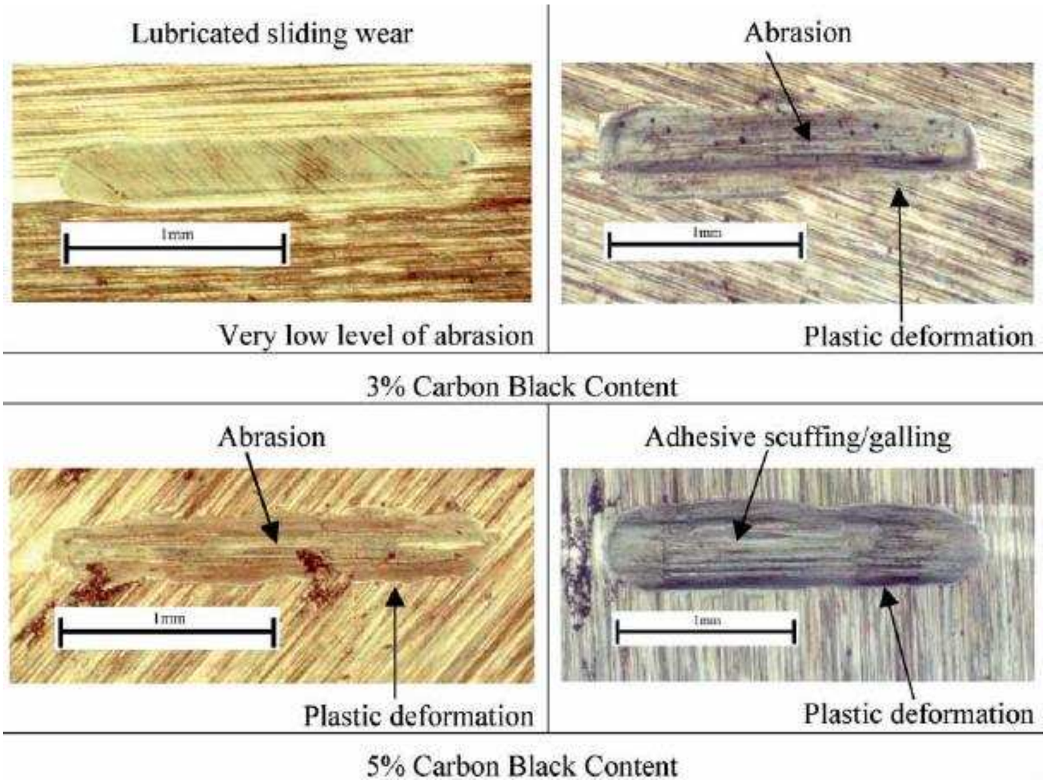


Figure 9: Images of abrasion mechanism at 3% and 5% carbon black content [3]

Soot size relative to the film thickness also plays a major role in determining whether wear would occur or not. If the lubricant film is thicker than the soot particle sizes, the metal surfaces can be separated by the lubricant film and no wear will occur. Contrary if the film thickness is less than the soot size, then abrasive wear will occur [8, 51, 52]. Li et al. [52] discovered that soot is harder than steel or cast iron thus the soot is hard enough to abrade metal engine parts. The investigation also shows that a number of groove widths are larger than the soot sizes. It is suggested that (wear debris) from the cast iron may have been responsible for these.

4.3 Soot effects on wear and friction of non-metallic materials

Elastomers are widely used in engine components due to its common characteristics such as viscoelasticity and high elasticity [53] and are widely used as seals in ICE applications. Seals are made from polymers such as rubber, polyurethane elastomers and PEEK. Seals may be divided into static (e.g. gaskets, O-rings) or dynamic seals (e.g., in pumps) depending on their application.

Although no work has been published that has studied how friction and wear varies specifically with soot on elastomers, some work has been done using small particles [54-58].

