TEMPERATURE SENSORS FOR DETECTING FAILURE OF TRIBOLOGICAL COMPONENTS

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ABSTRACT

Frictional heating and the resulting increase in surface temperatures can have an important influence on the tribological behavior and failure of sliding or rolling/sliding components, whether they be lubricated or unlubricated. To avoid failure of those components, surface temperatures must be kept below critical values. Similarly, incipient failure of the components can be detected if the surface temperatures can be monitored during service. This monitoring task requires sensors which can respond very quickly and reliably to changes in temperatures, but which do not adversely change the operating characteristics of the components. This paper describes the development of single thin film thermocouples (TFTC) and arrays of TFTC devices, and the use of these devices in monitoring actual surface temperatures during operation of sliding mechanical components. TFTC sensors may be used to warn of impending surface failure of sliding components, such as thermoplastic bearings, and would aid in avoidance of component failure.

Key Words: Frictional heating; sliding bearings; surface temperatures; thin film thermocouples; wear

INTRODUCTION and BACKGROUND:

Sliding friction results in a loss of mechanical energy, and it has long been known that the vast majority of frictional energy is transformed into heat. This frictional energy dissipation takes place in the immediate vicinity of the real area of contact, where frictional interactions occur. The transformation of frictional energy to heat, called frictional heating, is responsible for increases in the temperatures in the contact region of the sliding bodies. Frictional heating and the resulting increase in surface temperatures can have an important influence on the tribological behavior and failure of sliding or rolling/sliding components. It has been known for many years that scoring (or scuffing) of gears is related to the maximum surface temperature rise (or flash temperature) in the contact zone, but work goes on to elucidate that relationship [1,2]. Mechanical face seals often fail by the phenomenon known as thermocracking or heat checking; this phenomenon has been shown to be directly related to frictional heating [3]. For dry sliding bearings, one of the primary design parameters, the PV (= pressure x velocity) factor, is really an indication of the amount of frictional heating, and therefore the surface temperature [4]. Many dry bearings are made of polymers, and it is well known that polymer wear is very dependent on surface temperature [5]. Much wear of sliding metallic or ceramic surfaces has been found to be thermomechanical in nature, with surface temperatures playing a critical role in its occurrence [6]. In fact, the recently developed wear-mechanism maps which enable the mode of wear of metallic surfaces to be determined are in actuality based on maps of surface temperature [7].

From these examples, it should be clear that surface temperatures play a major role in surface failure of sliding or sliding/rolling mechanical components, whether they be made of metals, ceramics or polymers. Because of the importance of surface temperatures, attempts have been made for many years to calculate those temperatures and use them in the design of critical components. Analytical models have been developed for calculating surface temperatures in sliding contacts [8-10], and a recently-published handbook contains a chapter devoted to surface temperature prediction [11]. All of these methods, however, require knowledge of a critical parameter which is seldom, if ever, known in actual sliding contacts - the actual area of contact over which frictional heat is being generated. Therefore, the accurate prediction of actual surface temperatures in sliding or rolling/sliding mechanical components is seldom possible. As an alternative, experimental measurements of surface temperature can be made.

Many different surface temperature measurement techniques have been used with some degree of success, and those methods are described in a recent handbook article [12]. Although each of the techniques is a useful engineering or research tool, each is also subject to some limitations, so there is no single surface temperature method which can be used for all applications. Some techniques, such as thermocouples, give a measure of temperature at a single point, while others, such as infrared imaging, give a field measurement. Some, such as thermocouples or thermistors, can be mounted on actual machine components, while others, particularly optical techniques, require a special counterface material (eg., a transparent sapphire). Response time varies considerably, from <50 ns for photon detection, to 1 μs or less for thin film thermocouples, to several seconds for infrared photography, and nearly a minute for metallographic techniques. The work described in this paper has aimed to develop fast response temperature sensors for use in measuring surface temperatures on machine components.

METHODS:

Temperature Sensor Selection:

Because of the peculiar environment encountered in sliding situations, the sensors developed for contact surface temperature measurement in this work had to satisfy the following requirements:

(1) The highest surface temperatures occur only at localized real contact areas and have very short duration. The sensor must enable measurement of the temperatures within the actual contact area. It must have small measuring junction dimensions and small thermal mass in order to achieve rapid thermal response and local area thermal sensitivities.

(2) The sensor must cause minimal disruption to the normal operation of the sliding mechanical component. It should be able to be installed in a wide variety of actual components and should pose no significant restriction on the choice of materials for the components.

