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Full paper

# Effect of hBN/$Al_2O_3$ Nanoparticle Additives on the Tribological Performance of Engine Oil

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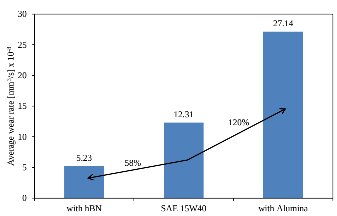
**Graphical abstract**




**Abstract**

Nanotechnology currently has an important role in reducing engine wear and improving fuel efficiency within engines using nanoparticle additives in engine oil. In this work, the effect of hexagonal boron nitride (hBN) and alumina ($Al_2O_3$) nanoparticle additives, on the tribological performance of SAE 15W40 diesel engine oil, was studied. A tribological test was conducted using a four-ball tribotester. The results show that the coefficient of friction (COF) and wear rate of the ball reduced significantly by dispersing hBN nanoparticle additives in SAE 15W40 diesel engine oil; compared to without or with $Al_2O_3$ nanoparticle additives. This is in accordance with the significant reduction of wear scar diameter and smoother worn surfaces observed on the balls.

*Keywords*: hBN; $Al_2O_3$; diesel engine oil; coefficient of friction; wear rate

**Abstrak**

Pada masa kini, teknologi nano memainkan peranan yang penting dalam mengurangkan kehausan pada enjin serta penambahbaikan kepada kecekapan bahan bakar dengan menggunakan nanopartikel di dalam minyak enjin. Dalam kajian ini, kesan bahan tambah nanopartikel *hexagonal boron nitride* (hBN) dan alumina ($Al_2O_3$) terhadap prestasi tribologi bagi minyak enjin diesel SAE 15W40 adalah dikaji. Ujikaji tribologi dijalankan dengan menggunakan pengujitribo empat-bola. Keputusan kajian menunjukkan bahawa pekali geseran dan kadar kehausan bola menurun dengan penyerakkan bahan tambah nanopartikel hBN ke dalam minyak enjin diesel 15W40; jika dibandingkan dengan atau tanpa bahan tambah nanopartikel $Al_2O_3$. Keputusan ini adalah sejajar dengan penurunan diameter dan kelicinan kehausan permukaan.

*Kata kunci*: hBN; $Al_2O_3$; minyak enjin diesel; pekali geseran, kadar kehausan



## 1.0 INTRODUCTION

In recent years, many related automotive studies have looked into ways of improving engine performance and efficiency. This prompts the future development of energy-efficient vehicles (EEV), by searching for low friction and anti-wear technologies [1-10], and improved emissions and engine performance. The need to improve fuel economy through this development of EEV, while reducing emissions, constantly motivates the demand for research to increase engine performance by improving lubricants.

Nanoparticles are categorized as a new low friction technology, and a method to reduce wear properties. Nanoparticles present several major advantages over organic molecules, and their nanometer size allows them to enter into contact areas easily. In the preparation of nano lubricants, various types of nanoparticles have been used, such as polymers, metals, and organic and inorganic materials [11-14].

Previous researchers have reported that copper (Cu) nanoparticles, used as an oil additive, can improve anti-wear, load-carrying, and friction-reduction performance of SJ 15W40 gasoline engine oils [15]. Other reports found that friction reduction and anti-wear behaviours are dependent on the characteristics of nanoparticles, such as size, shape, and concentration [16-18]. The size of the nanoparticles used average 2-120 nm. Besides, the addition of a low concentration of nanoparticles (between 0.2 vol.% and 3 vol.%) into lubricating oil is sufficient to improve tribological properties [17]. Qiu *et al*. [18] found that a concentration of nickel (Ni) nanoparticles, between 0.2% and 0.5%, provided the best friction reduction and anti-wear behaviours; while Tao *et al*. [19] demonstrated that 1 vol.% was considered the optimum concentration for diamond nanoparticles in paraffin oil.