Elastomers are prone to wear under contact sliding conditions and this is a common cause of failure for dynamic seals. There are several modes of failure in seals such as abrasion, compression, chemical and thermal degradation. Most of the work in this area suggests that the cause of abrasive wear of seal lips is mainly abrasive particles being deposited as contaminants in the lubricant [54-56]. Mofidi et al. [57] discovered that the abrasive wear of elastomers in lubricated conditions is higher than in dry due to the weakening of the elastomer by the lubricant. The presence of lubricant in the contact prevents the particles from agglomerating, and therefore more single particles can come into the contact with the surface of the elastomer and contribute to the abrasive wear as third bodies.

Other tests used ball-on-flat disc uni-directional sliding test apparatus to investigate the wear characteristics of the rubber seal material. Park et al. [55] showed that the rubber is plastically deformed by a ploughing mechanism caused by the abraded particles, and the particles were then embedded in the surface of the rubber. When the particles were removed from the surface, craters were formed at the surface as shown in Figure 10.

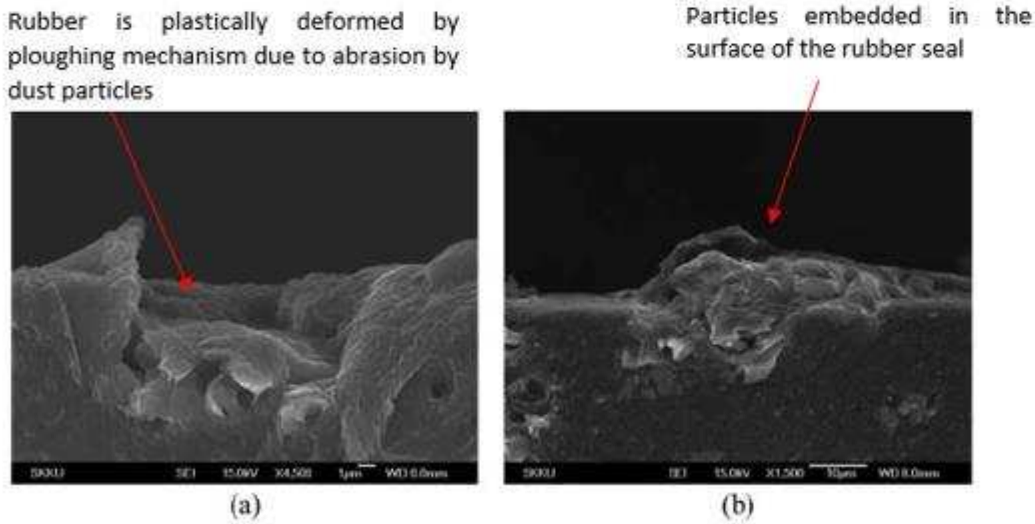


Figure 10: SEM Images of a rubber seal (a) wear crater due to particle (b) particle embedded into rubber [55]

Lee et al. [54] used a pin-on-plate reciprocating tribotester for the rubber wear tests. Lee discovered that the wear scars were mostly found at the centre region of the specimen thus the centre region was expected to be at high contact pressure under boundary lubrication. Alumina particles were added to the lubricant to increase the likelihood of wear, and it was found that a similar wear pattern emerged.

All of these studies [54-58] have investigated the effects of abrasive particles on the wear of seal materials; but there is no research yet published using soot, or its surrogate, to study the effects on wear and friction of seals that are made of elastomers.

Consequently, this is currently being explored by the authors of this review through the investigation of the effects of soot on a various types of polymers. Such as: nitrile butadine rubber (NBR), silicone, polytetrafluoroethylene (PTFE) and polyetheretherketone (PEEK). These types of polymers were chosen as they are regularly used as seals inICEs. These polymers were grouped and categorised as harder material (PEEK and PTFE) and softer materials (silicone and NBR). The investigation on wear effects on these materials are explained below.

4.3.1 Description of experiments

Carbon black (99% Acetylene, 100% compressed) blended with mineral oil (SAE 15w40) was used as a surrogate for diesel soot at different content levels and a standard test approach for friction and wear measurement on a High Frequency Reciprocating Rig (Plint TE77) was used for all the tests. The flat specimens were extracted from thin commercial sheets of each material (1-3 mm in thickness). On the other hand, the ball specimens made of Chrome Steel EN31 (6 mm in diameter) were used as the sliding counterface. The tests were executed according to the conditions given in Table 1.