(3) The sensor must have good wear resistance and reasonable durability during operation which includes friction and wear at the sliding interface.

To meet these requirements, the sensors developed in this work were thin film thermocouples deposited directly on the sliding surfaces of actual mechanical components. The thermocouples were designed to have miniature measuring junctions, sandwiched between wear-resistant, electrically insulating protective layers. A cross-section of a typical thin film thermocouple (TFTC) is shown in Figure 1.

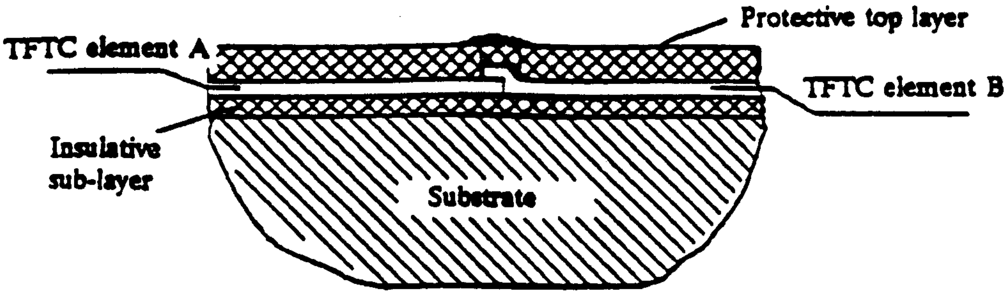

Figure 1. Schematic cross-section of thin film thermocouple.

Thin Film Thermocouple Fabrication:

The thermocouple devices used in this study were made from thin films of copper and nickel, vapor deposited on glass or metallic substrates. The TFTC measuring junctions have been from 0.5 to 2 μm thick, and are sandwiched between thin films of a hard, non-conducting ceramic (Al_2O_3 in our work) to insulate the thermocouple electrically from the substrate and protect it during sliding. Tests have shown that the TFTC devices have extremely rapid (< 1 μs) response to a sudden temperature change and do not significantly disturb the heat flow from the sliding contact [13].

Previously, our TFTC devices were deposited using a shadow mask technique, which enabled the production of devices with measuring junctions as small as $(80\ \mu m)^2$ [13]. In this work, we used microelectronic fabrication techniques to achieve junctions as small as $(10\ \mu m)^2$. Substrate surfaces for TFTC deposition were first polished smooth, then washed in water detergent, followed by ultrasonic degreasing in acetone and subsequent wiping with an methanol-soaked low particulate fabric. The substrates were precoated with Al_2O_3 evaporated from an electron gun source through a reactive oxygen vacuum chamber backfill of 1×10^{-4} Torr. This layer served to improve metal adhesion to nonconductive substrates (0.15 μm thick Al_2O_3), or to isolate the TFTC layers from metallic substrates electrically (> 1000 MΩ for 5 μm thick Al_2O_3). After the surface was cleaned, nickel from a 99.95+% pure source was vapor deposited on the surface to a thickness of about 0.5 μm. The substrate was then removed from vacuum, and photoresist was spin coated on the surface. The photoresist was then exposed lithographically and developed, to define the desired nickel TFTC contacts and wires (the darker portion of Figure 2). After exposure, the nickel was etched in a solution of H_3PO_4:HNO_3:HAc:DI water, until the nickel lines were defined visually. The remaining photoresist was then stripped, and the surface was cleaned using solvents. Copper was then vapor deposited using a 99.99% pure source in an alumina-coated, tungsten resistor boat. The copper was of the same thicknesses as the nickel, up to 1 μm. A second layer of photoresist was applied, exposed and developed, thus defining the copper TFTC contacts and wires (the lighter portion of Figure 2). After etching to remove the unwanted copper, the photoresist was stripped and the surface was cleaned. A protective layer of 2 μm Al_2O_3 was deposited over the completed TFTC in a manner similar to the precoat, except that a shadow mask was used to prevent Al_2O_3 coverage of the bond pads. Extension wires were connected to the finished device using rosin core tin solder.

Since a thermocouple gives a measure of temperature only at one point, it is often desirable to have many thermocouples on a sliding surface so that a distribution of surface temperatures can be obtained. We have produced arrays of up to four individual TFTC devices, each with its own output wiring, and have used those arrays successfully to determine how surface temperature distributions vary with time at a sliding interface. The techniques used to produce the thermocouple arrays were similar to those described above for a single thermocouple. A diagram of a TFTC array with three measuring junctions is shown in Figure 2. The junctions in that particular array were each (80 μm)^2 and were located in an area approximately (0.5 mm)^2.

