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# Effect of steel hardness on soot wear

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## ABSTRACT

Due to incomplete combustion, high levels of soot can accumulate in engine lubricants between drain intervals. This soot can promote wear of engine parts such as timing chains and cam followers. One standard approach to reducing wear is to increase the hardness of the rubbing components used. According to the Archard wear equation, wear rate should be broadly inversely proportional to hardness.

To explore this approach for controlling soot wear, wear tests have been conducted in a High Frequency Reciprocating Rig (HFRR) with HFRR steel discs of various hardness against a hard steel ball. Carbon black (soot surrogate) dispersions in model lubricants based on solutions of ZDDP and dispersant in GTL base oils have been studied. Wear volumes have been measured and wear scars and tribofilms analysed using scanning white light interferometry and SEM-EDS.

It is found that, while most oils show wear that reduces with increasing hardness, for blends that contain both ZDDP and carbon black, wear rate markedly increases with disc hardness as the latter approaches the hardness of the ball. The results support the prevalence of a corrosive-abrasive wear mechanism when carbon black and ZDDP are both present in a lubricant and suggests that selection of very hard surfaces may not be a useful way to control soot.

## 1. Introduction

High levels of soot in engine lubricants are frequently reported to induce high wear rates on engine components. Engine bearings, camshaft and crankshaft, piston rings, cylinder walls and timing chain are some of the engine parts that are most affected by wear induced by soot [1–3].

There has been extensive research to determine mechanisms by which dispersed soot particles in lubricants increase wear. Early work focussed on a possible negative impact of soot on the effectiveness of the anti-wear additive in engine oil and it was proposed that soot might adsorb anti-wear additives [4,5] or compete with them for rubbing surfaces [6]. Other suggested mechanisms were enhanced oil degradation by soot [7], metal reduction from anti-wear $Fe_3O_4$ to prowear FeO promoted by soot [8], lubricant starvation due to increased viscosity with high soot loading [9–11] and abrasion, either of the rubbing surfaces [12–14] or anti-wear film [4,12–21] by the soot particles.

In recent years attention has focussed on the concept that soot particles abrade ZDDP films as rapidly as they form, leading to a high rate of corrosive-abrasive wear. The main evidence for this is that when both ZDDP and the soot surrogate carbon black are present in a lubricant, this can lead to much higher wear than if either ZDDP or carbon black is absent. Booth et al. studied the additive interactions with soot using factorial analysis which showed that primary ZDDP appeared to increase pin wear [22]. He observed that blends containing both ZDDP and carbon black exhibited high wear on the ball, which he ascribed to due to immature anti-wear film formation. In 2009 Olomolehin et al. investigated the influence of carbon black and other nanoparticles on wear in antiwear additive-containing model lubricants [19]. They found that when carbon black was added to an oil containing ZDDP, the combination gave more wear than when no ZDDP was present; *i.e.* ZDDP became prowear. They suggested an adhesive corrosive-abrasive mechanism in which the carbon black removes the initial iron sulphide and phosphate antiwear film as rapidly as it forms, leading to a rapid loss of ferrous compounds and thus high wear levels. Very recently Salehi et al. have shown a similar wear mechanism for carbon black in formulated engine oil [21].

The process of obtaining engine soot from lubricants is time-consuming and the soot extracted will be contaminated by additives specific to the lubricant and fuel used. Soot can also vary in the degree of graphitization and particle size depending on engine conditions. Therefore a soot surrogate such as furnace or channel carbon black is generally used for wear studies. There has been some discussion in the literature concerning the similarity of carbon black with soot. It has

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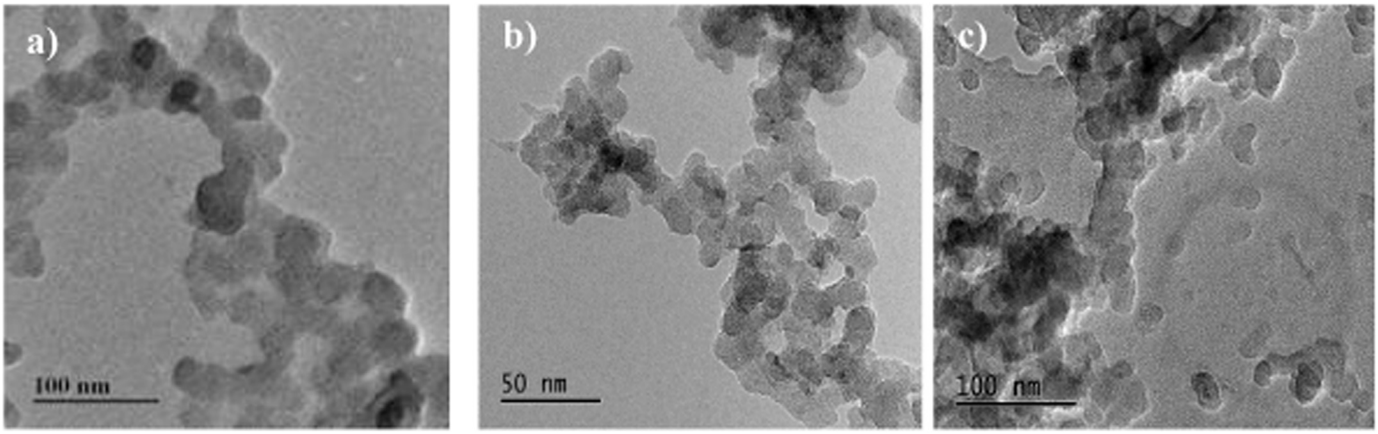