Table 1 Ball-on-flat test conditions

Parameter	**Test Conditions**
Temperature (̊C)	23±2 and 100
Normal Force (N)	10
Stroke Length (mm)	15
Sliding Linear Speed (m/s)	0.14
Test Duration (min)	25
Lubrication	0%, 5%, 12% CB

These test conditions were chosen to give measurable wear in a reasonable time and to produce required oil film thickness and lubrication regime. The range of pressure and speed condition was chosen to ensure that the fundamental behaviour could be characterised. The effects of soot on friction and wear were determined, as well as the wear mechanisms observed for each of the materials. Figure 11 presents the overall view of coefficient of friction as well as the hardness values for both low and high temperature at various carbon black concentrations.

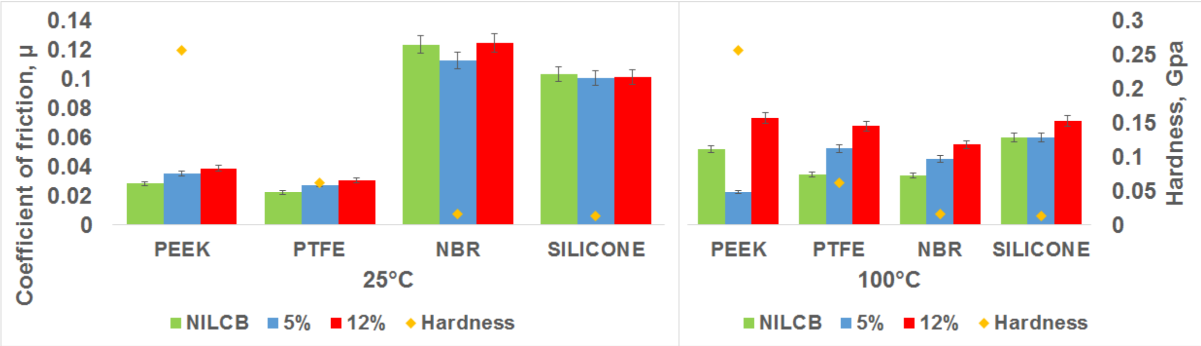


Figure 11: Coefficient of friction and hardness value for all polymers at low and high temperature for various carbon black contents

From these early results, it is obvious that the coefficient of friction is dominated by lubricant and soot for harder/softer materials as indicated in Figure 11 while for softer materials it is dominated by the material properties. This mechanism is depicted in Figure 12. All polymers show higher friction at higher carbon content level. This is because the sooty oils thicken which results in increasing viscosity and larger sizes of carbon black agglomerates restricting lubricant flow into the contact thus increasing the coefficient of friction. The increase in viscosity and predicted film thickness at lower temperature when operating in elasto-hydrodynamic lubrication regime will increase the friction due to the viscous resistance to shear. At higher temperature, the coefficient of friction is found to be low. This is due to the low viscosity of the lubricant at higher temperature thus lowering the friction. The decrease in viscosity suggests that it is operating within the boundary lubrication regime thus decreasing the contact friction.

And as soot is entrained into the contact zone of harder materials, it abrades the surface; while for softer materials, the soot is unable to entrain into the contact zone as the ball specimen pushes away softer flat material during sliding, thus restricting soot from entering and forming scratches and ridges in the process.