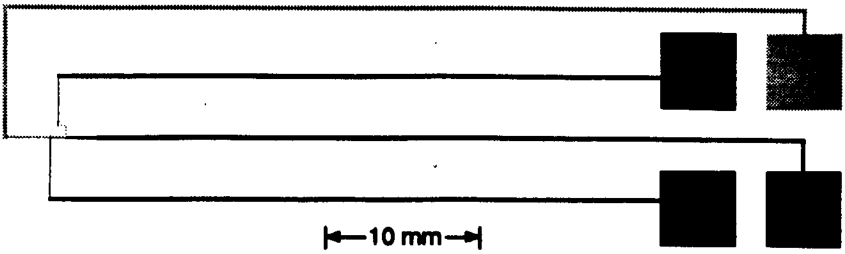

Figure 2. Top view of array of three thin film thermocouples.
Thermocouple junctions (40μm)^2 are at left. Bonding pads (5 mm)^2 are at right.
The lighter line on top is the common copper line.
The three darker lines are the nickel lines from each of the three thermocouples.

After testing the multiple TFTC arrays, we found that array design and data acquisition problems increase significantly as the number of individual thermocouples increases. Each thermocouple junction requires an additional bonding pad and an additional line running from the junction to the bonding pad. These lines cannot contact any other lines except at the active junction, posing severe geometrical constraints on the design of the array. In addition, each of the thermocouples must be attached to a separate channel of the data acquisition system, thus slowing down the data acquisition rate for each channel. The combination of these problems essentially prevents having TFTC arrays with more than four or five active junctions. To overcome these problems, a novel device has been developed to measure spatial surface temperature profiles. This device, a thin film thermocouple MOSFET array, enables measurement of a surface temperature distribution by switching through the measuring junctions of a TFTC array [14]. A cross-section of such a switchable thermocouple is shown in Figure 3. The MOSFET in the semi-conducting substrate acts as an electrically controlled switch connecting the two metals of a thermocouple pair. Because the switching device is fabricated using microelectronic techniques, the size of the junction can be kept very small, validating the assumption of constant temperature across the junction. Arrays have been designed and fabricated using a conventional bit-line/word-line scheme, allowing for increased packing density and ease of data acquisition. We have successfully fabricated several different arrays of sixteen Ni-Cu thermocouples, each with a junction size 40 μm square and less than 1 μm thick [15, 16]. A diagram of one such array is shown in Figure 4. These are by no means the limits of the size of TFTC thermocouple arrays; we foresee arrays of 100 or more thermocouples, with sizes of individual thermocouple junctions being less than 10 μm square. The arrays were produced on silicon wafers using a microelectronic fabrication process described in detail elsewhere [15]. The final stages of the process, i.e., the fabrication of the nickel and copper lines, are essentially the same as described above.

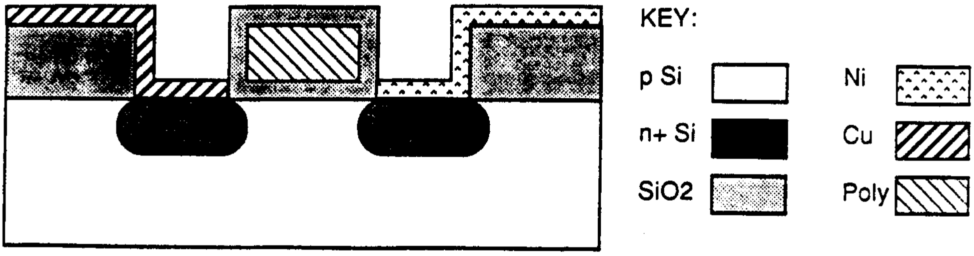

Figure 3. Cross-section of thermocouple MOSFET.

