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Coefficient of Friction of PTFE-Impregnated Porous Bronze Versus Temperature

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DU (registered trademark of The Glacier Medal Company, Ltd.) is a composite material consisting of sintered bronze, impregnated primarily with polytetrafluorethylene (PTFE), mounted on a steel backing. It is used as a dry lubricant in bushings and for such components as hinges both on the ground and in space. The coefficient of friction in vacuum of DU on hard anodized aluminum coated with DU was shown to double as the temperature was lowered from 60 to -20°C. The expression $\mu = 1.33 \exp(-0.01092T)$ was derived to describe this behavior. The derivation was made with the expression $\mu = s/p$ as a basis,

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where s = shear strength of PTFE, and p = hardness of bronze. The resulting equation for μ fits the data excellently, thereby demonstrating the validity of the adhesion theory of friction for this material.

MU

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INTRODUCTION

The extremely low coefficient of friction of polytetrafluorethylene (PTFE) makes it an attractive material in the lubrication of any kind of sliding components. The usually quoted value for μ of 0.04 is lower than that for graphite, MoS_2, or any other known solid [1]. In addition, its low vapor pressure, 2.5×10^{-25} atm [2], allows it to be used in high-vacuum applications.

There are, however, several properties of PTFE that limit its applicability. It is a poor conductor of heat; thus, the excess heat that is generated under sliding friction is not readily dissipated and, in fact, contributes to the decomposition of the PTFE [3]. It also has a relatively low compressive strength, 2000 lb/in^2, which allows the cold flow of PTFE films so that tolerances are changed. In thin-film applications, the films are removed to the point that the underlying surfaces are exposed [4].

Composite materials incorporating PTFE have been developed to eliminate these problems. One composite, which has the trade name DU, consists of a 0.010-in.-thick layer of sintered porous bronze ($Cu_{89}Sn_{11}$) into which is impregnated a PTFE-lead mixture (20% Pb). This PTFE-lead mixture also forms an overlay up to 0.001 in. thick [5]. By means of this technique, the low-friction characteristics of PTFE are combined with the superior hardness and thermal conductivity of bronze.

The objective in this study was to determine the manner by which the coefficient of friction of DU is affected by temperature under high vacuum.

The application of concern here is the sliding friction of DU on black, hard-anodized aluminum. However, since a film of PTFE would be rapidly transferred from the DU onto any metal [6], the composition of the underlying metal would not alter significantly the results (unless it was considerably softer than the anodized aluminum).

APPARATUS

The apparatus is shown in Fig. 1. The DU, a 1/8-in.-diam disc, was mounted so that it pressed against a hard-anodized aluminum plate. This geometry was used because it closely corresponds to a specific application of DU in a particular spacecraft component. The aluminum plate was made to oscillate back and forth by means of a motor-driven cam located outside the vacuum chamber. Coupling to the motor was achieved by means of metal bellows. The oscillatory motion was chosen for several reasons. First, it corresponded to the start-stop motion involved in the specific spacecraft application mentioned above. Second, it eliminated problems in determining the absolute value of friction force. Third, it allowed the use of a small aluminum plate, thereby simplyfing the measurement and control of temperature. Fourth, it allowed the measurement of both the static coefficient of friction and the dynamic coefficient of friction over a range of velocities during each cycle.

The DU was mounted on the end of a hollow stainless-steel tube, which was open to the outside air. The diameter of the tube was such that the pressure difference between the inside of the tube, 14.7 lb/in^2, and the outside, the vacuum of the chamber, caused it to press against the aluminum with a force of 10 oz. A bellows was provided so that the tube was free to expand or contract as required. However, the position of the DU was adjusted with a rack and pinion arrangement before pump-down so that the DU disc just

