Table AI   Material constants for thermal analysis

	Constants	k W/m°C	ρ Kg/m³	c J/Kg°C	$\alpha = k/\rho \cdot c$ m²/S
Pin	STABILO (8040)	0,23	1750	1220	$1,08 \cdot 10^{-7}$
	PEG 1500-2000	0,9	1273	1410	$5,01 \cdot 10^{-7}$
Counterface	GLASS	0,6	2448	1047	$3,51 \cdot 10^{-7}$
	PMMA	0,23	1196	1220	$1,58 \cdot 10^{-7}$
	STEEL	43	7890	591	$92,69 \cdot 10^{-7}$

μ : coefficient of friction

R : non dimensional parameter $R = \dfrac{va}{4\alpha}$

$I(R)$: $\pi R^{-1/2}$

σ : heat ratio

for $R = \dfrac{va}{4\alpha_2} = 0$, $\sigma = \dfrac{1}{1 + \dfrac{k_2}{k_1}}$

for $0 < R < 5$, $\sigma = \dfrac{1}{1 + \dfrac{k_2}{k_1}\left[\dfrac{2\pi}{1 + 0.414(1 - e^{-1.3R})\,I/R}\right]}$

for $R > 5$, $\sigma = \dfrac{1}{1 + \dfrac{k_2}{k_1}\sqrt{2R}}$

Subscript 1 refers to the fixed pin, subscript 2 to the mobile flat.

Contact temperature is thus:

$$T_{\max} = \frac{\pi^{-3/2}(1 - \sigma)qaI(R)}{k_2}$$

II.   Material Constants

Material constants are given in Table A-I. Values of k and c for the PEG pins were obtained by linear interpolation between values given for the pure polymer and for carbon. These are:

PEG 1500, 2000 (pure) k = 0.29 W/m°C
                                  c = 1464 J/Kg°C

CARBON (pure)

                                  k = 5→9 W/m°C
                                  c = 86.5 J/Kg°C

Reference

Blok, H., "The Temperature of Surfaces Under Conditions of Extreme Pressure Lubricating Conditions," 2nd World Petr. Cong., Paris, Vol. 3, 1937, p. 471-486.

─────── **DISCUSSION** ───────

J. K. Lancaster[2]

This paper is one of only a very few in which quantitative measurements have been made of the thickness of transfer films produced from polymeric materials during sliding. The technique developed for the thickness measurements is relatively simple and could, presumably, be used with equal success for studying transfer from more practical dry-bearing materials such as PTFE composites. In this connection, it would be helpful if the authors could provide a little more information. For example – what was the thickness of the evaporated nickel film; is there a critical minimum film thickness; does the film closely follow the contours of the transferred patches or are there bridges between them; what is the ultimate resolution in thickness measurement?

In retrospect, it seems rather a pity that the two samples of polyethylene glycol used differed so little in their viscoelastic properties. What were the constraints preventing the choice of more widely-different fractions? Because the differences are so small, the attempts to relate viscoelasticity to sliding behaviour rely rather critically on the accuracy of the calculated contact temperatures. No data is given, however, to indicate the uncertainty in the contact temperature values. Would this be appreciably greater than the ±2° quoted for the viscoelastic transition temperatures, or not?

The effects of the type of counterface material on the transfer film thicknesses (Fig. 13) are particularly interesting. The authors suggest that the greater thicknesses on steel at low speeds could be attributable to greater adhesion, but it is difficult to visualize any physico-chemical reasons why this should be so. There could, however, be a more mechanistic explanation. If the surfaces of the glass and PMMA were used "as-received," their method of production would lead to a micro topography consisting of asperities of relatively large radii of curvature and long wavelength. In contrast, with abraded/polished steel, the asperity radii are likely to be much smaller and their wavelengths shorter. A greater degree of physical "keying" of the polymer could thus occur on the steel surface, despite the fact that its R_a, or R_T, roughness might not greatly differ from those of the glass or the PMMA. Were any detailed analyses made of the initial counterface topographies?

Finally, also in connection with Fig. 13, the first discontinuity in the film thickness-pressure curves on glass and PMMA at 0.1 m/s is presumably associated with a viscoelastic temperature transition, by analogy with the later results with the polyethylene glycols. This being so, why does the film thickness not increase very rapidly as, for example, in Fig. 16? In addition, what would be the physical significance of the second discontinuities at which the slopes of the lines return to their initial, lower temperature values?

R. L. Fusaro[3]

The authors have written a very interesting academic paper

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on the wear of polymer-type materials. They determined the amount of wear by measuring the thickness of transfer films produced by sliding polymer pins against steel, glass and polymethyl methacrylate (PMM). Such parameters as contact area, contact pressure, and sliding velocity were investigated. The authors concluded that wear is strongly dependent on temperature. Since polymer viscosity, shear modulus, and yield strength were also strongly dependent on temperature there most likely was a relationship; but they conclude a finer rheological analysis was necessary to understand the relationship. Do the authors plan to attempt such a study and what approach would they consider?

The authors imply that temperature and the mechanical properties of the polymer are dominant in the wear process. What role do the author's believe that adhesion plays in the wear process? A few questions about the experiments seem to be in order.

