stle
Nashville
MAY 19-23, 2019

TRACTION CURVES AND RHEOLOGICAL PROPERTIES OF SEVERAL LUBRICATING FLUIDS

Lubrication Fundamentals

Robert Erck, Applied Materials Division, Argonne National Laboratory, 9700 S. Cass, Lemont, IL

INTRODUCTION

Tribological sliding tests under boundary conditions, where counterface/oil/surface interactions occur, are necessary for understanding the role of tribochemical films and asperities in friction. However, most machine contact configurations minimize metal-to-metal contact in order to reduce wear.

For several years, work that this research group has performed has involved boundary-regime sliding in which one of the counterfaces has been stationary. Coefficients of friction, wear rates, and tribochemical film formation have been studied in fully flooded and in starved conditions, and insight has been obtained for boundary-regime sliding involving piston rings, skirts, injectors, and coatings. Asperity heating, additive interactions, texture effects and tribochemical film formation have been described.

An understanding of the traction properties of fluids under high contact pressures typical of elastohydrodynamic conditions is necessary for modeling and predicting real systems. For rheological studies of existing and experimental fluids, it is necessary to determine the fluid properties in the elastohydrodynamic regime, i.e., rolling-sliding contacts, separated by a fluid film, where the fluid confined between them is at high pressure. The rheological properties, film thickness, frictional heating, and limiting shear stress have been intensively studied since the 1960s.

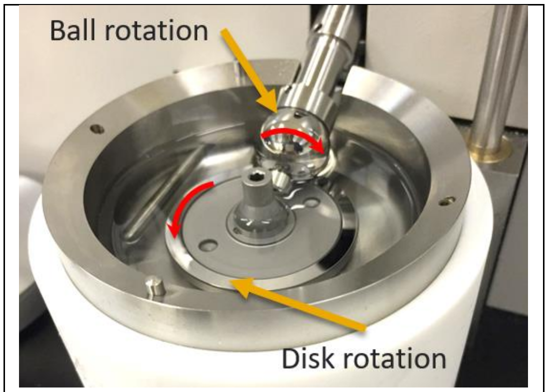

Fig 1. Image of test machine showing ball and disk

Spikes and Zhang [1] wrote a recent review concentrating on deriving rheology at high pressure under EHL conditions from friction measurements, vs models based on high-stress viscometry. Lugt and Morales-Espejel [2] reviewed EHL giving particular emphasis to theory and observation, addressing micro-EHL, rough surfaces, and starvation. The reader can find many more reviews addressing the various properties that have been modelled at high pressure. In this work, we start to look at rheology of sample fluids where the lambda ratio is deliberately made large to assure good counterface separation.

EXPERIMENTAL PROCEDURE

A traction machine was purchased (PCS-brand, type MTM), which uses a steel rotating ball pushing against a steel rotating disk to measure the "traction" or friction force properties of fluids. The machine is capable of performing tests in full EHL, mixed, or boundary lubrication regimes, and the internal arrangement is shown in Fig. 1. A variety of fluids, polyalkylene glycol monobutyl ether, fatty acid methyl ester poly-di-n-butyl phosphonate (palm), pure diester, hindered polyol ester,

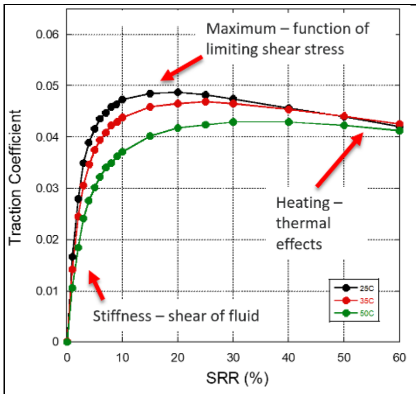

Fig 2. Sample graph showing traction curve features.

polyalphaolefin base, polyvalerate (soy), penta erythritol, polyol ester, polypropionate (soy), synthetic oil base, commercial motor oil, adipate diester, and polypropylene glycol monobutyl ether were studied.