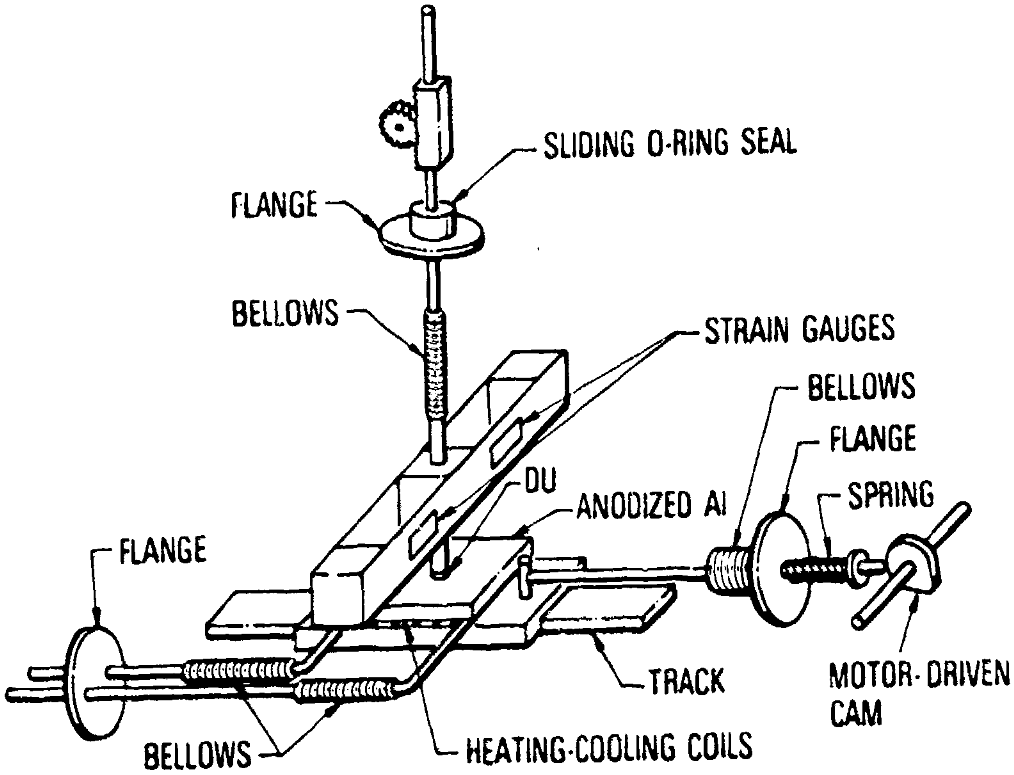

Fig. 1. Experimental apparatus used to measure coefficient of friction in vacuum

barely touched the aluminum surface and the subsequent pressure difference would not cause any significant distension of the bellows.

The temperature of the aluminum plate was varied through the use of copper tubing, which carried hot or cold fluid. Heating was accomplished by flowing 100° C water through the tubes. Cooling was accomplished by the use of nitrogen gas that had been initially cooled-down by flowing it through a copper coil immersed in liquid nitrogen. The temperature of the plate was monitored with a thermistor, which was attached to the side.

The friction force was determined by means of four resistance strain gauges. The strain gauges were self-temperature-compensated and were arranged in a Wheatstone bridge configuration. The strain gauges were mounted on Be-Cu beams in such a manner as to measure any displacement of the DU disc in the direction of motion of the plate below. Deflections of the beams thus were converted directly into a voltage signal proportional to the frictional force. The circuit was calibrated by exerting a known horizontal force on the DU and noting the resulting change in output voltage. The calibrating force was produced by means of a weight and pulley.

The beam arrangement was originally designed to measure displacements in one direction only. This earlier method was not successful, however, because residual strain and electronic drift made it extremely difficult to determine the voltage that corresponded to the relaxed (zero friction) position and thus prevented a determination of the absolute frictional force. The oscillatory motion used here eliminated this problem, since it is only necessary to measure the peak-to-peak voltage excursions and then to divide this value by two.

A further advantage of the oscillatory method is that a range of velocities is covered during each cycle. Thus, the coefficient of friction as a function of velocity can be easily determined, which applies as well to the coefficient of friction at zero velocity, i.e., the static coefficient of friction. The output voltage of the bridge circuit with time for a system with a dynamic coefficient of friction that is independent of velocity and a static coefficient of friction that is greater than the dynamic coefficient is shown in Fig. 2. The higher static coefficient of friction causes the signal voltage to be higher before slippage occurs. The typical trace for a system, e.g., DU, in which the dynamic coefficient increases with increasing velocity is shown in Fig. 3.