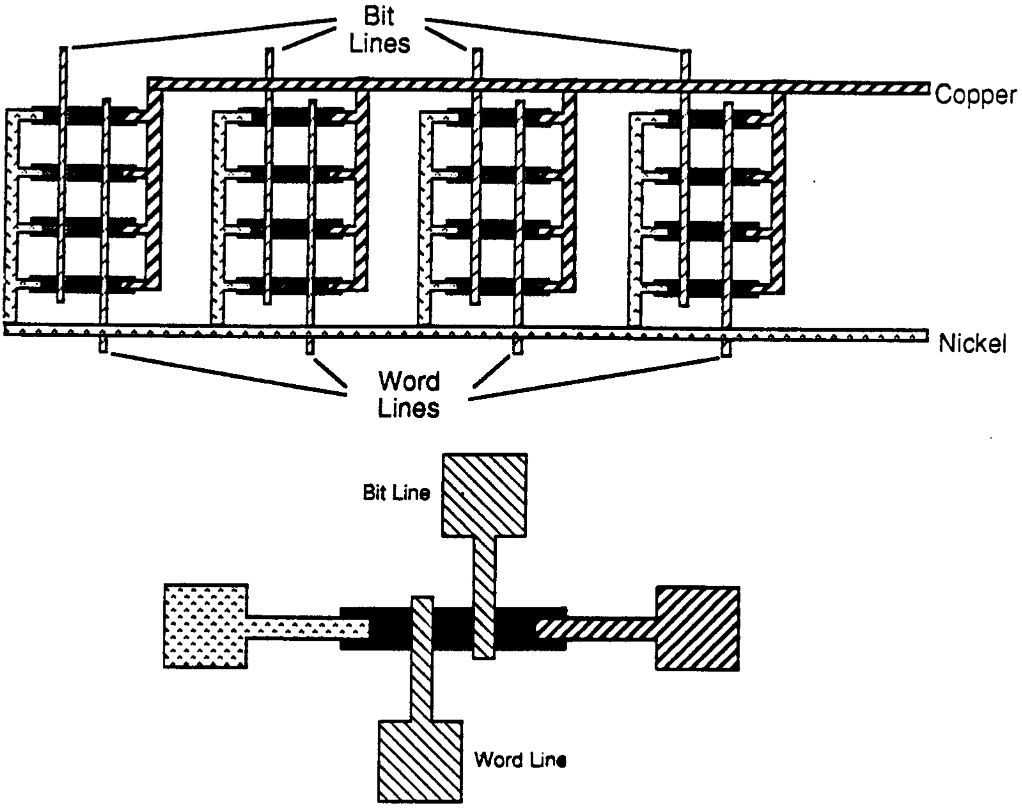

Figure 4. Layout of thin film MOSFET thermocouple array.

Testing:

Many tests were performed to confirm the efficacy of the TFTC devices as temperature sensors for sliding components. The particular application studied was dry sliding bearings made from a thermoplastic polymer. Such bearings are widely used in situations where lubrication during operation is difficult or impossible, and failure of the bearings is a common occurrence. In the tests, a polymer specimen was rubbed against a flat counterface containing TFTC devices on its contact surface. Two thermoplastic polymers were tested, Ultrahigh Molecular Weight Polyethylene (UHMWPE) and Polymethylmethacrylate (PMMA). Pins of dimensions 2mm x 4mm (4 mm in the sliding direction) were machined from the polymer materials and were held in a stationary pin holder on a test apparatus which had been used in earlier studies of polymer wear [17]. A weight was applied to the top of the specimen holder to provide the desired normal load. The flat specimens were made from either glass or stainless steel, and Ni-Cu thermocouples were deposited on their contact surface as described above. The specimen holders for both pin and flat specimens were fitted with thermoelectric heaters which enabled their background (or bulk) temperature to be controlled at temperatures ranging from 15°C to 50°C. Tests were conducted at a wide range of normal loads, sliding speeds and background temperatures. All tests were run in air. During a test, a chosen normal force was applied to the top of the polymer pin, background temperatures were set to their desired values, and the flat specimen was set in motion at the chosen oscillatory frequency. The friction force was measured by a piezolectric force transducer and the linear wear of the pin specimen was monitored using a displacement transducer (LVDT). Contact temperature, friction force, and linear wear were all monitored continuously with the aid of a computer-based data acquisition system.

RESULTS AND DISCUSSION:

