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Thermal transport and tribological properties of nanogreases for metal-mechanic applications

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ABSTRACT

This study investigates the effect of incorporating nanoparticles – TiO_2, Al_2O_3, CuO, and multi-walled carbon nanotubes (MWNTs) – within greases Mobilgrease 28 and Uniflor 8623B on their thermal transport and tribological properties. Nanoparticle filler fractions, varying from 0.01 to 0.10 wt%, were homogeneously dispersed within selected greases. Two tribological tests were performed on a four-ball tribotester; ASTM D5183, and the ITeEPib Polish method for testing lubricants under scuffing conditions. Anti-wear properties resulted in up to 20% wear scar diameter (WSD) reduction using a very low filler fraction of 0.01 wt% TiO_2. For the extreme pressure test, the increase on the load-carrying capacity was found to be ~19% with a filler fraction of 0.05 wt% CuO. A guarded hot-plate method-based apparatus was used in order to characterize thermal conductivity of nanogreases, showing an enhancement of ~28% in thermal conductivity with the addition of 0.10 wt% MWNTs. These results demonstrate the potential of nanoparticle additives for improving thermal properties of greases while decreasing friction and wear of mechanical components.

1. Introduction

Nanofluids have been on the rise in recent years as a way to solve thermal and tribological issues and needs in diverse industries [1]. Nanofluids possess the ability to better perform in a wide variety of fields such as high voltage power transmission systems, automobiles, solar cells, bio-pharmaceuticals, medical therapy/diagnosis and nuclear cooling [2–7].

As has been recently studied, the incorporation of nanoparticles into conventional fluids has shown excellent results in tribological performance; reducing wear and coefficient of friction (COF), as well as improving load carrying capacity [8–16]. Hernández-Battez et al. [12] studied the friction behavior of NiCrBSi coatings lubricated by CuO nanoparticles suspended in a poly-alpha olefin (PAO6) lubricant with a block-on-ring set-up; results showed a decrease of ~100% in COF with 2.0 wt% CuO. Similarly, Yu et al. [13] reported improved lubricating properties of conventional oils by adding 0.2 wt% of Cu nanoparticles; in their study they observed that Cu formed a soft film by friction-shearing and high pressure reducing the COF by 20%. Furthermore, Ji et al. [14] found that $CaCO_3$ nanoparticle additives improve the anti-wear performance and extreme pressure properties of lithium gr ease in concentrations up to 5 wt%, this was attributed to $CaCO_3$ nanoparticle being deposited on rubbing surfaces forming a boundary film during the friction process. On a broad investigation by Wu et al. [15], the tribological behavior of nanofluids of API-SF oil (SAE 30 LB51153) and a base oil, with the addition of sphere-like CuO, TiO_2, and diamond nanoparticles was studied. The anti-wear behavior of these nanofluids is attributed to the nanoparticles morphology, as the sphere-like shape resulted in a rolling effect [15,16] between the surfaces, and the deposition of the nanoparticles on the worn surface, thus decreasing the shearing stress and COF. Another important phenomenon is the spacer effect, at extreme loadings, the dispersed nanoparticles form a film-like coating that protects the metallic surfaces from direct contact among the surface roughness, promoting stress relief, friction reduction and premature wear [15]. Generated heat during wear and frictional operations needs to be dissipated from the system in an efficient manner; thus a good heat transfer fluid (HTF) must possess adequate thermal conductivity. Conventional HTFs have been studied with the incorporation of nanoparticles as reinforcing components [17–28]. For example, Hong et al. [17] successfully developed stable and homogeneous nanolubricants and nanogreases based on carbon nanotubes (CNTs) in poly-olefin oils. Thermal conductivity experiments showed an increment of 20% at 0.10 wt% filler fraction. Similarly, at 3.0 wt% and 10 wt% nanofluids showed a thermal conductivity increment of 50% and 80%, respectively. CNTs thermal transport properties improved the systems performance, acting as reinforcing agent.

In this study, we propose the multifunctional aspects of nanogreases, demonstrated previously [28], as they may be used

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for thermal management while reducing the contact friction and wear, at very small nanofiller fractions. For this purpose two base greases (Mobilgrease 28 and Uniflor 8623B) were modified with the addition of nanoparticles of Al_2O_3, CuO, TiO_2, and multi-wall carbon nanotubes (MWNTs). Tribological behavior was investigated using a four-ball tribotester by two different methods, the ASTM D5183 for anti-wear properties, and pressure of seizure (p_{oz}) by the ITEePib Polish method for testing lubricants under scuffing conditions. Thermal conductivity was measured by following the principle of the guarded hot-plate apparatus.