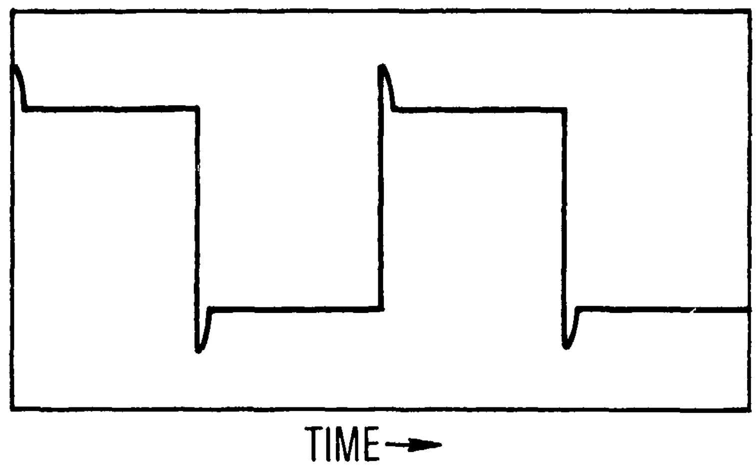

Fig. 2. Output of strain-gauge circuit for material with velocity-independent coefficient of dynamic friction and larger coefficient of static friction

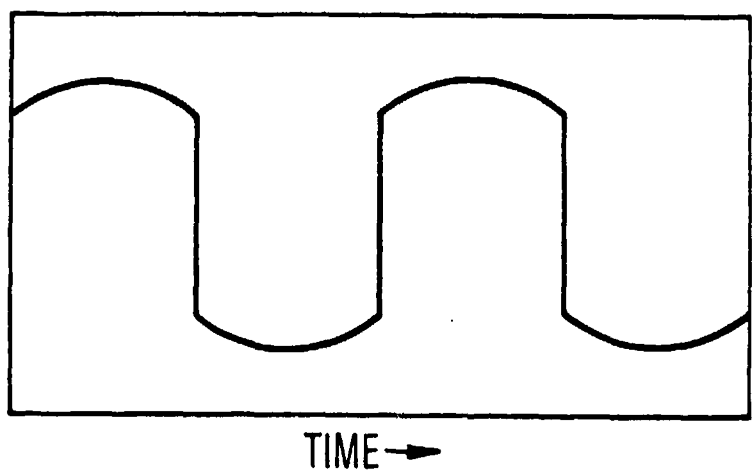

Fig. 3. Output of strain-gauge circuit for material whose coefficient of friction increases with velocity

SAMPLE PREPARATION

The aluminum plates used in the experiments were given a finish of 8 to 16 rms. They were then hard black-anodized to a depth of 2 mil and repolished to an 8 rms finish with No. 600 emory paper.

The aluminum plates and the DU test discs were then cleaned in an ultrasonic bath for 5 min in a solution of 10% acetone in xylene and for 5 min in pure acetone. They were blown dry with dry nitrogen.

The aluminum plate was subsequently pretreated with DU in the following manner. A small piece of DU, cleaned as above, was rubbed against the plate with approximately 15 lb of force for 10 min. The surface was inspected under a microscope for complete coverage. It was also tested for coverage with xylene because xylene does not wet DU.

THEORY

The adhesion theory of friction predicts that the coefficient of friction between two low-surface-energy materials is given by

$$\mu = \frac{s}{p} \qquad [1]$$

where s and p are the resistance to plastic flow of the weaker of the contacting materials in shear and in compression, respectively [7]. In the absence of any phase transitions of either the bulk materials or of the oxides residing on the surfaces, the coefficient of friction remains constant with temperature because both s and p exhibit the same temperature-dependence [8]. PTFE, however, exhibits a phase transition at about 19° C [9].

A study conducted on the coefficient of friction of four plastics in vacuum [10] revealed that, whereas the ratio s/p did not predict the absolute value for μ very well, it did predict the temperature-dependence fairly well. The results of that study for PTFE are shown in Figs. 4 and 5. These data indicate that, for PTFE in the temperature range studied, μ is given approximately by the expression

$$\mu \doteq 0.3 \frac{s}{p}$$

where s is the shear strength (in kg/mm^2), and p is the static yield pressure or hardness (in kg/mm^2).

