VAPOR PHASE LUBRICATION FOR HIGH PERFORMANCE ROTARY MEMS APPLICATIONS

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Abstract: This work demonstrates the first use of vapor-phase lubrication (VPL) within a high-performance, rotary MEMS device supported on ball bearings. VPL in this study provides reduced system friction and confirmation that micro-scale rolling friction is dominated by surface adhesion rather than hysteresis loss. A significant change in the relationship between friction torque and normal load takes place due to the reduction of adhesive energy between the balls and raceway provided by lubrication. Microturbine friction testing is performed with dry actuation gas and with relative saturations of water vapor at 18%, 48%, and 88%, representing three distinct adsorption regimes. Up to a 61% reduction in friction torque has been observed for a microturbine operated with water vapor lubrication versus dry air.

Keywords: lubrication, microturbine, ball bearings, adhesion, adsorption

INTRODUCTION

Ball bearings are ubiquitous in macro-scale machinery where relative motion is needed under variable speeds and loads. Recently, micro-electro-mechanical systems (MEMS) have utilized microball bearings in numerous power and energy related applications, such as micro-generators [1], micro-pumps [2], and micro-motors [3]. When going from macro-scale components to the micro-scale, there is an increased surface area-to-volume ratio which causes surface effects such as adhesion to dominate over volumetric effects such as inertia. This work demonstrates the integration of vapor-phase lubrication (VPL) within a microturbine (Fig. 1) supported on ball bearings to investigate the influence of adhesion on micro-scale rolling friction.

Microball bearing friction has been the focus of multiple studies [4-5]. By determining the relationship between friction torque and normal load, Hanrahan et al. has shown that adhesion plays a significant role in micro-scale rolling friction [4]. Observed adhesive wear of ball material to the raceways helps confirm the adhesion-dominated friction hypothesis.

The adhesive mechanism depends on the area of adhered material and the energy available for such adhesions. This study is focused on specifically addressing surface energy through the introduction of adsorbed lubricant molecules within a VPL system. This will be another step toward proving friction is dominated by adhesion at the micro-scale.

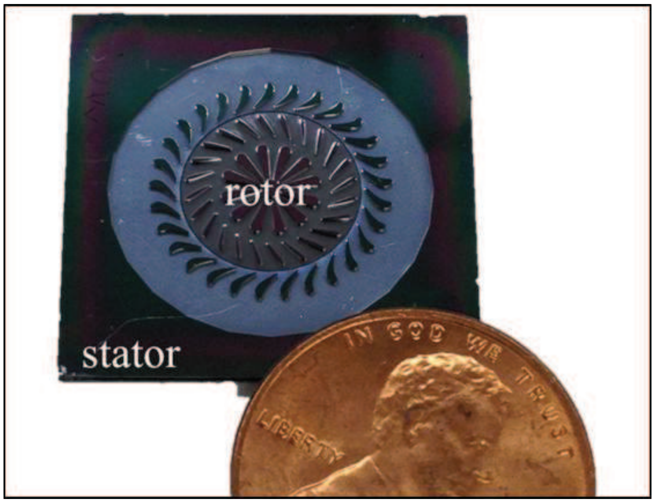

Fig. 1. Photograph of tested microturbine with U.S. penny shown for size comparison.

VPL functions by coating contacting surfaces with an inter-layer of adsorbed vapor molecules, preventing solid-solid contact and reducing surface energy. VPL is a promising lubrication mechanism for micro-scale applications due to its lack of capillary forces, replenishment capabilities, conformality, as well as high temperature stability [6-7]. Lubricating molecules entering from the vapor-phase can be utilized within tight geometries which make it useful for micro- to nano-scale operation. VPL has advantages over hard thin film coatings that gradually fail due to excessive wear and a lack of a replenishment mechanism. VPL schemes are fast replenishing due to the kinetics of gas phase molecules [6]. Additionally, vapor-phase lubricants can exist at much higher temperatures than liquid lubricants that eventually evaporate or break down.

Background Theory

VPL relies on the adsorption of molecules on to bearing surfaces delivered from the gas-phase. The thickness and morphology of the adsorbed VPL films is measured for varying partial pressures of lubricants at a static temperature within an adsorption isotherm [6, 8]. Water was utilized in this study as the lubricant of choice due to its high vapor-pressure and ease of use. The isotherm of water follows the Brunauer, Emmett, and Teller (BET) model where adsorbent molecules have the ability to assemble multiple layers. Asay *et al*. characterized three different relative humidity-morphology regimes that exist for water adsorption [6]. These three regimes are shown schematically in Fig. 2. Regime 1 exists between 0-29% relative humidity and represents a strained ice-like structure. Regime 2 is a transition region at 30-59% relative humidity, between ice-like and the third, water-like, regime at greater than 60% relative humidity. Region 3 is hydrogen terminated. The molecular configuration of water plays an important role in determining the available surface energy in the system which ultimately correlates with adhesion. This study utilizes each regime for VPL, comparing them to dry nitrogen to determine the affects of adhesion on micro-scale rolling friction.