1. Surface roughnesses of the glass, steel, and PMM may be similar but the surface topographies are most likely very different. Did the authors consider this affect, and was there any attempt to characterize the surface more fully?

2. Relative humidity in the atmosphere can markedly affect the friction and wear of polymers. Was it monitored and what was the value?

3. Comparing the data of Table 1 and Table 2, might not the increased trace thickness at constant pressure for the larger pin diameter, compared to the smaller diameter pin, be due to the higher total load needed to achieve the pressure?

Authors' Closure

The authors wish to thank both Drs. Lancaster and Fusaro for their kind comments. In answer first to Dr. Lancaster's questions:

1) The thickness of the Ni coating varied between 0.2 and 0.5 micrometer depending on application. As the coating technique used is the one employed before SEM pictures are taken, the authors believe that contours are faithfully reproduced. The ultimate resolution is of the order of 0.1 micrometer.

Table 9 Surface characteristics

Profile Height	Steel	Glass	PMMA
Rt (μm)	0.079	0.066	0.062
Ra (μm)	0.011	0.015	0.013
Rms (μm)	0.013	0.017	0.015
Peak Height			
Average (μm)	0.002	0.001	0.001
Stand deviation	0.013	0.017	0.015
Peak radius of curvature			
Average (μm)	3700	7000	7600
Stand. Devi.	3600	5600	5400
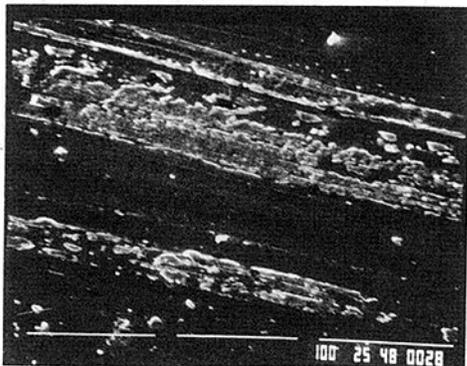
Fig. 16   How speed trace (PEG 2000)

2) The authors also regret in retrospect that the bulk behaviors of the two materials used were so close. In choosing similar materials it was hoped to minimize any variation caused by surface effects that could alter adhesion.

3) As discussed in paragraph VI, there is some uncertainty in the values given by the calculation of contact temperature. The authors feel that until the actual mode of transfer (or deformation) is understood, it is pointless to try to improve on the methods used to calculate the thermal field. It is for the same reason difficult to give more than an intuitive feeling as to the difference between the maximum temperature which might exist in the viscosity of the shear plane and the calculated interface temperature which is recorded in the paper. A guess of $\pm 2°$ is as good as any.

In order to answer the questions on surface roughness put by both discussors, additional data using more sophisticated profilometric analysis was gathered in representative surfaces of steel, glass and P.M.M.A. (reference [1]) and are presented in Table 9.

The unusually large peak radius of curvature are due to the surface generation procedure. Glass and PMMA surfaces were moulded while the steel blocs were polished. The only difference noted is between the peak radius of curvature of the steel and that of the other surface. A 2 to 1 ratio is still fairly small and its effect difficult to interpret.

Turning to Dr. Fusaro's questions:

− Yes, the authors hope in time to be able to pursue this type of work and run finer rheological analyses. No decision concerning apparatus has however been taken.

− We are convinced that adhesion plays a very strong role in the wear process. It acts as a boundary condition on the bulk material, and the depth of shear planes in the bulk which governs trace thickness depends on boundary conditions.

− Relative humidity was not controlled, however trace thickness did not vary with the seasons.

− Yes, we believe that the larger trace thickness obtained at constant pressure for the larger pin could be attributed to the larger load.

− SEM pictures of the trace are given in Figs. 16 and 17. Figure 16 shows a nonhomogeneous trace obtained at low speed (0.005 m/s) with PEG 2000 while Fig. 17 shows a fairly homogeneous trace obtained at moderate speed (0.1 m/s) with the same material. The picture shows approximately one tenth of the 3.5 mm trace. Each white segment corresponds to 100 micrometers. The dark spaces in Fig. 16 correspond to voids in the trace.
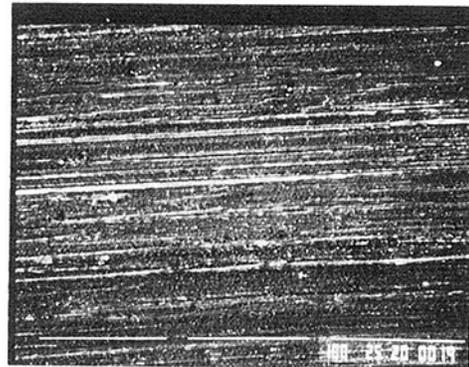
Fig. 17   Moderate speed trace (PEG 2000)

Additional Reference

24 Foucher, D., Flamand, L., Berthe, D., "Variation of Surface Roughness Parameters During Running-In of Lubricated Contacts," in "Surface Roughness Effects in Lubrication," by D. Dowson, C. M. Taylor, M. Godet and D. Berthe, M.E.P. London, 1978.