A typical plot of measured surface temperature rise (above background temperature) as a function of time during a test is shown in Figure 5. In this test a PMMA pin was in contact with an alumina-coated glass flat upon which a three-element thermocouple array (similar to that shown in Figure 2) had been deposited. Figure 5 shows the variation of each of the three thermocouples in the array during a 5 second period of the test. As can be seen, all of the thermocouples show two temperature peaks during each oscillation cycle, one as the pin slides over the thermocouple junction in one direction and the other as the pin passes the junction during the return trip. These temperature peaks (called flash temperature rises) are superimposed upon a nominal temperature rise which is due to the repeated frictional heating of the entire surface. In this case, the nominal temperature rise (above the 27°C background temperature) was between 20°C and 24°C, while the flash temperature rise added an additional 32-53°C, depending on the thermocouple. Thus, the peak surface temperature ranged from about 78-87°C for thermocouple #3 to over 100°C for thermocouple #1. The difference in flash temperatures between the three thermocouples is presumably due to differences in contact pressure at the three points, since contact temperature rise is proportional to the rate of frictional heat generation [11]. The frictional heat generation at a point is determined by μPV, where μ is the friction coefficient, P is the contact pressure, and V is the sliding velocity. V is the same for all three points, and differences in friction coefficient across the surface are probably small. The relative magnitude of contact temperature for the different thermocouple locations changed over time because of variations in contact pressure resulting from wear of the polymer pin. Whereas thermocouple #1 gave the highest temperatures during this particular time period, its temperature could be lower than that of the other thermocouples at other times during the sliding test. It is difficult to tell beforehand where the highest contact pressure, and therefore the highest contact temperature, will occur at any particular time. For that reason, a single thermocouple on the contact surface will be unlikely to register the highest surface temperature at any given instant. An array of thermocouples would be much better in detecting the actual maximum surface temperature.

The testing apparatus allowed the variation of background temperature as well as sliding velocity (or oscillation frequency), and in some tests both parameters were varied. Partial results for one such test are shown in Figure 6. During that test the data aquisition system gathered temperature data from the thin film thermocouple in 5 second bursts every 30 seconds. [Temperature data were not gathered continuously because the 125 sample/sec data aquisition rate would rapidly result in too many temperature data for the computer to handle.] Friction data were gathered continuously at a slower acquisition rate. Oscillation frequency was set at 2 Hz for most of the test and at 4 Hz for two intervals. The background temperature was held constant at 25°C for the first 380 seconds and then increased to 45°C for a period before ramping back to 25°C. It can be seen that both higher oscillation frequency (higher sliding velocity) and higher background temperature led to a higher peak contact temperature, although the higher background temperature did not result in a higher flash temperature rise, or temperature change per oscillation cycle. This is in agreement with theoretical calculations, which show that flash temperature rise is a function of heat generation rate, but is independent of background temperature [18]. In fact, the contact temperatures measured here were in very good agreement with those predicted analytically [18].

An examination of the friction data in Figure 6 shows that an increase in friction is brought about by either an increase in velocity (frequency) or an increase in background temperature. In fact, it appears that the friction is quite temperature dependent and an increase in contact temperature brings about an increase in friction, whether the temperature increase is caused by an increase in velocity or by a change in background temperature.