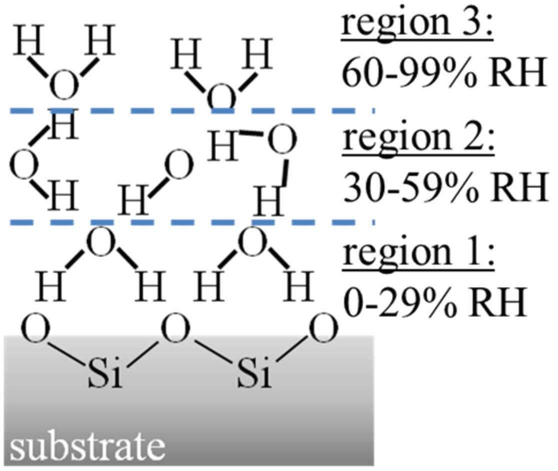

Fig. 2. Schematic of the adsorbed layer morphology through the range of relative saturations for water adsorbing on silicon. Reproduced from [6].

EXPERIMENTAL

Testing Platform

A silicon MEMS microturbine supported on ball bearings serves as the platform for the study of rolling friction and the efficacy of VPL. The microturbine is pneumatically actuated, which allows for a constant source of lubricant replenishment. The device consists of two silicon wafers with etched raceways and alignment features, bonded together to encapsulate the balls. The stainless steel microballs are housed in deep reactive ion-etched silicon raceways that are designed to be 5% larger than the balls to prevent ball jamming and encourage smooth turbine operation. These balls are 500 μm in diameter and they encase 75% of the raceway. A full description of the fabrication process of the microturbine can be found in [2]. During testing the device is placed inside a custom packaging manifold providing for distinct actuated flow and thrust plenum flow to enter the device, allowing for control over rotor speed and normal load.

Characterization Procedure

Spin-down testing methodology is used for characterizing the relationship between dynamic friction torque (DFT) and normal load. The DFT is the product of angular deceleration and mass moment of inertia, calculated from known geometries. To begin a spin-down test, the thrust plenum flow is pre-set to provide a certain normal load. The turbine is then actuated to 15-20krpm. Once a stable speed is achieved, the actuation flow is cut-off which allows the rotor to decelerate under the influence of friction and the pre-set normal load. During this time the position of the rotor is recorded from 10-1 krpm using an optical sensor. The normal load is then reset and the test is repeated. The loads investigated in this work range from 3 mN to 100 mN. Position data from the spin-down is fit to an exponential equation where the second derivative of this equation is used to determine the angular deceleration of system.

Spin-down tests were performed separately at 18%, 48%, and 88% relative humidity. These saturation levels were chosen to represent the three regimes of the adsorbed molecular configuration of water. Spin-down testing integrated with a VPL delivery system provides a platform to analyze the effect of adhesion on friction in rotary MEMS.

Vapor Phase Delivery

A vapor-phase delivery system is used to saturate N_2 gas for delivery to the testing platform. Compressed N_2 gas pressure is stepped-down to a desired level using a pressure regulator. The pressurized gas then enters a bubbler stage where a high-density polyethylene tank of liquid water saturates the gas. The saturated gas then leaves the bubbler stage to a condenser. The condenser was employed to ensure there would be no condensation inside the microturbine. After saturation and condensation, flow is split into the actuated flow and thrust flow lines described previously. The actuated flow is controlled by a mass flow controller providing turbine actuation. The thrust flow provides normal load to the rotor to allow for normal load-resolved spin-down friction testing. A schematic of the VPL transport system is shown below in Fig. 3.

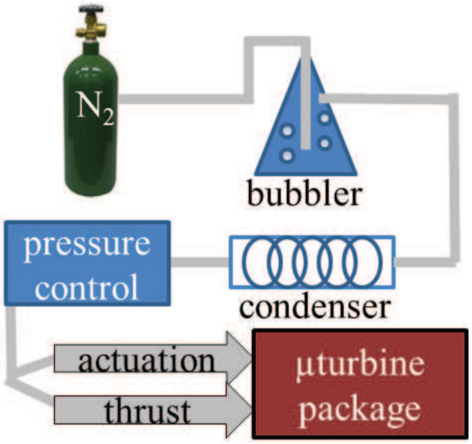

Fig. 3. Schematic of the VPL integration set-up. N_2 carrier gas is saturated in the bubbler with vapor lubricant. Excess lubricant vapor is removed in the condenser stage, and then the flow is split into two paths for turbine actuation and thrust load.