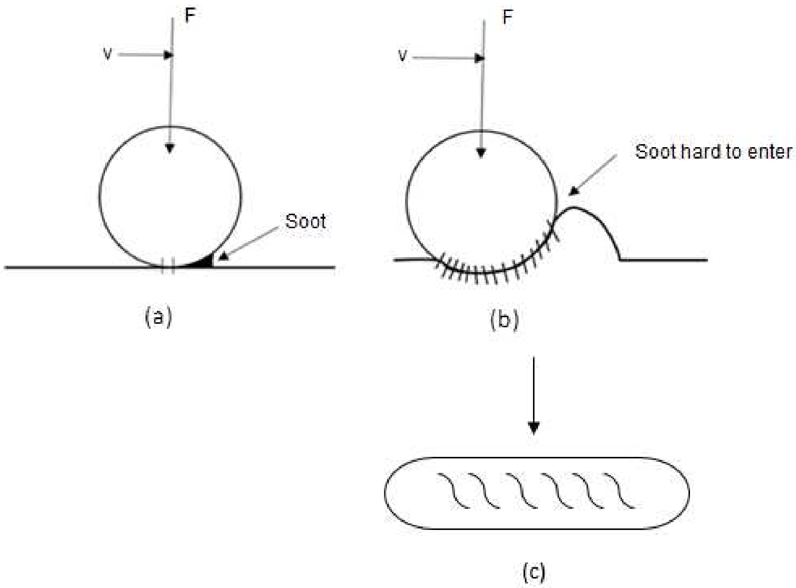


Figure 12: A schematic diagram of wear mechanism for softer materials

The wear mechanism for the materials is not dependent on the friction obtained. For softer materials, the surfaces demonstrate little signs of abrasive wear, but more on deformation of the materials itself; harder materials show signs of abrasion and also signs of a starved interface due to the contaminated lubricant. To understand the wear mechanisms of each material, especially for softer materials, in-situ visualisation of the soot entrainment is needed.

5.0 Modelling of soot wear mechanisms

The literature on numerical simulation and modelling of soot has been limited to its formation [58-61], oxidation [62, 63] and particle size distribution [64, 65]. An area of automotive soot study that has not received any attention is modelling of soot wear mechanisms, because they are still not fully understood.

The complexity of soot wear mechanism makes the task of accurately simulating and predicting soot wear behaviour very difficult [66]. Nonetheless, work in this direction is overdue.

6.0 Automotive engine testing simulation approaches

Tribological investigation of automotive engine components can be carried out at various levels ranging from specimens in a bench test to vehicle tests in the field. While a specimen test gives good control and repeatability but less complexities and less representative, the real engine test produces less repeatability and control but more complexities and therefore more representative [1]. Figure 13 illustrates various automotive engine simulation approaches.