The mechanisms of friction reduction and anti-wear of nanoparticles in lubricants have been reported as colloidal effect, rolling effect, protective film, and third body [20]. Chinas-Castillo and Spikes [21] investigated the mechanism of colloidal solid nanoparticle action in lubricant oils. Their study showed that in thin film contacts, colloid nanoparticles penetrated elastohydrodynamic (EHD) contacts mainly by a mechanism of mechanical entrapment. Chen *et al*. [22] studied on a wide range of different colloid solid nanoparticles, using a four-ball tribotester. They concluded that the deposition of tribochemical reaction products, produced by nanoparticles during the friction process, resulted in an anti-wear boundary film, and a decreased shearing rate. Hwang *et al*. [23] also reported that the form of deposit film in the contacting region prevented the direct rubbing surfaces and greatly reduced the frictional force between the contacting surfaces.

To date, no previous studies have investigated the potential combination of low cost and environmental friendly hBN/$Al_2O_3$ nanoparticles, used as diesel engine oil additives. Therefore, in this study, it is imperative to investigate the effect of hBN/$Al_2O_3$ nanoparticle additives on the tribological performance of conventional diesel engine oils using a systematic approach; otherwise known as the Taguchi method. Good lubrication and thermal conductivity properties, which can simultaneously improve tribological performance and boost heat transfer in engines, were the key factors for using hBN and $Al_2O_3$ nanoparticles.

## 2.0 EXPERIMENTAL PROCEDURES

### 2.1 Design of Experiment (DoE)

The Taguchi method consists of $L_9$ orthogonal arrays with nine rows (corresponding to the number of tests), and three columns at three levels, and is used prior to sampling, testing, and analysis of the results. Three design parameters were determined (i.e., volume percentage of $Al_2O_3$, hBN, and surfactant) and three levels were taken for each parameter (as shown in Table 1). In this study, the $L_9$ ($3^3$) orthogonal arrays were selected using Minitab statistical software (as shown in Table 2).

**Table 1** Design parameters at three different levels

| Level | Parameters | | |
|---|---|---|---|
| | $Al_2O_3$ (vol.%) | hBN (vol.%) | Surfactant (vol.%) |
| 1 | 0 | 0 | 0 |
| 2 | 0.05 | 0.05 | 0.1 |
| 3 | 0.5 | 0.5 | 0.3 |

**Table 2** DOE with $L_9$ ($3^3$) orthogonal arrays

| Test | Parameters | | |
|---|---|---|---|
| | $Al_2O_3$ (vol.%) | hBN (vol.%) | Surfactant (vol.%) |
| 1 | 0 | 0 | 0 |
| 2 | 0 | 0.05 | 0.1 |
| 3 | 0 | 0.5 | 0.3 |
| 4 | 0.05 | 0 | 0.1 |
| 5 | 0.05 | 0.05 | 0.3 |
| 6 | 0.05 | 0.5 | 0 |
| 7 | 0.5 | 0 | 0.3 |
| 8 | 0.5 | 0.05 | 0 |
| 9 | 0.5 | 0.5 | 0.1 |

### 2.2 Sample Preparation

Referring to Table 2, a set of samples were prepared by dispersing several concentrations of 70 nm sized hBN and $Al_2O_3$ in two different brands of SAE 15W40 diesel engine oil. The diesel engine oil brands were set as a noise factor. The samples were stabilized through the addition of an appropriate amount of surfactant (oleic acid). The mixture of nanoparticles in the diesel engine oil was homogenized using an ultrasonic homogenizer for 30 minutes.

### 2.3 Tribological Test

Tribological testing was performed to determine friction coefficient and wear rate between the contact surfaces using a four-ball tester (as shown in Figure 1). The testing procedure followed ASTM D4172 [24]. The speed, load, time, and temperature used, were 1200 rpm, 392.4 N, 3600 secs, and 75°C, respectively. The four-ball tester incorporated three 12.7 mm diameter carbon chromium steel balls, clamped together, and covered with lubricant for evaluation. A fourth steel ball of the same diameter (referred to as the top ball), held in a special collet inside a spindle, was rotated by an AC motor. The top ball was rotated in contact with the three fixed balls that were immersed in the sample oil. The COF was recorded using a data terminal processing system. The detailed mechanical properties of the balls are shown in Table 3.

The volume of the ball's worn material was estimated geometrically; using the basis of the radius of the wear scar and its height using the following equations:

$$V = (\pi h^2/3)(3R - h) \tag{1}$$

$$h = R - \sqrt{R^2 - a^2} \tag{2}$$

Where, $V$ is the wear volume in mm$^3$, $h$ is the height of wear scar in mm, $R$ is the radius of the ball in mm, and $a$ is the radius of the wear scar in mm.

