NANO- AND MACROSCALE EVIDENCE OF THERMALLY ACTIVATED FRICTION

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ABSTRACT

The recent availability of very low wear materials that undergo primarily interfacial sliding has enabled studies that more directly probe the fundamental aspects of friction. This paper reports on variable temperature experiments that were conducted with common polymeric and lamellar solid lubricant materials. Friction coefficient consistently increased with decreased temperature well into the cryogenic temperature regime in a manner consistent with the proposed notion of thermally activated friction. As wear and deformation components increased, friction coefficients became larger and less thermally sensitive. AFM experiments on the nanometer length-scale showed large relative increases in friction coefficient and a transition to athermal behavior when the friction forces became high enough to induce tip wear. Findings from these studies, which span wide length and time-scales, consistently suggest that thermally activated barriers to sliding constitute a fundamental component of friction.

INTRODUCTION

There are many applications where the use of a solid lubricant is needed to survive the operational temperature extremes, yet the effects of changing temperature on the friction coefficients of these materials remain unclear. There are both practical and scientific needs to study the temperature dependent friction coefficients of common solid lubricants.

Polymer friction has been widely studied at temperatures above room temperature and the data are consistent with viscoelastic behavior (reduced friction at elevated temperature and reduced speed) [1-6]. The cryogenic friction literature [7-9], on the other hand, which primarily contains data collected at or below 77K (often submerged in the liquid cryogen), shows reduced friction compared to that collected during ambient testing in open air. These data suggest a cryogenic specific friction reduction mechanism such as increased hardness [8].

Currently, there is a bifurcation in the trends of friction with changing temperature, but neither the cause nor the temperature at which it occurs are known. In addition, the entire aerospace-relevant temperature regime from 77-273K remains essentially unstudied. This paper reports on dry-sliding tribological studies of solid lubricants over this critical range of temperatures. Several experiments, materials, environments and length-scales are discussed.

EXPERIMENTAL

Macroscale friction experiments were conducted using two different pin-on-flat tribometers with PTFE-based and MoS2-based solid lubricants. Ambient pressure experiments used impinging jets of dry nitrogen (LN2 boil-off) to cool the disk and evaporate ice contamination. The experimental setup is described in detail in McCook et al. [10]. A linear reciprocating tribometer was constructed in a vacuum chamber for operation at pressures below 10^-6 torr; operation in vacuum further reduces potential for ice contamination. The design of the tribometer and uncertainties closely follow those described in Schmitz et al. [11, 12]. The counterface is mounted to a copper block that is directly heated with a PID controlled heater and cooled with flexible copper braids that are chilled with liquid nitrogen. The pin and counterface were thermally insulated from the rest of the system using Polyetheretherketone (PEEK) sample holders.

Temperature dependent friction was studied at a more fundamental level using Molecular Dynamics simulation (MD) and Atomic Force Microscopy (AFM) techniques. The MD experiments were conducted on a 4.5 nm cubic PTFE system that is described in Jang et al. [13]. AFM experiments were
RESULTS

Variable Temperature Friction of PTFE

Extreme differences in sliding conditions of tribometry and MD experiments (4.3MPa, 5 mm/s and 250 MPa and 10,000 mm/s, respectively) make magnitude comparisons difficult. Relative trends with temperature are examined as described in McCook et al. [10] by taking the ratio of the friction coefficient at temperature to that at room temperature under the same conditions. The relative friction coefficients, $\mu^*$, are plotted versus temperature for the high temperature PTFE literature, MD experiments, vacuum experiments and dry nitrogen blanketed experiments in Figure 1. Friction coefficient consistently increased by a factor of five over the temperature range from 150K to 425K, and the entire dataset is fit to an activation energy of 2-4 kJ/mol.

![Figure 1](image1)

**Figure 1.** Relative friction coefficient, $\mu^*$, plotted versus temperature for MD, macroscale vacuum and dry nitrogen tribometry experiments. The high temperature PTFE tribology literature agrees well with the trends found at low temperature.

Variable Temperature Friction of Lamellar Solids

Several MoS$_2$-based coatings were blanketed with dry nitrogen and tested over a temperature range from 175K to 425K on a rotating pin-on-disk tribometer. In all cases, friction coefficient increased with decreased temperature; activation energies ranged from 3-10 kJ/mol. Since MoS$_2$ is not generally considered a viscoelastic material, these results suggest that thermally activate barriers to sliding cause the increase in friction rather than viscoelastic behavior. Activation energy is plotted versus the steady state wear rate for the five coatings tested in Figure 2. As wear rate reduced to approach interfacial sliding conditions, the activation energy increased. These results suggest that the components of friction related to deformation and wear are thermally insensitive and dominate the thermally activated components.

![Figure 2](image2)

**Figure 2.** Activation energy plotted versus steady state wear rate for five MoS$_2$ based solid lubricant coatings. Thermally activated components of friction are only detectable when deformation and wear components are small.

![Figure 3](image3)

**Figure 3.** Friction coefficient in arbitrary units plotted versus temperature for AFM experiments of HOPG and single crystal MoS$_2$ against a 20 nm radius silicon nitride tip. Error bars represent the standard deviations of repeat experiments.

Atomic Force Microscopy studies of HOPG and single crystal MoS$_2$ were conducted to study variable temperature behavior in the absence of ice and wear at the nano-scale. Friction coefficient is plotted in arbitrary units versus temperature for single crystal MoS$_2$ and HOPG against a silicon nitride tip in Figure 3. In both cases, thermally activated
friction behavior is observed; friction became thermally insensitive at a critical friction coefficient that is thought to be associated with the onset of wear. Post-test AFM imaging of the samples revealed uninterrupted lattice structures that indicated wear-free sliding. Tip reconstruction showed no signs of damage during thermally activated sliding, but significant blunting during athermal behavior. HOPG and MoS₂ had unique activation energies, unique transition temperatures and similar transition friction coefficients. All of these facts suggest that 1) thermally activated behavior is not an artifact of ice contamination; 2) the activation energy depends on the nature of the bonding at the interface; 3) the presence of wear and deformation reduces the effective activation energy, 4) transitions are not due to ice or tribometer dynamics; 5) athermal behavior results when stresses induce wear.

CONCLUSIONS

1) Friction coefficients consistently and reversibly increased with decreased temperatures for viscoelastic and lamellar solids.
2) Thermally activated behavior became more pronounced as the systems approached interfacial sliding conditions. The effective activation energies depended on the material pair and the influence of wear and deformation.
3) In the presence of wear and deformation, friction coefficients became less sensitive to temperature but were generally greater in magnitude.

ACKNOWLEDGMENTS

This material is based upon an AFOSR-MURI grant FA9550-04-1-0367. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Air Force Office of Scientific Research.

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