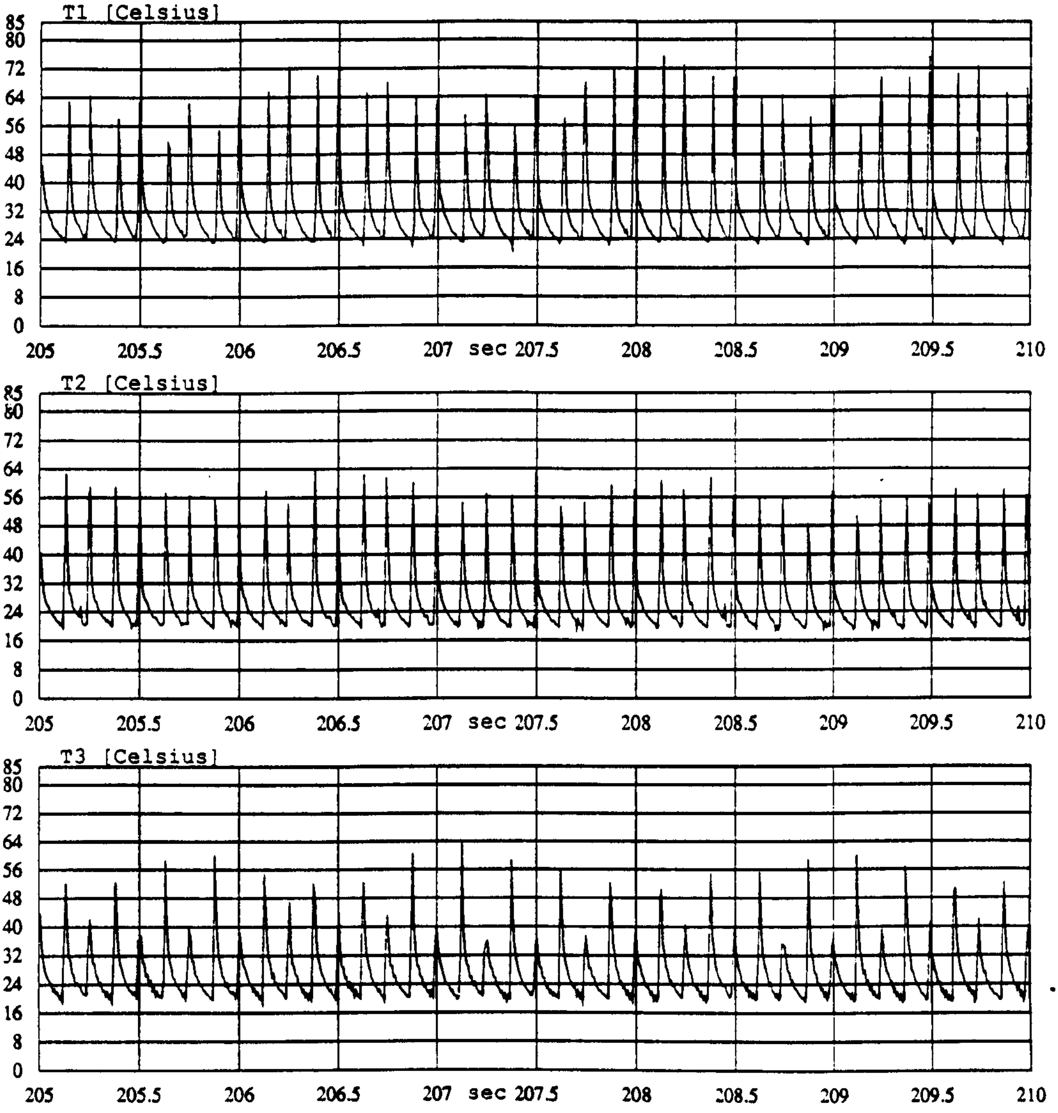

Figure 5. Temperature output from 3-element thin film thermocouple array during 5 sec. period for sliding test of PMMA pin against oscillating alumina-covered glass specimen. Normal load = 9.8 N. Oscillating frequency = 4 Hz. Background temperature = 27°C.