The wear rate was then calculated using the following equation:

$$k = V/t \tag{3}$$

Where, $k$ is the wear rate in mm$^3$/s and $t$ is the sliding time in seconds.

The surface roughness of the worn surfaces was measured using a profilometer. Furthermore, the morphology of the worn surfaces was observed using Scanning Electron Microscopy (SEM).

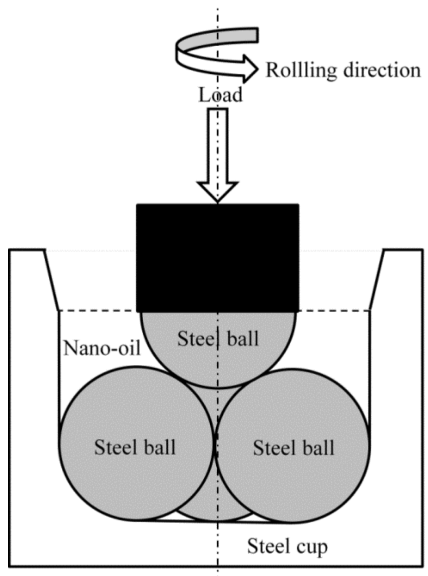



**Figure 1** Schematic diagram of a four-ball tester

**Table 3** Mechanical material properties

| Properties [a] | Ball bearing (Carbon chromium steel) |
|---|---|
| Hardness ($H$), HRC | 61 |
| Density ($\rho$), g/cm$^3$ | 7.79 |
| Surface roughness ($R_a$), µm | 0.022 |

[a]From laboratory measurements

## 3.0 RESULTS AND DISCUSSION

### 3.1 Effect of hBN/$Al_2O_3$ Nanoparticles on the Coefficient of Friction (COF)

According to other Taguchi method studies, response variation using the signal-to-noise (*SN*) ratio is important, because it can result in the minimization of quality characteristic variation, due to uncontrollable parameters. The COF was considered as being the quality characteristic; using the concept of "the smaller-the-better". The related equations of the Taguchi method can be found in the previous study [25].

From Figure 2, a greater *SN* ratio value corresponds to a better performance (i.e., low COF). Even though SAE 15W40 diesel engine oil containing $Al_2O_3$ nanoparticles showed a greater influence on the *SN* ratio, it affected in the negative impact; where the COF increased significantly with the addition of $Al_2O_3$ concentration. The explanation for this is shown in Section 3.2.

However, the COF decreased significantly with hBN nanoparticles concentration. To some extent, this suggests that hBN nanoparticles effectively played the role of ball bearings

(Figure 3); where the sliding friction was changed to rolling friction between the frictional pairs, resulting in reducing the contact area (as shown in Figure 4). However, further scientific investigation is required for that a ball bearing effect. In addition, there was no significant difference in surfactant concentrations.

