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Taiho Kogyo Tribology Research Foundation

Main report

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Theme: Discovering the Mechanisms of Nano-lubrication by Studying the Effect of Nanoparticle Additives on Wear

1. Progress and result of the research

The project went largely as planned and was successful. The proposal funded the completion of Hamed Ghaednia's PhD degree and dissertation on "An Analytical and Experimental Investigation of Nanoparticle Lubricants". The research identified and confirmed the real area of contact as a major mechanism allowing nanoparticles to function properly. In addition, in the elasto-hydrodynamic regime it was found that the nanoparticles induced a plugged flow that allows the lubricant to shear more easily, which also reduces friction. We also showed that nanoparticles can even work in a dry environment as a solid lubricant.

Although many different nanoparticle materials were tested such as copper oxide and diamond, the most successful we silver. A nano-lubricant was synthesized and studied which consists of metallic silver nanoparticles suspended in polyethylene glycol (PEG). Silver nanoparticles were prepared directly in liquid PEG by introducing aqueous silver nitrate and subsequent reduction by PEG. The nano-lubricant exhibits excellent stability thanks to poly(vinyl pyrollidone) used as the coating agent. Thorough tribological analysis were performed on the nano-lubricant including rheology, friction, wear and Stribeck curve analysis. Results show that the nanoparticle additives are capable of reducing both friction and wear at low concentrations. Stribeck curve analysis also revealed that the particles are effective in reducing friction in both the boundary and mixed lubrication regimes. The possible friction and wear reduction mechanism of silver nanoparticles were also evaluated.

Using commercially available diamond nanoparticle, some interesting results were also found. We investigates the tribological properties of a nano-lubricant consisting of a fully formulated lubricant (SAE 5W20) with diamond nanoparticle additives. A pin-on-disk setup was used to conduct the friction experiments under various conditions. Nano-lubricants with various concentrations of diamond nanoparticles up to 0.12%wt were prepared and used in the studies. Wear volume was measured based on the wear track profile and was used to study the effect of nanoparticles on wear. In addition, elaborate surface analysis and measurements were performed to investigate the interaction between the diamond nanoparticles and the surfaces. The diamond nanoparticle could actually polish the surfaces in some cases. Results show that the diamond nanoparticles can affect the coefficient of friction in the concentration as low as 0.01%wt. Moreover, nanoparticles can have positive or negative effects on friction and wear based on the test conditions. Based on the findings, an optimal nanoparticle concentration was proposed to enhance the tribological performance of the lubricant. In addition, possible active mechanisms of nanoparticles in regards to friction and wear with diamond nanoparticles were discussed and proposed.

Custom-prepared and stable nano-lubricant that consists of CuO nanoparticles (9nm average diameter) suspended in mineral base oil using sodium oleate (SOA) as a surfactant. Nano-lubricants with weight fractions of 0.5, 1.0 and 2.0% were also investigated using a disk-on-disk friction and wear test. Results indicate that CuO/SOA nanoparticle additives reduce the friction between the lubricated surfaces in the absence of any other conventional additives. The effect of nanoparticles is more influential at higher loads and concentrations. Also, the steady state temperature of the lubricant is lower in the presence of nanoparticles. Measurements show that the viscosity of the nano-lubricants increases as more nanoparticles are introduced in the lubricant. The Stribeck curve is utilized to generalize the friction, temperature and the viscosity results into a single plot which can help to compare the performance of different nano-lubricants. Wear analysis based on profilometry results show that the wear increases with the nanoparticle concentration up to a 1.0%wt and then decreases for a 2.0%wt nano-lubricant. SEM/EDS results suggest that nanoparticles bond to the surface and form protective layers. Based on the results, different possible mechanisms for nanoparticles at the boundary lubrication were evaluated and the "reduction in the real area of contact" was suggested as the possible mechanism for this lubrication system.

Based on these experimental measurements, it is clear that nanoparticles can indeed reduce friction. This resulting work also presents and uses a novel methodology to model nanoparticles in contact between rough surfaces. The model uses two sub-models to handle different scales of contact, namely the nano-sized particles and micron-sized roughness features. Silicon nanoparticles suspended in conventional lubricant are modeled in contact between steel rough surfaces. The effect of the particles on contact force and real area of contact has been modeled. The model makes predictions of the coefficient of friction and wear using fundamental models. The results suggest that particles would reduce the real area of contact and therefore decrease the friction force. Also, particles could induce abrasive wear by scratching the surfaces. The implications of the model are also discussed and the arguments and results have been linked to available experimental data. This work finds that particle size and distribution are playing a key role in tribology characteristics of the nano-lubricants.

As mentioned above, carefully conducted friction tests of a nano-lubricant in the thin film elasto-hydrodynamic lubrication regime showed that the presence of nanoparticles reduces friction. By using surface analyses techniques and molecular dynamics simulations, we explored the effectiveness of different interactions in the system, namely the interactions between nanoparticles with the lubricant or surfaces. Based on the results, the friction reduction mechanism was found to be that the nanoparticles induce an obstructed flow (plug flow) in the thin film between lubricated surfaces. This reduces friction by forcing only a few layers of lubricant molecules to slide on each other.

2. Subjects remain to be solved in future/Subjects required further investigation

Recent work in our group has shown that the preparation of concentrated yet stable colloids consisting of nm-sized crystallites of CuO and Ag in hydrocarbon solvents is feasible. While such colloids have shown very promising lubrication characteristics, they exhibit dark colors, and cost is also a concern in the case of Ag systems. To improve the properties of the nano-lubricants we propose to synthesize concentrated but stable colloids of SiO_2 nm-sized particles in alkanes since both of these oxides are colorless materials. We have conducted preliminary tests of this material during the Summer of 2016. These experiments were also made possible by the foundation established by the original TTRF funding.

In the future it will also be important to optimize the size and concentration of particles within a fully formulated lubricant. This is a difficult task because the other additives in the lubricant could react with the nanoparticles. Our research group had started to investigate this by adding silver and diamond nanoparticle to fully formulated oils, but a great deal of work still is required.

3. Plan and past presentation or publication of your research results

Below are the current publications.

Peer-reviewed papers

Ghaednia, H.*, Jackson, R. L., Tribological Performance of Silver Nanoparticle-Enhanced Polyethylene Glycol Lubricants, Accepted to *STLE Tribology Transactions*; DOI: 10.1080/10402004.2015.1092623.

Ghaednia, H.*, Jackson, R. L., Khodadadi, J. M., Experimental Analysis of Stable CuO Nanoparticle-Enhanced Lubricants, 2015, *Journal of Experimental Nanoscience, 10, 1,* p. 1-18, DOI: 10.1080/17458080.2013.778424.

Conference paper

Ghaednia, H., Jackson, R. L., Gao, J., A third body contact model for particle contaminated electrical contacts, *The 60th IEEE Holm Conference on Electrical Contacts*, New Orleans, LA, USA, Oct. 12-15, 2014, pp. 1-5, DOI: 10.1109/HOLM.2014.7031018

Conference presentations

Ghaednia, H., Zhao, Y., Jackson, R. L., Experimental Analysis of the Tribological Properties of a Fully Formulated Lubricant with Diamond Nanoparticles Additives, *STLE Tribology Frontiers Conference*, Rosemont, IL, Oct. 26-28, 2014.

Ghaednia, H., Jackson, R. L., The Role of Nanoparticles in Nano-lubricants; Performing Lubricated and Dry Friction Tests, *STLE 69th Annual Meeting*, Orlando FL, May 18-22, 2014.