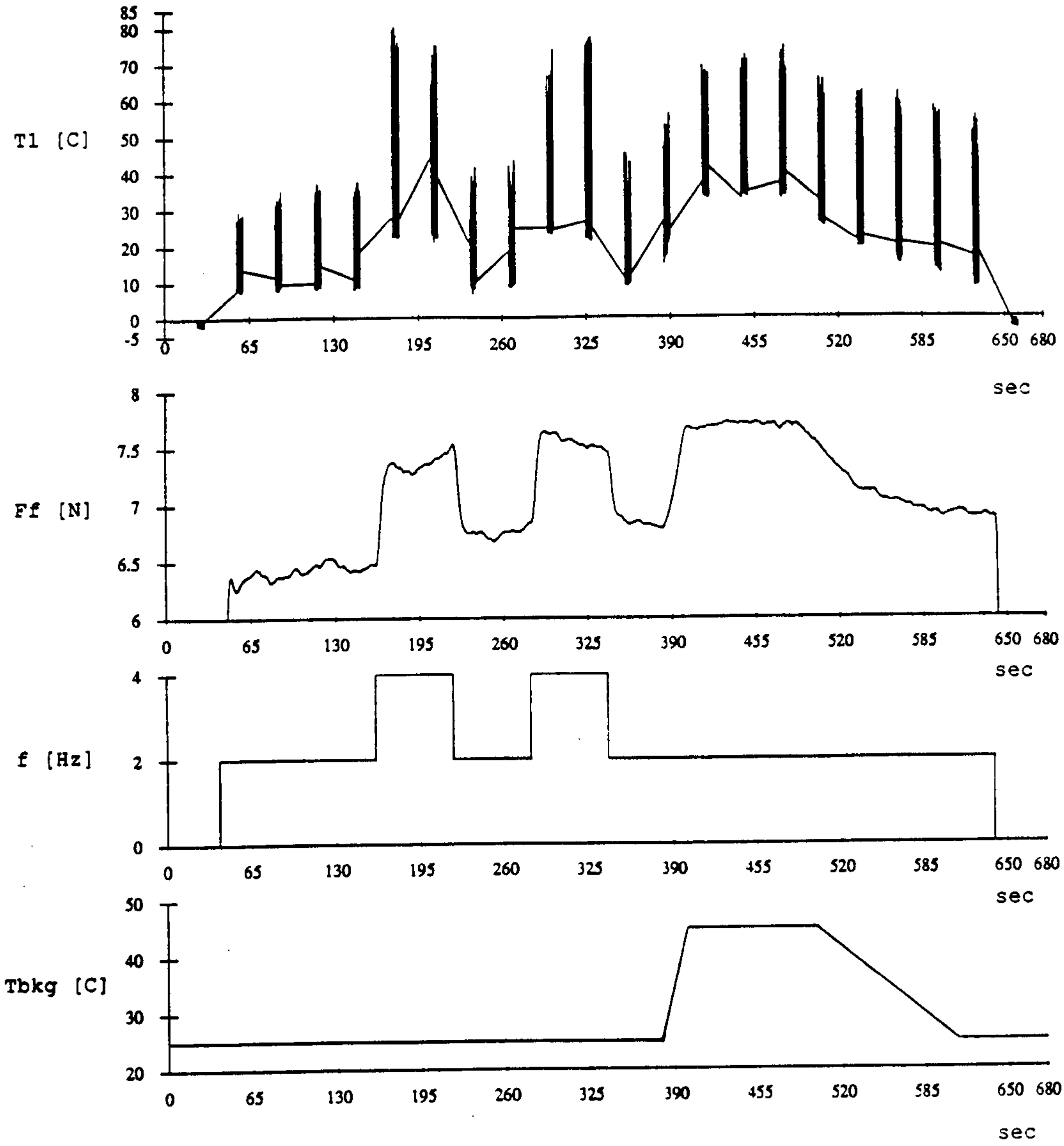

Figure 6. Contact temperature (T1) and friction (Ff) measurements during sliding test of PMMA pin against oscillating alumina-covered glass specimen. Normal load = 9.8 N. Frequency (f) varied from 2 to 4 Hz. Background temperature (Tbkg) varied from 25°C to 45°C.

Tests of both PMMA and UHMWPE were run at a large number of operating conditions leading to a wide range of surface temperatures. The resulting wear rates are shown in Figures 7 and 8 as a function of the measured total surface temperature. The wear coefficient used in the figures is defined as the volume lost per unit sliding distance per unit normal load, and it has units of m^2/N. It is evident from the figures that both materials experienced relatively low wear until the peak surface temperature reached a critical value. For the PMMA material, the critical temperature was about 162°C, whereas for the UHMWPE material the critical temperature was about 137°C. The critical temperature for UHMWPE is approximately equal to the melting temperature of that material. For PMMA, however, the critical temperature is about 30-35°C below its melting temperature and is determined by the temperature at which the PMMA material softens while under compressive stress. It might also be noted that the wear coefficient of UHMWPE was much lower than that for PMMA, even in the severe wear regime at $T_{critical}$.

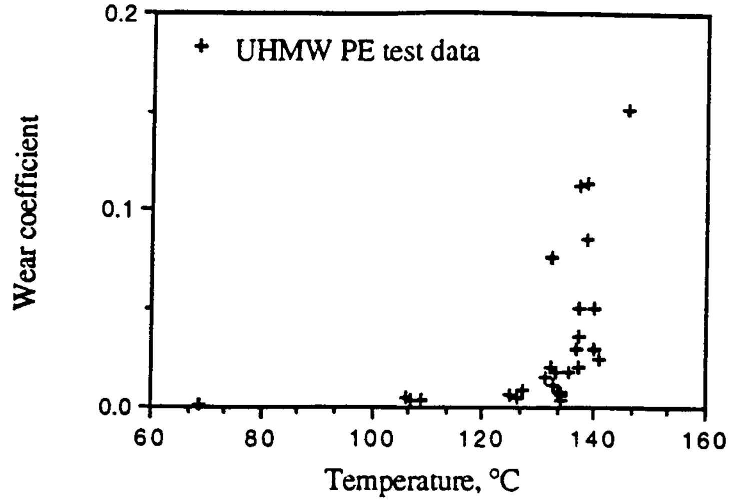

Figure 7. Wear data for UHMWPE pins in oscillatory sliding against glass flats at different contact tamperatures. The wear coefficient is defined as volume lost per unit sliding distance per unit normal load.