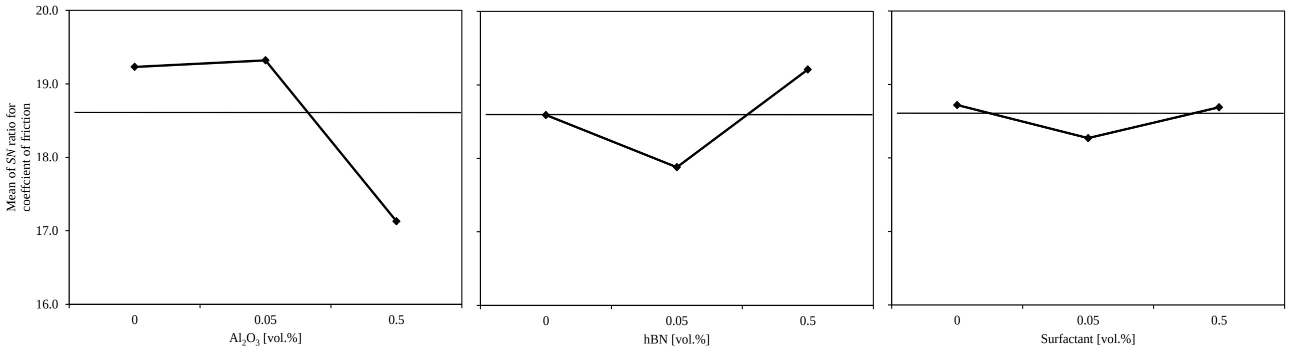



**Figure 2** Main effect plot for *SN* ratio's effect on COF

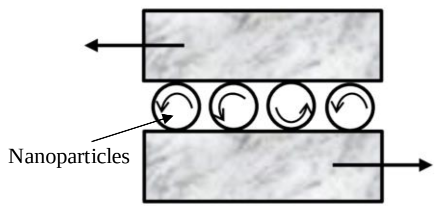
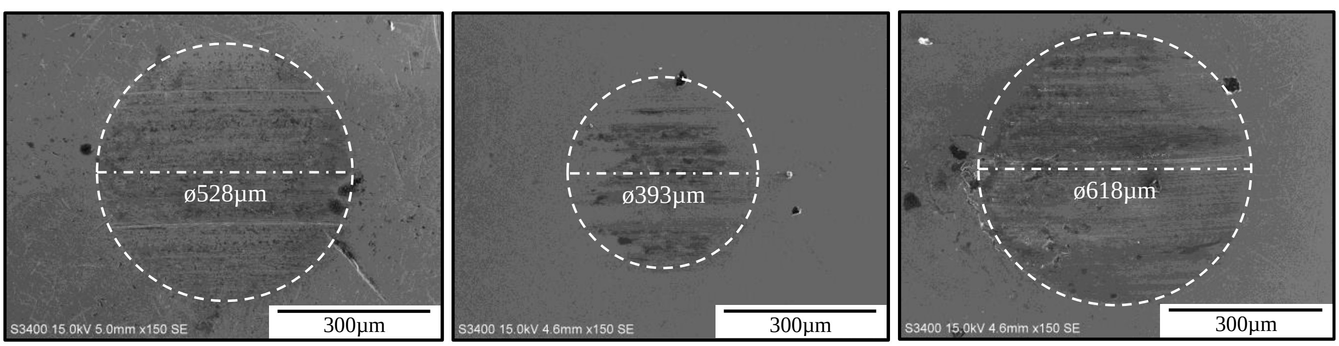



**Figure 3** Schematic diagram of the ball bearing effect




(a) (b) (c)

**Figure 4** Wear scar diameter of a ball under lubrication of (a) 15W40 diesel engine oil, (b) with 0.5 vol. % of hBN nanoparticles additive, and (c) with 0.5 vol. % of $Al_2O_3$ nanoparticles additive

## 3.2 Effect of hBN/$Al_2O_3$ Nanoparticles on Wear Properties

The optimized concentration values of the nanoparticle additives in 15W40 diesel engine oil from the previous study [25] were used to study the effect of hBN/$Al_2O_3$ nanoparticles on wear properties. From Figure 5, hBN nanoparticles additive reduced the wear rate of materials by approximately 58%, which is half of the total wear gained by the 15W40 diesel engine oil. This was in good quantitative agreement with COF; as discussed in Section 3.1. However, $Al_2O_3$ nanoparticles additive showed an increment of 120% in wear rate, as compared to 15W40 diesel engine oil. This was probably because the $Al_2O_3$ nanoparticles themselves made tiny grooves on the contact surface (Figure 6c), which may have been formed by a ploughing effect of the harder $Al_2O_3$ nanoparticles. This increased material wear consequently increased the COF. Furthermore, a smoother worn surface ($R_a$ = 0.043 µm) was obtained with hBN nanoparticles additive (as shown in Figure 6b).

The above explanation shows that the 15W40 diesel engine oil, containing hBN nanoparticles additive, could provide good anti-wear effects in the frictional pairs.