**Fig. 1.** TEM pictures of **a)** engine soot extracted from used diesel engine oil **b)** furnace CB (Cabot Vulcan XC72R) **c)** soot collected from cylinder walls of diesel engine.

**Table 1**
Test materials.

| | |
|---|---|
| Base Oil | Gas to Liquid (GTL) 18.3 cSt at 40 °C, 4.2 cSt at 100 °C |
| ZDDP | Secondary zinc dialkyldithiophosphate antiwear additive at 0.08 wt% P |
| Dispersant | Polyisobutylene succinimide polyamine dispersant at 0.02 wt% N |
| Carbon Black | Carbon black Cabot Vulcan XC72R (soot surrogate) at 5 wt% |
| Ball hardness (HV) | 880 ± 3 |
| Disc hardness (HV) | 196 ± 2, 295 ± 2, 398 ± 13, 658 ± 25, 772 ± 0.57 |
| Ball Roughness, Ra (nm) | 5 ± 0.1 |
| Disc Roughness, Ra (nm) | 5.6 ± 0.4 (196 HV), 6.2 ± 0.1 (295 HV), 4.9 ± 0.3 (398 HV), 5.8 ± 0.5 (658 HV), 5.1 ± 0.2 (772 HV) |

* ± is standard deviation of repeats.

**Table 2**
HFRR wear test conditions.

| | |
|---|---|
| Load (N) | 3.92 |
| Maximum Hertz contact pressure (GPa) | 1.03 |
| Frequency (Hz) | 50 |
| Stroke length (mm) | 1 |
| Test temperature (°C) | 100 |
| Test duration (min) | 60 |

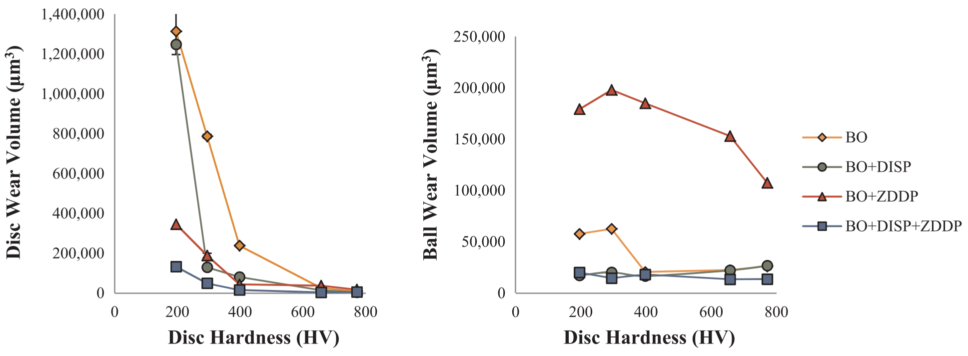
been suggested that some carbon blacks are similar in composition, size and morphology to engine soot [22] although considerable differences in surface properties have been noted between carbon blacks and exhaust soot, especially with respect to their combustion properties and toxicity [23–25]. In this study the furnace carbon black Cabot Vulcan XC72R was selected as being quite similar in primary particle size, structure, porosity and carbon content to engine soot [22] and because it has been used in previous soot-wear studies [19]. It also forms very similar secondary particles, as shown in Fig. 1, which makes it a realistic soot-surrogate in morphological terms.

In tribology in general, the material property that is found to improve wear resistance most reliably is hardness. This means that in engineering practice, one recognised approach to overcoming wear problems is to increase the hardness of the solid materials used. According to the Archard wear equation, the volume of material loss ($V$) during rubbing is directly proportional to the applied load, $W$, and the sliding distance, $s$, and inversely proportional to the hardness of the material, $H$:

$$V = KWs/H$$

where K is a wear coefficient. This equation is only approximate for most systems but can be derived theoretically from models of abrasive and adhesive wear [26].

No research appears to have been published to investigate the impact of hardness on soot wear although the hardness of engine components is considered crucial for the lifetime and durability of the engine. The minimum requirement limits of hardness for crankshafts and camshafts set by manufacturers and international standards range between 500 and 570 HV [27,28]. It is difficult to find definitive hardness values of some engine components since engine manufacturers hold these confidential. However, the research literature mentions finger followers in overhead camshafts with hardness of approximately 800 to



(a)

(b)

**Fig. 2.** HFRR disc (a) and ball (b) wear volumes from tests with different disc hardness for oils without CB.