2. Materials and methods

The selected nanoparticles were obtained from Sigma-Aldrich and are described in Table 1. Nanoparticles were incorporated within two different greases, Mobilgrease 28 and Uniflor 8623B (see Table 1) in various filler concentrations: 0.01 wt%, 0.05 wt%, and 0.10 wt%. Nanoparticles were homogeneously dispersed using a homogenizer for 5 min, followed by of ultrasonication performed with a Cole-Parmer 500 W ultrasonic probe with a fixed frequency of 20 kHz. The dispersion process was performed following optimization procedures by Peña-Parás [29].

3. Experimental details

3.1. Viscosity measurements

As stated by Nield et al. [30], viscosity plays a paramount role on nanofluids performance, due to various effects on devices, such as microchannels clogging, flow, and pressure, amongst others. Thus, dynamic viscosity was measured with a rotational viscometer in order to characterize the greases and the effect of nanoparticles addition within them. A K447-MX viscometer was used, which allows pre-settings for different viscosities, and a variety of spindles to adapt to the fluid.

3.2. Tribological experimentation

The tribological properties were measured by a four-ball tribotester (T-02U). The tribotester consists of an upper ball that applies a load (P), whilst rotating at a given speed (n) in a perpendicular axis against three stationary balls, generating friction and wear on the contact points of the balls. The balls' material is an AISI 52100 steel (see Table 1). The ASTM D5183 [31] method was used to obtain the wear scar diameter (WSD) and COF, under the following conditions: 40 kg f, 600 rpm, and 60 min at 75 °C. WSD was calculated from the average diameter of the three lower balls, by an optical microscope. Additionally, the ITEePib [32] Polish method was used to analyze the load-carrying capacity. The extreme pressure (EP) conditions were evaluated at room temperature (23 °C), load varying from 0 to 7200 N, a speed of 1760 rpm, over the course of 18 s. Even if both tests work under a four-ball tribo-system, a comparison between results is not possible, mainly because of the difference in loads and the nanoparticles mechanisms, where on low pressures they may act as nanobearings [33], whilst the extreme pressures may cause tribo-sintering between rubbing surfaces [34]. This is the reason why even if a specific material performs well on the anti-wear test, for the extreme pressure test it may perform poorly.

3.3. Thermal conductivity measurements

A guarded hot-plate apparatus was used to determine the changes in thermal resistivity (TR) of nanogreases, according to ASTM C177 and C518 [35,36]. The TR of 2 glasses of 0.002 cm of thickness, and an area of 1 cm by 1 cm were taken in order to have a comparison point. Then tests were performed by introducing a layer of grease between the glasses, measuring the change in TR. The thermal resistivity was obtained with the help of a specialized software, which measures the temperature of both layers of glass. With the temperature of the 2 glasses a ΔT_r was found; and for each sample with a layer of grease different ΔT_s were obtained. Once these results were found for alshe following equation was applied:

$$\Delta T = \Delta T_r - \Delta T_s$$

The TR comes from the next equation

$$r = \Delta T / P$$

where (r) is the thermal resistivity, (ΔT) the temperature differential, and (P) the power. Then the thermal conductivity was obtained by the following equation:

$$\lambda = \frac{e}{Ar}$$

where (e) is the sample thickness, (A) the sample area, and (r) the thermal resistivity.

4. Results and discussion

Fig. 1 and Fig. 2 depict the WSD of steel balls and COF results of nanogreases, compared to base greases, respectively, according to ASTM D5183 tribo-tests. WSD was calculated through diameter averages of the three lower-balls on the four-ball tribo-system. In order to get a reliable statistical result, at least 3 tests for each fluid were run, following the Dixon test [37,38]. As seen in Fig. 1, most results for Mobilgrease show an increase on WSD. A small decrease on wear was only found for MWNTs, at all filler fractions, with the highest improvement of 4% at 0.10 wt%. For Uniflor 8623B, a reduction of up to 20% on WSD was obtained with 0.01 wt% TiO_2, however, for 0.05 and 0.10 wt%, WSD was higher

Table 1
Material properties.

Materials	Properties	
Base grease	***Base oil***	***Thickener***
Mobilgrease 28	Polyalphaolefin syntethic fluid	Organic clay (non-soap)
Uniflor 8623B	Perfluoropolyether	Silica
Nanoparticles		
TiO_2	Morphology: spherical, < 21 nm in diameter	
CuO	Morphology: spherical, < 50 nm in diameter	
Al_2O_3	Morphology: tubular, < 50 nm	
MWNTs	Morphology: tubular, 6–9 nm by 5μm	
Test Balls	***Chemical Composition***	
AISI 52100	0.98–1.1% C, 0.15–0.30% Si, 0.25–0.45% Mn, 1.30–1.60% Cr, < 0.025% P, < 0.025% S Diameter: 12.7 mm, 60 HRC	

Note: base fluids viscosities will be further discussed.