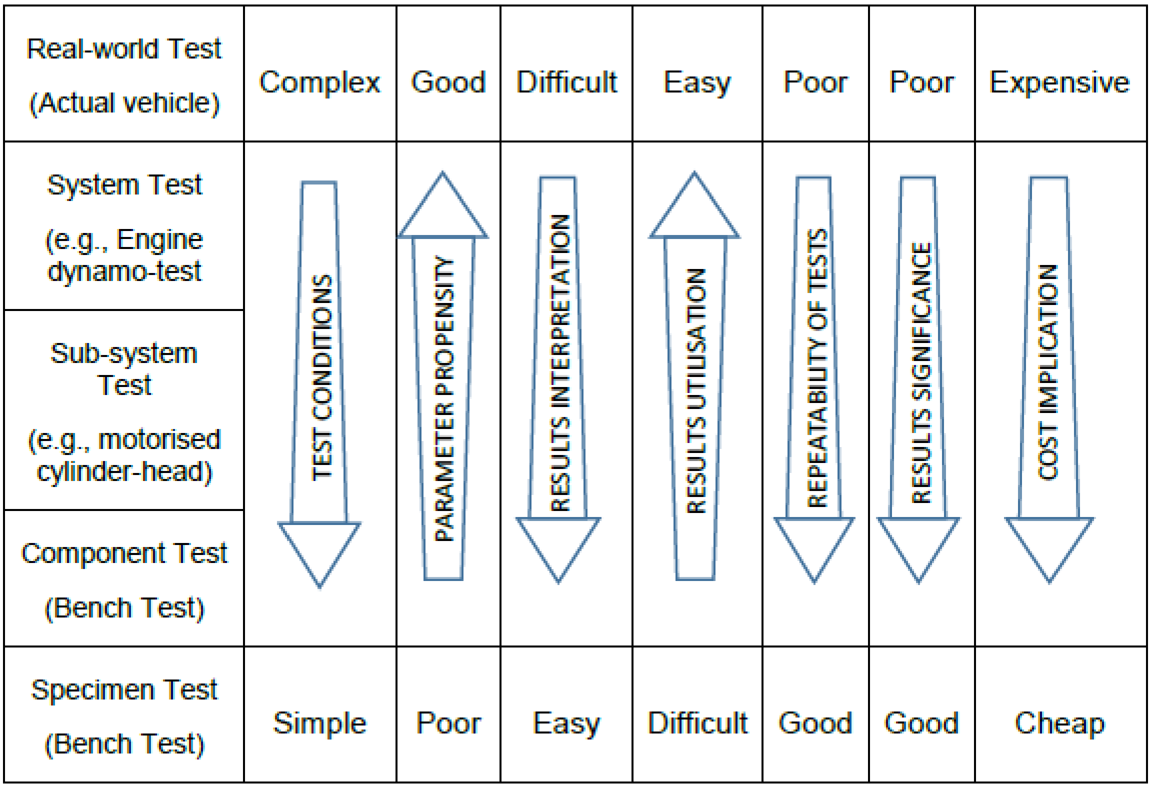


Figure 13: Simulation approaches in automotive engine [1]

6.1 Component-based wear test

The use of actual engine components may be the preferred approach towards getting a good representation when evaluating the effect of various parameters on individual components. Unfortunately, only few researches are actual engine components based. For instance, only five papers [1], [3], [7], [12] and [21] are components-based in the paper grading system presented in Figure 14. And, only two of these, namely [1] and [7] are soot-related. Specifically, there is a dearth of research on chain-drive system wear emanating from soot effects.

7.0 Paper grading methodology

A grading system has been created to indicate the status of the current research on soot effects in ICEs. This grading system is constructed to allow quick visualisation of where data is available and related to this review paper by scoring each reference according to a set of criteria. Each reference paper is also assigned to a primary and secondary group according to the main focus of the research. The grading of the papers are separated into 5 areas that are related to soot effects which are:

- General review on soot and where does it go and how is it a problem?
- Wear testing methods from small-scale specimen testing to full-scale engine testing
- Wear theories and its mechanism
- Effects of soot on lubrication
- Effects of soot on different materials if applicable

The relevancy of the research is then assessed according to the criteria as listed below:

- Is the document peer reviewed?
- Is the theory of the document supported by testing?
- Are the conclusions in the document evidenced within the data?
- Does the document contain a small-scale specimen testing?
- Does the document contain component laboratory testing?
- Does the document contain a full-scale engine testing?

The research outputs are evaluated against either having met (score of 1) or not met (score of 0) each criteria to generate a mark out of 6 (engine testing, component testing and small-scale testing are treated as separate criteria). Papers were then ranked as Not related (1-2), Related (3-4) and Highly Related (5-6). The evaluation results are then plotted as knowledge maps to highlight the extent and quality of available information on soot and its effect in the engine contacts. This grading is quite focused which means that it will score highly for some of the evaluation criteria, but low for others. Even where information on small scaled test are highly available, critical pieces of information are missing, for example there are very few records on the full-scale engine test, most likely due to the high chance of commercial sensitivity. This grading system for this research is not a criticism of the research in general, but to highlight the availability of information and the current status of this research according to the criteria mentioned above.

The chart displaying the results of the grading is shown in Figure 14. From the chart it is obvious that most of the research is ranked as “Related” with only four papers ranked as “Highly Related”. The small number of papers ranked as “Highly Related” is mainly because they are on full-scale tests that help to validate the research. According to the paper grading method, there has been less research completed to study the effects of soot on wear and friction using full-scale tests. Although a full-scale engine test is preferable due to the more realistic results that will be produced, results from bench specimen testing are displaying similar results that are reliable. A large variety of test rigs have been used to try to understand the wear created by soot contaminated lubricants which makes comparing results potentially difficult.

Figure 15 shows a chart describing the grading of work concerning the wear of materials by abrasive particles. This shows that only a few papers investigate the wear of polymers using abrasive particles and no research has yet been published where the particles are soot. The difference between these two charts clearly shows that there is a large research gap and suggests that work is required to determine the effects of soot on different materials other than steel and cast iron that are generally used in an ICE.