The coefficient of friction of DU is different from PTFE both in being lower in value and by having a stronger variation with temperature over the

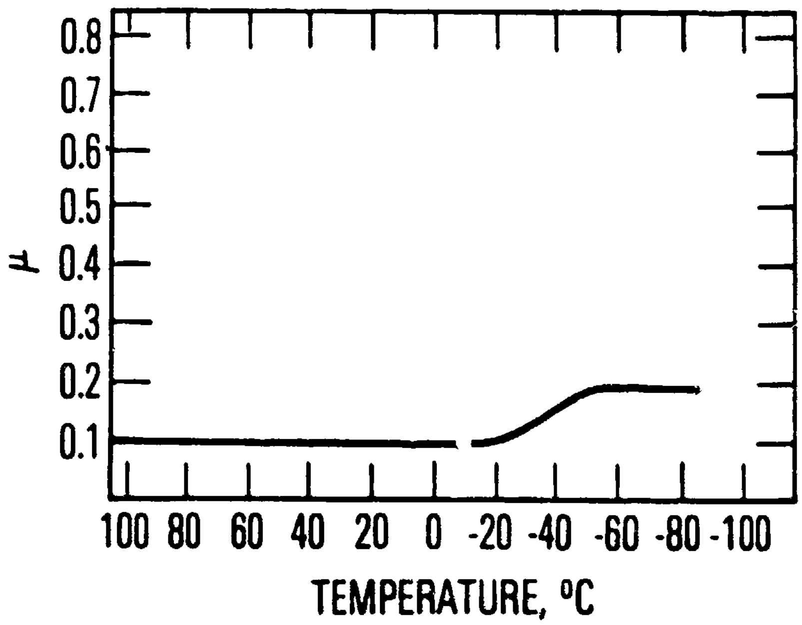

Fig. 4. Effect of temperature on friction of PTFE [10]

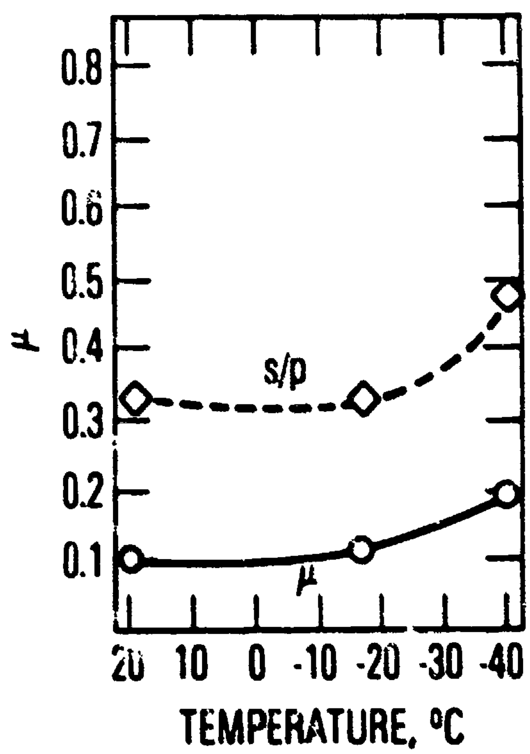

Fig. 5. Comparison of μ and s/p of PTFE as a function of temperature [10]

range studied. Both of these differences can be explained through use of eqn. 1. It has been pointed out [11] that, if a soft plastic is backed by a hard material such as a metal, s remains that of the plastic, whereas the hardness is substantially increased. The result is a significant reduction in the coefficient of friction from that of the plastic alone. It is reasonable to assume therefore, that the temperature-dependence of DU could be described by an equation of the form s/p, where s is the shear strength of the PTFE, and p is the hardness of the metal (in this case, bronze).