Managing the VPL system input pressure is essential to control the relative humidity at the output. This is due to the fact that the final relative humidity delivered to the microturbine depends on the ratio of the pressure in the bubbler to the pressure at the VPL system output. For example, if 100% saturation is reached at 10 PSI in the bubbler stage and the output is at 1 PSI, then the saturation level would be 10% relative humidity, other conditions equal. Temperature of the VPL stages can also determine the relative humidity at the output. Higher temperatures result in higher vapor pressures, therefore a heated bubbler will provide more gas-phase lubricants than one at room temperature. For these tests, temperature of the bubbler stage was at room temperature.

RESULTS AND DISCUSSION

Results displayed in Fig. 4 show the reduction of the DFT with the introduction of VPL. At the maximum, the water vapor lubricated microturbine has demonstrated a 61% reduction of friction versus dry nitrogen (blue dots in Fig. 4) at a normal load of 82 mN in spin-down testing at 18% RH (green triangles in Fig. 4) due to a reduction of overall adhesive energy. At 18% relative humidity, the experimentally determined DFT for a given normal load is generally lower than that of 48% (yellow dots in Fig. 4) and 88% (red squares in Fig. 4) which produced similar DFT relationships. These results agree with adhesion testing for adsorbed water vapor on silicon performed by Jones, *et al*. [9] where the adhesion force increases with rising humidity until it reaches a maximum in regime 2 where it will start to slowly drop as it enters regime 3. The reduction of DFT by VPL is not evident for low normal loads due to the increased influence of sliding friction and load-independent contributions. Load-independent contributions to friction torque for the microturbine system can include viscous drag and gyroscopic spin. These contributions encompass a significantly higher percentage of the total friction torque at low loads.

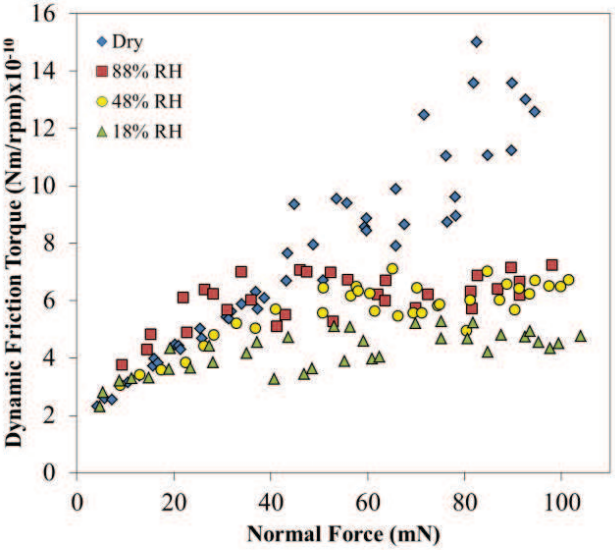

Fig. 4. Spin-down friction testing for a single microturbine operated with dry and saturated gas. Three relative saturations were chosen which fall within the three regions described in Fig. 2.

The results of VPL testing shown in Fig. 4 also reveal the isolation of the adhesive component of rolling friction through the flattening of the DFT/normal load relationship. VPL affects the surface chemistry of the system without changing its mechanical properties; therefore adhesion can be specifically addressed. The DFT value encompasses all of the contributions to friction torque within the microturbine, categorized as load-dependent, such as adhesion, or load-independent as mentioned previously. Since there is an observed loss of load dependence within the system through the flattening of the DFT/normal load relationship, then it is assumed adhesion plays a significant role in the load-dependant contribution to friction torque within the microturbine system.

To assure the rate of lubrication is adequate, the rate of adsorption needs to be fast enough for the replenishment of water molecules to outpace the rate of ball movement. The rate of adsorption per unit area is defined as the product of the flux of water molecules and their probability of sticking to the surface. This flux is found using the Hertz-Knudsen equation to be

$$F = \frac{P_{vap}}{\sqrt{2\pi mkT}} \tag{1}$$

The flux of water molecules is calculated at room temperature and saturated vapor conditions. With the sticking probability assumed to be 100%, it was calculated that the rate of adsorption requires 8.5 μs to coat a total of $5\text{x}10^{14}$ available atomic sites in the raceway. The period of successive balls contacting a particular point in the raceway was estimated to be 0.1 s for a rotor spinning at 10 krpm, which is several orders of magnitude greater than the rate of adsorption.

CONCLUSION

The results presented herein demonstrate the reduction in friction through the addition of the first-ever vapor-phase lubrication scheme within a microball bearing supported device and revealed advanced knowledge of the fundamental source of rolling friction on the micro-scale. Spin-down testing methodology was used in concert with a VPL delivery system to show adhesion playing a major role in rolling friction via the observed change in relationship between DFT and normal load. In the VPL experiments, saturation levels from three different regimes of the water adsorption isotherm are chosen to determine the varying adhesion force in the device. Future work will involve employing 1-pentanol vapor lubricant for studying adhesion due to its non-BET isotherm and lower surface energy.

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