Here we define the "slide-to-roll" ratio in the standard manner, where SRR in % is equal to $200(u_1 - u_2)/(u_1 + u_2)$, where u_1 and u_2 are the speeds of the two counterfaces, measured with respect to the point of contact.

In this work, the average speed was kept at 3 m/s, temperatures were either 25 °C, 35 °C, or 50 °C, SRR was from -60% to 60%, and the load was 37 N. The factory-supplied ball (diameter 19.05 mm) roughness was 5 nm Sa and disk was 14 nm Sa. Maximum Hertzian contact pressure is thus 1 GPa and the diameter of the contacting area is about 260 µm

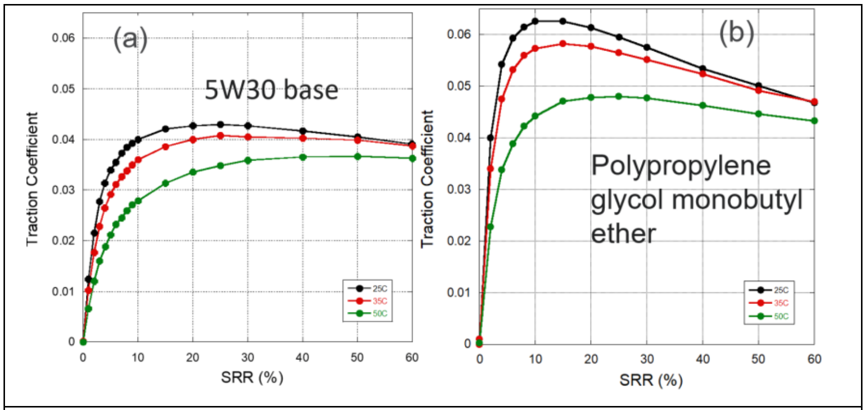

Fig. 3. Traction curves for a) polypropylene glycol monobutyl ether and b) a base oil formulated for 5W30

The ball and disk both rotate to entrain fluid between them. It is necessary to assure that complete separation of the counterfaces always occurred. The smallest Couette film thickness would have been for the diester at 50 °C, where the viscosity would be approximately 8.3 mPa.s, and $\alpha \approx 10$ for bioblends, as reported by Biresaw [3]. In this case a simple online solver finds the thickness to be about 130 nm, which is many times larger than the 15 nm composite roughness, thus assuring full film separation. The machine is operated by computer, and the tests consisted of programmed slide/roll, load, and temperature steps.

RESULTS AND DISCUSSION

The rheological properties of fluids under these conditions are influenced by several factors which govern the behavior of fluids confined under high EHL pressures. The piezoviscosity coefficient and the limiting shear stress are two that become dominant under EHL and unlike simple viscosity, these parameters depend to a great deal on the nature of the fluid and the molecular structure. That is, the low-pressure viscosity is a poor predictor of behavior under EHL conditions.

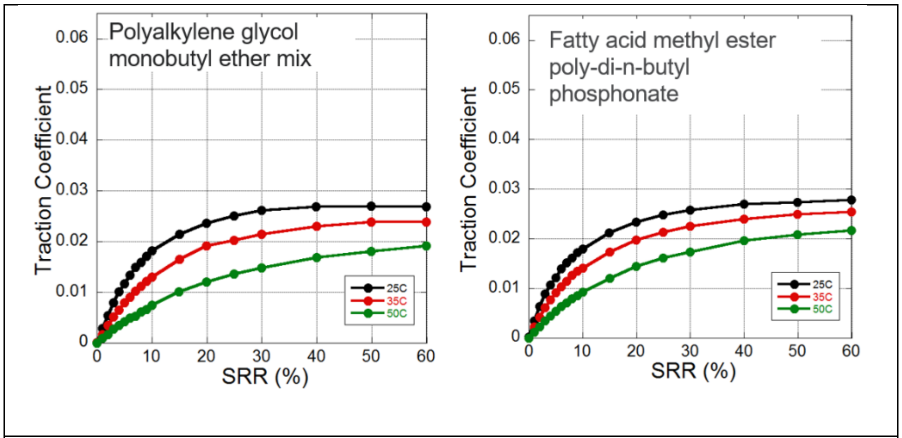

Fig 4. Traction curves for mix of polyalkylene glycol monobutyl ether and for a palm-derived fatty acid methyl ester poly-di-n-butyl phosphonate

