7th World Tribology Congress, WTC 2022
July 10-15, 2022, Lyon, France

Lubrication regimes during superlubricity of water-lubricated ceramics

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Stribeck-like curves were employed to evaluate the lubrication regimes governing the superlubricity ($\mu < 0.01$) of water-lubricated ceramic tribopairs: Si_3N_4/Al_2O_3, Si_3N_4/SiC, ZrO_2/SiC, and SiO_2/SiO_2. Best fit of ball-on-disc experimental data points (μ) was observed using S_N parameter as abscissa in a power regression analysis, where $S_N = \eta V/(P_m S_{pk}{}^2 E'^{2/3})$, η: viscosity, V: speed, P_m: pressure, S_{pk}: reduced peak height (roughness), and E': reduced Young's modulus. Therefore, superlubricity is governed by mixed lubrication regime where roughness and elastic deformation of asperities have fundamental roles. A lateral force microscopy investigation revealed that water-hydroxylated ceramic surfaces reduces shearing resistance during asperity contact.

Keywords: thin film lubrication, friction, ceramic, lateral force microscopy

1. Introduction

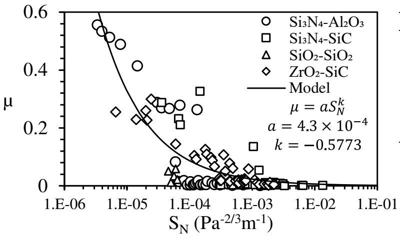
Superlubricity ($\mu < 0.01$) can be achieved during sliding of water-lubricated ceramics, such as SiC and Al_2O_3. Distinct lubrication regimes were suggested to explain superlubricity for specific combination of ceramics and operational conditions [1]: boundary (BL), hydrodynamic (HL), elasto-hydrodynamic (EHL), or mixed (ML), but there is no unified explanation yet.
Stribeck curves correlate Hersey's number ($S = \eta V/P_m$) and friction coefficients (μ), to evaluate bearing performance and lubrication regimes as function of viscosity (η), speed (V), and pressure (P_m). These curves are bearing-specific, especially for low S, although some attempts explained bearing behavior in all regimes through a single Stribeck-like "master curve" (SMC) [2]. The aim is to identify lubrication regimes responsible for superlubricity of water-lubricated ceramics using SMCs and worn surface characterizations.

2. Methods

Interrupted ball-on-disc tests (PLINT TE67, Phoenix Tribology Ltd) were performed for Si_3N_4/Al_2O_3, Si_3N_4/SiC, ZrO_2/SiC, and SiO_2/SiO_2 ceramic tribopairs. Load was kept at 26.7 N, while sliding speed was changed, in steps, after each interruption, progressively from 1.0 m/s to 0.01 m/s. Interruptions were made after stabilization of friction coefficient to determine ball's wear scar radius and to characterize worn surfaces using DIC optical microscopy. Power law regressions of data to SMCs with six distinct abscissa parameters and a goodness of fit analysis using mean square errors (MSE), were performed using Tibco® Statistica™ 13.3 software. Unworn and worn surfaces were characterized by 3D optical profilometry (OP) and atomic force microscopy (tapping). A lateral force microscopy (LFM) study of polished and worn ceramics using a Si probe (BudgetSensors ContAl-G), 20 nN of load and 5 μm/s of speed, in "dry" (40-60% RH) and "wet" (water immersion for 1 h and N_2 drying just before measurements) environments evaluated BL properties.

3. Results and Discussion

Fig. 1 shows that the power function was a good model for the SMC, and that the S_N parameter provided the best fit (i.e., lower MSE). Nevertheless, S still should be the preferred parameter to evaluate the absolute performance of different bearings. The result suggests that, besides the classic bearing variables (η, V and P_m), roughness' peak heights (S_{pk}) and elastic deformation of asperities (related to E') have a fundamental role on determining lubricant film thickness and, therefore, the lubrication regime. The Reynolds' solution for a 1D bearing indicates that $\mu < 0.001$ for pure HL regime, which is below measurement resolution. Therefore, ML should govern superlubricity.
LFM experiments revealed that the "wet" environment attenuates lateral forces of a Si tip sliding against different ceramics (Fig. 2a). This is attributed to shearing of weak H-bonds of hydroxyls formed on all ceramic surfaces in water. Fib 2b shows that some asperity contact is occurring during superlubricity of ZrO_2/SiC in water, where the BL contribution takes place.



Parameter	MSE ($\times 10^{-3}$)
$S = \eta V/P_m$	9.0
$S_D = S/D$	6.5
$S_E = S/S_{pk}^2$	5.0
$S_F = 3S_E S_{al}$	6.6
$S_N = S_E/E'^{2/3}$	3.9
$\lambda = h_0/S_{pk}$	5.4

D - bearing diameter;
S_{pk} - reduced peak height;
S_{al} - autocorrelation length;
E' - reduced Young's modulus;
h_0: min. film thickness.

Figure 1: SMC (μ *vs* S_N) and MSE for all parameters.

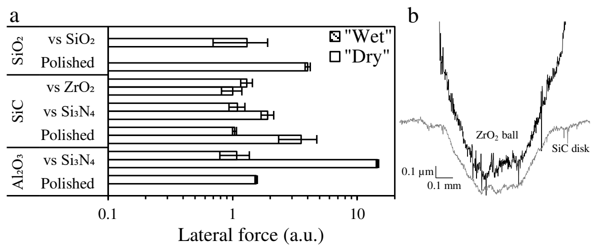


Figure 2: (a) LFM results. (b) ZrO_2/SiC contact profile.

4. References

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