The Effect of Particulate Additives on the Tribological Performance of Bio-based and Ionic Liquid-based Lubricants for Energy Conservation and Sustainability

Track: Material Tribology

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Abstract
Recently, the use of green lubricants has grown in the lubrication industry due to environmental concerns and increasingly more stringent government regulations to curb the use of petroleum-based lubricants. The present investigation seeks to determine alternatives to the toxic petroleum-based lubricants by developing green lubricants. In this study, efforts were made to examine the influence of multiple additives (such as hexagonal boron nitride, tungsten disulfide, molybdenum disulfide, graphite and carbon nanotubes) of various shapes and sizes in lubricant mixtures for their tribological performance. Here, a natural oil and an ecofriendly ionic liquid (IL) were used as base oils for the lubricant mixtures. In the natural oil mixtures, improved tribological performance was dependent on the particle type followed by the particle size. On the contrary, the tribological performance of the IL-based mixtures was dependent on particle size and independent of the particle type.

Introduction (can be reduced to half)
Recent studies \cite{1} have focused on developing hybrid biolubricants by combining natural oils with solid particle additives in an attempt to provide a suitable alternative to petroleum-based lubricants. The primary reason for these hybrid biolubricants is due to the fact that solid particle lubricants such as boric acid and MoS\textsubscript{2} can be forced out of the contact zone during sliding contact resulting in an unlubricated scenario which can cause high friction and high wear with severe damage to components \cite{1-3}. In an attempt to remedy this problem, a carrier fluid is needed. The carrier fluids allow the particle additives to remain in the contacting interface thus, enhances the tribological properties. The secondary reason is concerned with replacing the toxic petroleum component with a more environmentally friendly lubricant such as canola oil, avocado oil, or more recently developed environmentally benign room temperature ionic liquid (IL) lubricants \cite{3-6}.

Experimental Details
In this study, avocado oil and an environmentally friendly phosphonium-based IL lubricant were used as carrier fluids with various particulate additives to form colloidal mixtures. Avocado oil was chosen, because it is a natural oil that has been demonstrated superior tribological performance \cite{2,3}. The IL consist of a trihexyl(tetradecyl)phosphonium cation and an appropriate organic anion. The particles consisted of 70nm, 0.5µm, 1.5µm, and 5µm hexagonal boron nitride (hBN); 55nm and 0.6µm tungsten disulfide (WS\textsubscript{2}); 50nm graphite; 2µm molybdenum disulfide (MoS\textsubscript{2}); and 5µm multi-walled carbon nanotubes (MWNT). In each lubricant mixture, solid particles accounted for 5% by weight having different sizes, shapes, and
compositions. The lubricant mixtures were studied using a pin-on-disk apparatus to evaluate their tribological properties. The experimental materials consisted of 440C stainless steel hemispherical-shaped pins sliding against 2024 aluminum disks with a normal load of 10N, a sliding velocity of 36 mm/s, and a test duration of 13 hours.

Results and Discussion

Figure 1 shows the coefficient of friction (COF) results for lubricant mixtures. Figure 1(a) shows the COF results for the avocado oil mixtures. It can be seen that the COF is dependent on the particle type and its ability to lubricate within the natural oil and not necessarily dependent on the particle size, although smaller particles do lower friction. Interestingly, for individual particle types smaller particles have the lowest friction, for example, the hBN particles show a clear trend that smaller particles exhibit lower COF values. Of the four particle types investigated only the hBN and MoS$_2$ particles improved the friction properties of the avocado oil. The WS$_2$, graphite, and MWNT particles did not enhance the lubricity. The carbon nanotube particulate mixtures witnessed capillary effects that absorbed the avocado oil, creating a highly viscous slurry rendering the particulate mixture useless as a lubricant.

Figure 1(b) shows the COF values of IL lubricant mixture. The COF results reveal that the smaller nanometer and submicron-sized particles predominantly have lower COF values with the 70nm hBN particles having the lowest COF, preceded by the 55nm WS$_2$, 0.5µm hBN, and 0.6µm WS$_2$ particles. Here, the 70nm hBN particle demonstrates how an environmentally friendly particulate additive can maintain low friction in the presence of an ecofriendly IL. In the lubricant mixtures, larger particles of 1.5µm or 2µm exhibited lower COF values than that of the pure IL lubricant with no additives. This further revealed how smaller particles enhanced the tribological properties by establishing smooth protective layers. Larger micron-sized particles such as the 5µm hBN particles and the 5µm MWNT exhibited higher friction coefficients beyond that of the pure IL. It is speculated that the abrasive nature of the larger plate-shaped 5µm hBN particles reduced their effectiveness [1] and capillary effects of the MWNTs hindered lubricity resulting in high friction.

Figure 2 shows scanning electron micrographs of the wear scars for the IL lubricant mixtures. Interestingly, the wear scar becomes wider as the particle size increases. Thus, substantiating the trends witnessed, the smaller particles, independent of particle type, enhance the tribological properties of the IL lubricant mixtures. Similar trends were witnessed for the natural oil SEM images. Better lubricating materials have lower wear scars and smaller particles of the same particle type also showed a decrease in surface damage.
The results of this study illustrate the importance of choosing an appropriate particle additive to enhance the tribological performance. In natural oils, particle type followed by particle size, were criteria for selecting particle additives that improve lubricity. In contrast, it was shown in the ionic liquid particulate mixtures that particle type was not as important as selecting the smallest particle size to improve upon the tribological performance. These results indicate that intrinsic properties of the base fluids should be investigated to understand why the particle additives perform differently within the two fluids. Nevertheless, the use of particle additives in natural oils or in ILs does have the ability to enhance the tribological performance. By optimizing the particle type and size and selecting a bio-based natural oil or ecofriendly ionic liquid oil to act as a carrier fluid, a colloidal solution can be established that does not degrade or separate. This in turn allows for a sustainable biolubricant to be developed that has properties that will lower friction and wear, thereby improving a systems energy economy by ultimately conserving energy.

Conclusions
The following conclusions can be drawn from the current research.

• In natural oils, the dominating parameter that influences the effectiveness of solid particle additives is particle type and is independent of particle size.
• In ionic liquids, the dominating parameter that influences the effectiveness of solid particle additives is particle size and is independent of the particle type.
• Nanometer and submicron-sized particulate additives enhance the tribological properties of the base fluid with smaller particles having the greatest effect.
• Larger micron-sized particles are detrimental to the tribological performance and increase the friction, wear, and surface damage of the worn surface.

References