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THERMAL PHENOMENA IN TRIBOLOGY

by

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Title: Thermal Phenomena in Tribology

Objective: To develop a basic understanding of selected problems associated with the thermal phenomena in tribology. The primary focus being to study the nature of surface temperatures in sliding contacts and the role of surface temperatures in wear and load capacity limitations of tribocontacts. High local surface temperatures are associated with tribocontact failure which is often a limiting factor in advanced mechanical system development.

Accomplishments: The studies can be divided along the lines of analytical modelling and experimental studies of surface temperatures in sliding contacts.

Analytical Modelling: Three papers have been published in which the behavior of surface temperatures in sliding contacts was reported. The first modelled the surface temperature transient occurring at a circular spot where frictional energy is dissipated on a semi-infinite solid [1 & Fig. 1]. The predicted transient times and peak temperatures predicted were consistent with those observed in the experimental portion of this study. The transient times can be of the order of 10 microseconds with peak temperature rises reaching 1000°C or more in typical real areas of friction contact 50 to 100 micrometers in diameter. The second paper was concerned with the role of the ever present surface layers on surface temperatures in frictional contacts [2 & Fig. 2]. Operational regimes defined by
dimensionless variables were determined showing where surface films substantially influence surface temperatures. The dimensionless groups were made up of the thermal transport properties of the film and substrate, the film thickness, the contact size, and the sliding speed.

In a third paper variations in the geometry and the thermal boundary conditions pertinent to the classical flash temperature theory were studied [3 & Fig. 3]. First, the case of multiple surface heat sources is presented. The relative location of the sources is the critical factor in predicting the local temperatures at each contact. Second, the case of a short cylinder (or a disk) is analyzed. In addition to the lateral surface boundary conditions, convective cooling from the side faces is considered. Third, the case of a hollow cylinder is studied where, in addition to the outer boundary conditions, uniform internal heating (or cooling) is considered.

A third analytical effort was the stochastic modelling of the surface temperatures at the real areas of contact in unlubricated sliding contacts. This model builds on the transient asperity temperature analysis. The location and size of the real areas of contact are generated randomly within specified limits. The specified limits are that the spot must be within the apparent area of contact, must have a diameter within a range consistent with experimental observation, and the total area of spots must be equal to the applied load divided by the material hardness. A given spot remains as an active load support as long as the maximum surface temperature is less than some fraction of the melting point of the material in degrees Kelvin. The last requirement is based on the assumption that as the surface temperature increases, as a result of frictional heating, it will reach a value where the material will flow under the applied stress. Once the flow begins the load is shifted to a new location. This model qualitatively fits some of the observations of surface temperature
dynamics as viewed in infrared video recordings. This modelling effort was redirected when funds became available from the DOE/ECUT program to undertake a transient thermal stress analysis with temperature dependent properties which could be used as the failure criteria. This research which was supported by this NSF grant and the DOE program resulted in one Ph.D. Thesis (B. Y. Ting, ref. 10) and two papers (ref. 13-15). This portion of the research showed that thermal softening and flow can be a mechanism of wear in brittle materials, such as ceramics, under some tribological conditions. The observation of that type of wear had been observed in the experimental part of this research program.

Experimental Observations of Surface Temperatures: Observations of surface temperatures proceeded along three distinct paths. These first two were concerned with hard bodies sliding against hard bodies. The third effort is concerned with the surface temperatures of compliant polymers sliding against a hard surface and is part of the cooperative program with BAM in West Berlin.

The pin-on-disk experiment was nominally steady (e.g., applied load and sliding speed) yet the real area of contact was very dynamic. By varying the film exposure time when photographing the hot spots at the sliding interface, the instantaneous number of real areas of contact could be estimated and was found to be less than or equal to seven. The results of this work are an important adjunct to the oxidational wear modelling work of T.F.J. Quinn [4 & Fig. 4].

The video analysis of the hotspots occurring on the surface of a steel pin in dry sliding against a sapphire disk resulted in several interesting observations. Using computer coupled video frame analysis statistics of spot size, number, total spot area, duration, and spot movement could be obtained. Typical results show that the average spot size is between 50 and 80 micrometers in diameter and the spot may persist for up to 200 milli-
seconds or more in some cases. As a rule, larger spots persist for longer periods. The average number of hotspots per frame appears to increase with load while the average diameter does not. The dependence of number, size, and intensity of hot spots on tribological operating parameters requires further study. The ratio of hotspot area to apparent area ranged from a high of 0.01 to 0.0001. In the limited attempt undertaken to relate the hotspot area to the load and the material hardness, no obvious relationship was found except that the load divided by the hardness may be an upper limit on the hotspot area as might be expected. One additional interesting observation was that in a few cases the hotspot persisted for several seconds and its position could be followed with the video analyzer. In one case, the hotspot persisted for three seconds and moved in the direction of sliding at an average velocity of about 100 micrometers per second before it disappeared. The surface sliding velocity was 2 meters per second. Therefore, the hotspot moved at a velocity about 5000 times slower than the opposing surface.