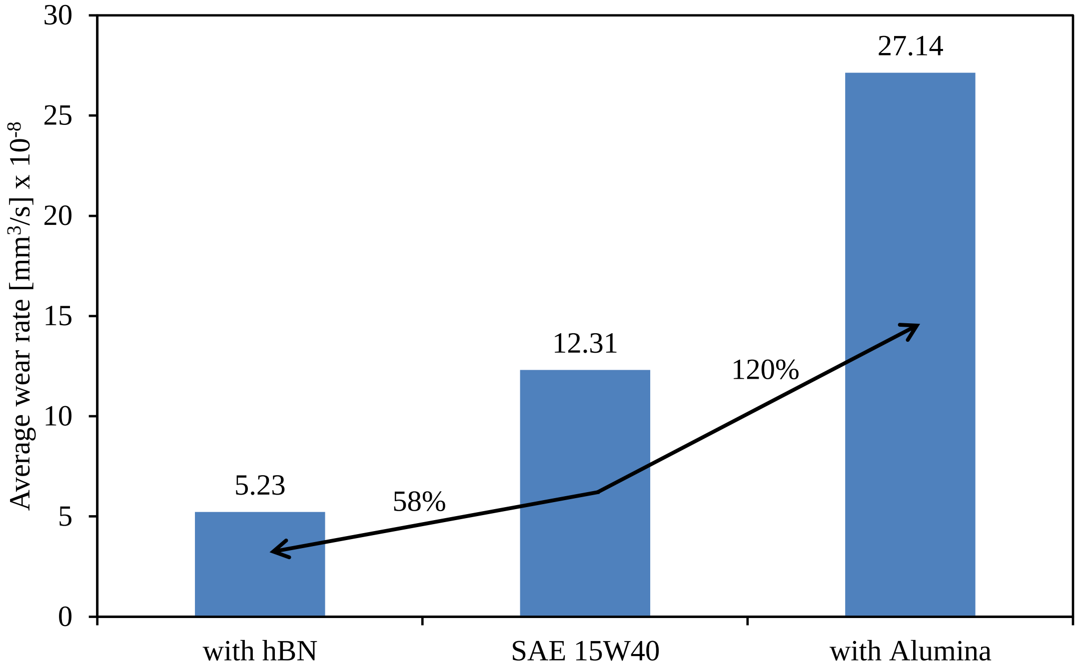



**Figure 5** Wear rates of ball materials under different types of lubricant additives

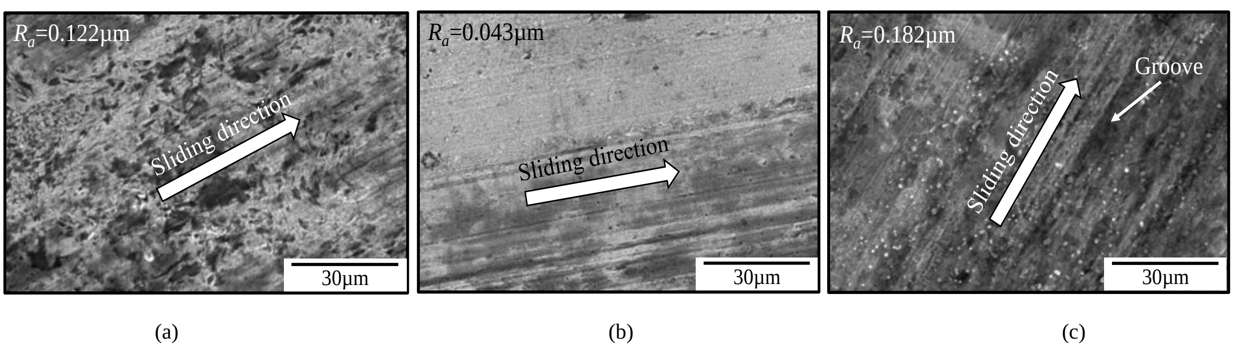



**Figure 6** SEM micrograph of worn surfaces on a ball under lubricated conditions of (a) 15W40 diesel engine oil, (b) with 0.5 vol.% of hBN nanoparticles additive, and (c) with 0.5 vol.% of $Al_2O_3$ nanoparticles additive

## 4.0 CONCLUSION

The following conclusions were drawn from this study, as a comparison of 15W40 diesel engine oil, with and without $Al_2O_3$ nanoparticles additive:

a) The presence of hBN nanoparticles additive in the 15W40 diesel engine oil lowered the COF. This suggests that hBN nanoparticles had a ball bearing effect, by changing the sliding friction to a rolling friction between the frictional pairs, resulting in a reduction of the contact area. However, further investigation to prove a ball bearing effect will be necessary and will be taken into consideration for next publication.

b) The presence of hBN nanoparticles additive in the 15W40 diesel engine oil also lowered the material's wear rate by 58%, which was in good quantitative agreement with COF. Furthermore, a smoother worn surface was obtained with hBN nanoparticles additive. This shows that the 15W40 diesel engine oil, containing hBN nanoparticle additives, could provide good anti-wear effects in the friction pairs.

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