The temperature-dependence of the hardness of bronze and of the shear strength of PTFE must be known to test this theory numerically. It has been demonstrated [12] that both pure metals and intermetallics exhibit an exponential dependence of hardness on temperature of the form

$$p = k \exp(-BT)$$

where k and B are constants, and T is in °K. With the Brinell hardness values of a typical bronze, $Cu_{90}Sn_{9.4}Zn_{0.5}$,[13] used,

$$p = 76.84 \exp(-6.277 \times 10^{-4}\ T)$$

is obtained. However, porous bronze instead of bulk bronze is used in DU, and, although the temperature-dependence should be the same for both, the absolute hardness should be reduced by an amount related to the porosity of the bronze. Thus, a multiplicative constant (σ) should also be included in this expression

$$p = \left(\frac{1}{\sigma}\right) 76.84 \exp(-6.277 \times 10^{-4}\ T) \qquad [2]$$

where α is greater than 1. If an exponential dependence for the shear strength of PTFE is assumed, then, by use of the data of King and Tabor [10], an equation for s can be obtained.

$$s = 53.09 \exp(-0.01155\ T) \qquad [3]$$

Dividing eqn. 3 by eqn. 2 gives the following theoretical expression for the coefficient of friction of DU.

$$\mu = \alpha\ 0.69 \exp(-0.01092\ T) \qquad (\alpha > 1) \qquad [4]$$

RESULTS

The data for the coefficient of friction of DU versus temperature on black, hard-anodized aluminum are shown in Fig. 6. These values correspond to a sliding speed of 17 mm/sec. These data are from five separate runs made on three different days. The data were recorded during both the heating and cooling cycles without any indication of hysteresis.

The continuous curve on the graph represents the equation

$$\mu = 1.33 \exp(-0.01092\ T)$$

This equation was generated from the theoretical expression, eqn. 4, with α chosen so that $\mu = 0.054$ at $T = 20^\circ C$. The resultant value for α is 1.93.

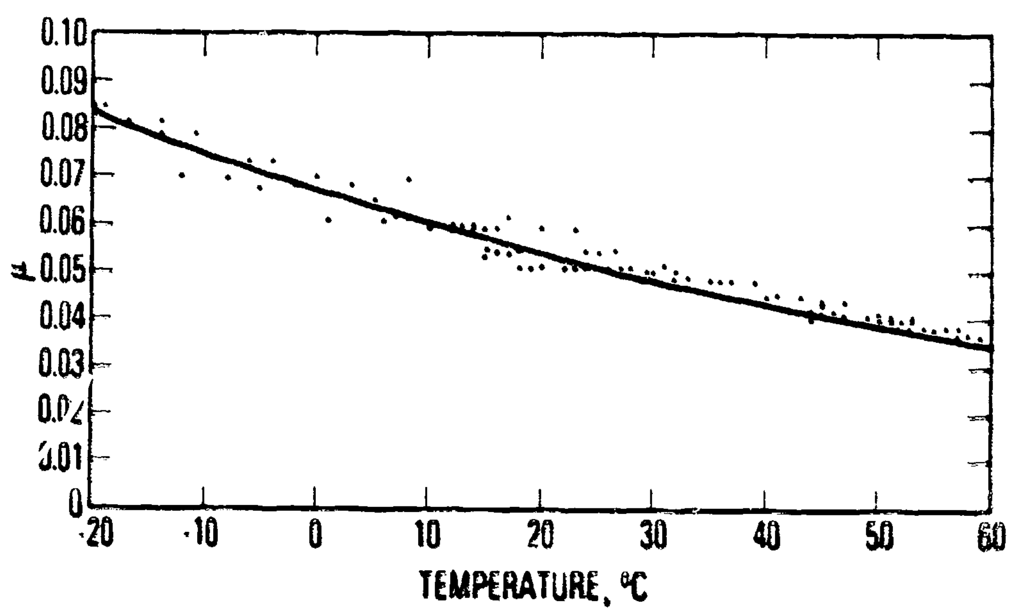

Fig. 6. Coefficient of friction of DU versus temperature in vacuum

CONCLUSIONS

The coefficient of friction of DU doubles as the temperature is lowered from 60 to -20°C. Although DU is a composite material consisting primarily of PTFE and bronze, the temperature-dependence of its coefficient of friction is described excellently by the adhesion-theory equation $\mu = s/p$, where s is the shear strength of PTFE, and p is the hardness of bronze. Since the hardness of bronze, as given by eqn. 2, varies by only about 5% over the temperature range studied, it is the variation of the shear strength of PTFE that primarily accounts for the change in μ with temperature. Also, the fit implies that the lead used in the PTFE-lead mixture does not play a significant role in this temperature range.

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