For example, Fig. 3 shows the traction curves for two different fluids that have been matched in viscosity at 40 °C. Fig. 3 shows traction curves for a base mixture for a 5W30 engine oil (η = 26.15 cSt) and polypropylene glycol monobutyl ether (η = 26.21 cSt). It is clear that the polypropylene glycol monobutyl ether has both stiffness and limiting shear stress at 1 GPa much larger than the 5W30 fluid.

Two fluids in particular showed distinctly low stiffness and limiting shear stress, a polyalkylene glycol monobutyl ether and a fatty acid methyl ester poly-di-n-butyl phosphonate based on palm oil (Fig. 4).

In contrast, two fluids showed large stiffness and limiting shear stress, the polypropylene glycol monobutyl ether shown in Fig. 3b and an adipate diester, shown in Fig. 5. Here, the large traction coefficient creates more appreciable heating and softening of the trapped fluid can be seen for SRR above 20%.

The traction curves which most differentiate limiting shear stress and stiffness are those at 25 °C. The higher-temperature data are valuable but do not as clearly demark the effect of frictional heating at large SRR values. The 25 °C compiled data are shown in Table 1, where MTC has the meaning of maximum traction coefficient and stiffness is the initial absolute slope. Neither have units.

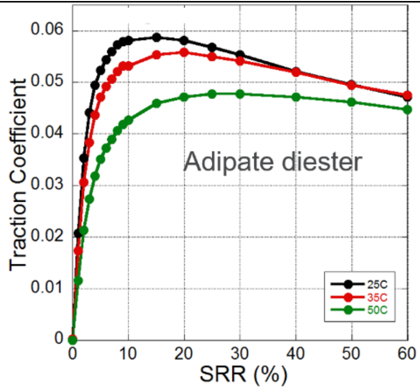

Fig 5. Traction curve for adipate diester which produced large stiffness and limiting shear stress

ACKNOWLEDGMENTS

The author would like to acknowledge discussions with Oyelayo Ajayi. The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory ("Argonne"). Argonne, a U.S. Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The U.S. Government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

REFERENCES

[1] Spikes, Hugh, and Zhang Jie. "History, origins and prediction of elastohydrodynamic friction." *Tribology Letters* 56.1 (2014): 1-25.

[2] Lugt, Pieter Martin, and Guillermo E. Morales-Espejel. "A review of elasto-hydrodynamic lubrication theory." *Tribology Transactions* 54.3 (2011): 470-496.

[3] Brandão, José A., et al. "Traction curves and rheological parameters of fully formulated gear oils." *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 225.7 (2011): 577-593

KEYWORDS

Traction, Lubrication, Elastohydrodynamic

Table 1. Measured parameters for fluids measured at 25 °C

Type of fluid	MTC	Stiffness
Polyalkylene glycol monobutyl ether, light	0.027	0.27
Fatty acid methyl ester poly-di-n-butyl phosphonate (palm)	0.028	0.31
Polyalkylene glycol monobutyl ether	0.033	0.60
Pure diester	0.033	0.48
Hindered polyol ester	0.035	0.64
PAO4	0.035	0.61
PAO10	0.035	0.91
Polyvalerate (soy)	0.036	0.75
Penta erythritol	0.037	0.77
Polyol ester	0.040	0.92
Polypropionate (soy)	0.040	1.03
PAO synthetic oil base 0W8	0.042	0.97
PAO synthetic oil base 5W30	0.043	1.07
PAO synthetic oil base 0W16/20	0.043	1.00
Commercial motor oil 5W30	0.049	1.40
Commercial motor oil 5W30	0.049	1.43
Commercial motor oil 5W30	0.049	1.44
Commercial motor oil 5W30	0.050	1.46
Adipate diester	0.059	1.77
Polypropylene glycol monobutyl ether	0.063	2.00