Figure 16 presents the grading map for actual component wear similarly showing a lack of research work on soot.

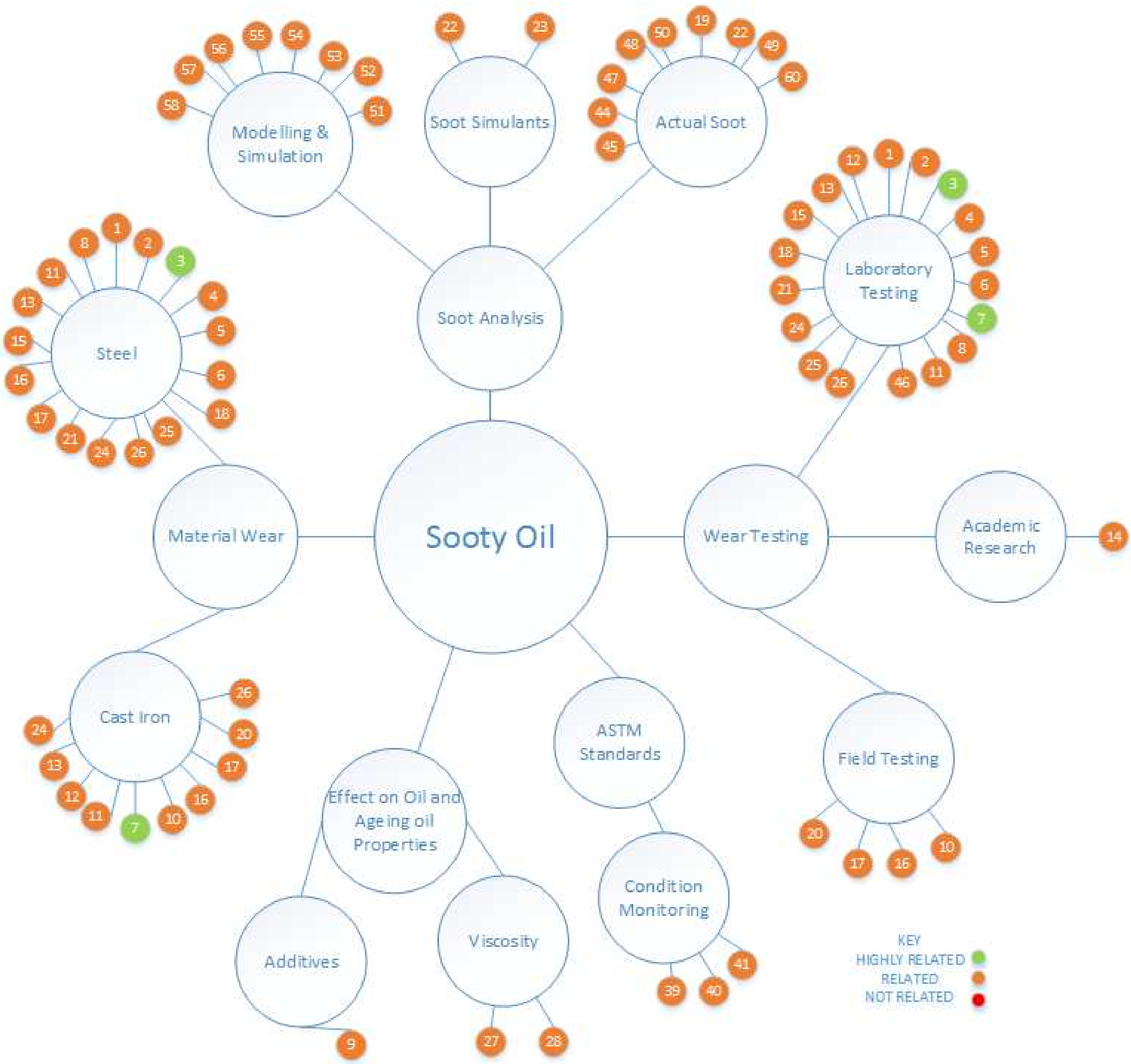


Figure 14: Knowledge map for soot effects on engine contacts

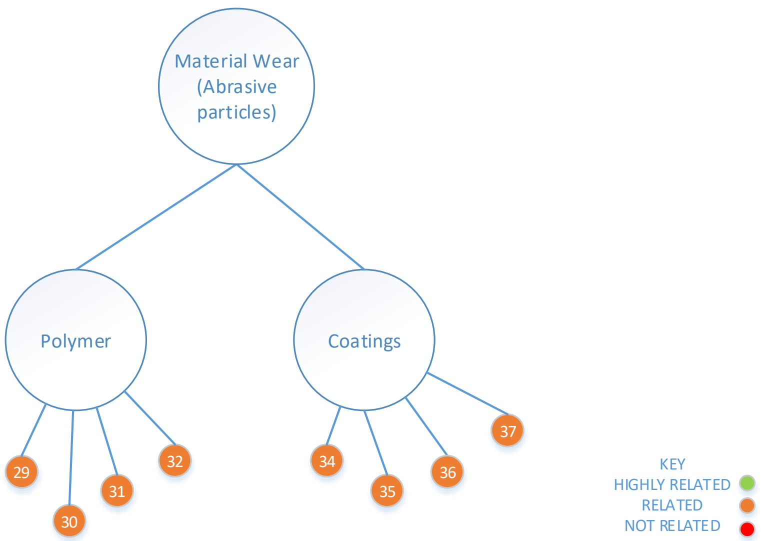


Figure 15: Knowledge map on material wear due to particles

Figure 16: Knowledge map on actual component wear

8.0 Conclusions and recommendations

8.1 Summary

This paper has reviewed current published research works and highlighted how current automotive technology development is often dictated by the need to comply with stringent emission legislations that continue to be periodically regularly reviewed. This state of affairs has particular consequences for investigations into the role of soot.

A more compact engine to minimize fuel consumption implies increase in specific power accompanied by higher cylinder pressures and oil temperatures; while emission reduction through the use of EGR results in soot build-up with consequent increase in lubricating oil viscosity which in-turn may lead to pumpability problems and increase fuel consumption.

In the same vein, use of lead-free fuel and the recently proposed replacement of ZDDP additives to enhance performance of catalytic converters in emissions reduction could threaten critical engine components as the beneficial tribofilms formed by lead and ZDDP to ameliorate the severe tribo-pairs contact conditions are eliminated.

The mechanisms of soot-induced wear of ICE components are quite complex and multi-dimensional. The contact zone between rubbing components are affected through direct entrainment or starvation by blocking of oil entrance, thus resulting in three-body or two-body abrasion respectively. Soot can also abrade anti-wear solid films formed by the oil on the metal surface; and its accumulation can alter chemical composition of oil, reducing its effectiveness.

Consequently, ASTM has designed standards to monitor, in-service, not only the soot but general conditions of the oil. This is also accompanied by the effective and efficient soot removal measures to ensure improved engine performance; improved fuel economy level and extended oil drain intervals.

Various tribological investigation approaches have their respective pros and cons. Laboratory tests generally provide platforms for the evaluation of the effect of varying parameters (lubrication, normal load, sliding speed, temperature, contact geometry, etc.) on the extent of wear and wear mechanism attributable to each. They would, however, be an appropriate representation of the real situation if they are real ICE component-based rather than being based on specimens. Apart from being very expensive, another pertinent issue with real engine test is that the combination of automotive engine operations often yields more severe wear on individual components than when a component is isolated for laboratory observation.

The paper grading system reveals that there are less research works on the study of soot effects on wear and friction using full-scale tests and real engine components; and no published work yet on its effects on polymers. This indicates a large research gap and suggests possibility of research opportunities in these areas.

8.2 Future research areas

There are three areas that have not been explored in the study of automotive soot, namely:

1) numerical simulation and modelling of soot wear,
2) soot effects on wear of automotive components,
3) wear and friction of seals that are made from polymers.

Exploring any of these areas will therefore be a worthwhile venture.

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