The coincidence of industry-supported automotive cam tribology studies and these thermal phenomena studies afforded the opportunity to measure the surface temperatures of operating cam and lifter surfaces. This work showed that at peak lift for cam speeds up to 1500 rpm and bulk oil temperatures of 100°C cam temperatures were up to 300°C. Temperatures of this magnitude have significant implications with respect to lubricant oxidation, lubricant surface reactions and surface layer formations [5 & Fig. 5].

The third area of surface temperature measurement is that of a polymer (PTFE) sliding against CaF₂. The program was in cooperation with H. Czichos at BAM in West Berlin. The West German group has conducted an extensive study of the tribological behavior of polymers sliding against glass. The conditions used are a sliding speed of 17 mm/s and a load of 20 N on a 2 mm diameter pin. Our part of the program was to measure the surface
temperatures of the PTFE during sliding. We duplicated IR video recordings made with the CaF$_2$ counterface. The CaF$_2$ single crystal was chosen for its high IR transmission and because the temperature rise anticipated is only a few degrees Celsius. Surface temperature and bulk temperature of the PTFE pin, as well as bulk temperature of the disk at the end of the experiment, are measured. At the conditions mentioned above, surface temperature is constant within one degree and about 5 to 7°C above the bulk pin temperature 3 mm below the surface. As sliding speed is increased, these surface temperatures increase. It could not be concluded from these observations that the polymer wear observed at these mild conditions was thermally driven.

The grant also permitted this laboratory to participate in the VAMAS international study on the development of wear standard testing procedures. In addition to normal cooperation as a participating laboratory in the round robin procedures, experiments were conducted to measure the surface temperatures during the standard experiments. These measurements were incorporated in the summary publication by Czichos (ref. 7).

**Additional Use of Infrared System:** The scanning infrared system used in this program was a major capital equipment instrument purchased on this grant. This equipment was also used on two research projects of doctoral students; both in the School of Mechanical Engineering, and one of which is in the Tribology Laboratory. The equipment continues to be a major asset of the laboratory.

The first was a doctoral student, Stephen Fook-Geow Heng, under the direction of Dr. Black who was studying the heat transfer from and temperature distribution on an integrated electronic circuit on a chip. The second was a class special project done by a doctoral student under my direction, Scott Bair [6 & Fig. 6]. In a class taught by Dr. D.
McDowell (a current NSF PYI), the question arose as to whether the material temperature rises at the tip of a propagating crack in steel and, if so, can it be measured. Scott utilized the infrared camera and was able to obtain images of the crack tip temperature rise for a crack propagating in steel. He also was able to measure the crack tip velocity to be about 25 meters per second. Although it is clear that the plastic zone dimension is smaller than the instantaneous field of view of the camera, the measurement suggests that the temperature rise is at least 90 C and may be 300 C or more. This research may be continued because of its obvious relevance to crack formation processes in tribological phenomena.

**Continued Studies:** The capabilities, both experimental and analytical, for studying thermal phenomena in tribology developed under this NSF grant have established a firm basis for further research and development in the area. They have been a major reason for attracting additional governmental and industrial research funds to this laboratory.

**References:** (reprint copies attached)


Doctoral Theses supported or partially supported by this grant (copies of abstracts attached).

8. B. Gecim, "Temperature Prediction in Mechanical Components, An Analytical Approach," March, 1984. (This thesis was completed just before the grant started. Gecim was employed as a postdoc on the grant for about nine months resulting in some of the published work cited.)


Additional papers published where work was supported or partially supported under this grant.


NOTE:
Copies of all referenced papers and thesis abstracts were submitted to NSF with original of report. The papers are not attached here. If copies of the referenced papers are required, they can be obtained in the Tribology Lab of the School of Mechanical Engineering.
Fig. 1. Transient surface temperature versus radial position for three different Fourier numbers \( r_0 \) is radius of spot where friction generated heat flux \( q \) is dissipated [Fig. 1, Ref. 1].

Fig. 2. The ratio of maximum surface temperature rise with the film to that without the film versus the product of dimensionless film thickness and square root of Peclet number [Fig. 4, Ref. 2].

Fig. 3. The dimensionless surface temperature versus the angular location where the second heat source is placed at different positions as indicated by the arrows. The temperature distribution due to the first source along is shown by the thick solid line [Fig. 4, Ref. 3].

Fig. 4. Spot Size Diameter Distributions
(a) Exposure Times (ms)
(b) Average Number of Spots Per Photograph
(c) Spot Area/Apparent Area of Contact \((x10^{-3})\) [Fig. 9, Ref. 4]
Fig. 6. Colorized thermogram of dynamically propagating crack in tool steel plate 0.4 mm thick. Original notch position noted. Scanning rate 4 kHz with an instantaneous field of view of 300 micrometers diameter [Ref. 6].

Fig. 5. Cam surface temperature at peak life for stated conditions [Figures 16-18, Ref. 5]