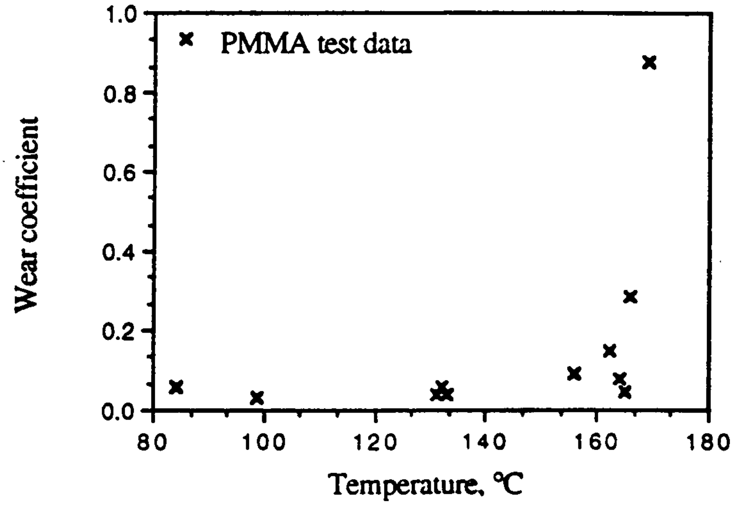

Figure 8. Wear data for PMMA pins in oscillatory sliding against glass flats at different contact tamperatures. The wear coefficient is defined as volume lost per unit sliding distance per unit normal load.

Tests have shown that the drastic increase in wear rate of these thermoplastic materials as their contact temperature approaches $T_{critical}$ is relatively unaffected by the method used to raise the surface temperature [19]. Thus, the temperature increase could be caused by an increase in either sliding velocity, background temperature, or normal load, or a combination of the three factors. It was also found that this result holds true whether the material is amorphous, like PMMA, or semi-crystalline, like UHMWPE. When the critical temperature is reached, changes occur in real area of contact and/or friction coefficient to keep the maximum surface temperature from exceeding the critical value [19].

Use of the TFTC device enabled accurate measurement of the sliding contact temperature responsible for failure of the polymer. Measured temperatures correlated well with a recently-developed analytical model for prediction of surface temperature rise at the contact interface for cases of oscillatory sliding [18].

It is apparent from the evidence presented above that significant changes in wear of thermoplastic materials can occur if the sliding surface temperature reaches the critical temperature for the material. It is important that such temperature excursions not occur in bearings employing thermoplastic bearings. The peak surface temperatures are dependent on the actual friction coefficient and the real area of contact during sliding, and those quantities are seldom known with any certainty, especially since they vary during operation. One way to overcome the possibility of temperature-induced wear failure of the components is to use in-situ temperature sensors to determine the actual surface temperatures in service. An array of thin film thermocouples would be a very appropriate sensor for such a measurement. The multi-thermocouple array would have a better chance of detecting the highest contact temperature than would a single thermocouple or any other single temperature sensor. The sensors could provide a warning when the peak surface temperature approached the critical temperature, and they can therefore enable failure of the components to be avoided. This could be especially helpful when sliding conditions occur which are more severe than had been anticipated in the design stage.

An array of TFTC devices would be very useful in monitoring potentially damaging contact temperatures over a large nominal contact area in a machine component. The design of such thermocouple arrays and the aquisition of data from them would be rather difficult if the arrays were of the form shown in Figure 2. Incorporation of a switch in each thermocouple, such as that shown in Figure 3, would greatly ease the data acquisition task. Switchable thermocouple arrays similar to the one shown in Figure 4 could make it possible to monitor surface temperature at a large number of points within a contact region without very much data acquisition burden (a single temperature output channel is all that would need to be monitored). Our tests of these arrays have been limited to devices on silicon [15,16], and more development work is needed before similar switchable arrays are possible on other substrates.

Although the work reported here concentrated on only one type of mechanical component (thermoplastic sliding bearings), the methodology used here could be applied to a wide variety of tribological components which encounter friction and frictional heating during operation. Although the failure mechanism for the component might be different, as long as that failure mechanism is temperature-dependent, the use of thin film thermocouple contact temperature sensors could aid in detecting the presence of surface temeratures which could lead to failure of the components.

CONCLUSIONS:

Thin film thermocouples and arrays of such devices have proven to be very effective in measuring surface temperatures in sliding contacts. The TFTC devices have a very small measuring junction which enables rapid response to changes in contact temperature resulting from changes in sliding velocity, contact pressure, or background temperature.

It was found that the wear rate of thermoplastic bearing materials increases dramatically when the contacting surface of the material reaches a critical temperature which is related to its melting or softening temperature. This holds true whether the material is amorphous, like PMMA, or semi-crystalline, like UHMWPE.

An in-situ temperature sensor, such as the thin film thermocouple employed in this study, is one of the most effective ways to accurately determine actual sliding surface temperature during operation. Such a sensor could be used to warn of impending surface failure of thermoplastic components, and could be of similar benefit in avoiding surface failure of other tribological components.

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