THE INFLUENCE OF THERMAL EXPANSION ON THE FRICTION AND WEAR PROCESS

J. R. BARBER
Engineering Department, Cambridge University, Cambridge (Gt. Britain)
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SUMMARY

Experimental results are presented for temperatures of two metal surfaces in sliding contact. Considerable fluctuations are observed. It is suggested that temperature gradients, set up by irregular heating at the surface, cause local thermal expansion at the areas of contact, thus perpetuating the irregular contact conditions. The system is limited by the wear at the areas of contact which eventually reduces the level of the contact areas to that of the surrounding surface. Subsequent cooling causes contraction and produces depressions which correspond to the wear volume during the cycle. Further experiments to confirm this explanation show good agreement.

INTRODUCTION

During some recent work on the dissipation of heat in braking systems, it was observed that "hot spots", with a life cycle of the order of seconds, were caused on the surface of the stationary member, a cast iron block. In order to investigate this more fully, a thermocouple was fitted near the block surface, approaching along a normal to minimise interference with the heat flow. Typical temperature fluctuations are shown in Fig. 1. They consist of a period of rapid growth followed by a cooling curve which sometimes includes a further peak.

The duration of the temperature increase is generally about two seconds and, as the sliding speed is in the range 20–120 ft./sec the heat input is clearly not due to the interaction of a single asperity pair.

TEMPERATURE MEASUREMENTS AND DEDUCTIONS

It was observed that, over a sufficiently long period of sliding, the maximum temperature fluctuation is a constant for a given load and speed. In order to obtain more information about heat inputs and contact areas, four thermocouples were fitted at different depths below separate areas of the surface, it being assumed that the fluctuations measured were identical at each area. The maximum temperature fluctuation was therefore measured as a function of depth.

It can be shown that the temperature at a depth x, due to a uniform heat input over a circular area of radius a, tends to a maximum value of $T_0\{(1+x/a)^2-x/a\}$

where T_0 is the surface temperature above ambient. By extrapolating from the experimental data according to this curve it is possible to obtain values for T_0, a, and Q, where Q is the rate of heat input to the point, given by $Q = \pi k a T_0$, k being the thermal conductivity. The values obtained for different sliding speeds are shown in Table I.

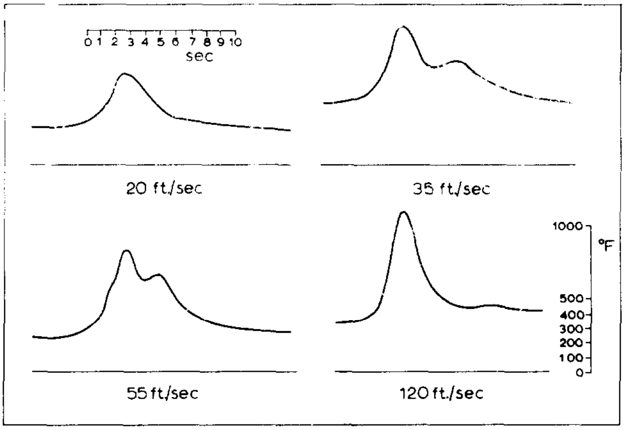

Fig. 1. Typical temperature fluctuations.

TABLE I

DEDUCTIONS FROM TEMPERATURE PROFILES

Speed (ft./sec)	T_0 *(°F)*	*a (in.)*	*Q (B.Th.U./sec)*	*Total frictional heat (B.Th.U./sec)*	*Maximum surface temperature (T_0+ambient) (°F)*
120	1150	0.085	0.204	2.46	1630
55	1170	0.067	0.165	1.42	1530
35	1050	0.058	0.128	0.92	1440
20	1000	0.050	0.105	0.64	1250

The ambient temperature, referred to in Table I, is the mean temperature of the block before the fluctuation. It will be observed that the maximum surface temperature, shown in column 6, is insensitive to changes in speed since the yield stress of cast iron falls off rapidly with temperature in this range. The value of T_0 is therefore heavily dependent on the ambient temperature.

It is significant that Q is a notably larger fraction of the total heat generated (column five of Table I) than would be predicted by BOWDEN AND THOMAS[1] particularly if the reduction of yield stress with temperature is taken into consideration.

THE EFFECT OF THERMAL EXPANSION ON FRICTION

If we consider a system consisting of a single point of contact between two sliding surfaces, it is clear that the heat transferred away from the point will set up a temperature gradient, rising towards the point, and the resultant thermal stresses will cause the point to rise above the surrounding surface. The point will also wear and will eventually be worn down once more to the level of the surroundings. Suppose a second point, some distance from the first, is brought into contact as a result of this wear. The new point will now carry a little of the load and the heat input to the first point will be reduced. The result will be a thermal contraction of point one and expansion of point two causing an increase in the proportion of the load carried by point two. It would therefore appear that point two would shortly carry all the load and point one, being no longer heated, would contract below the surface by an amount corresponding to the total wear during the cycle. This effect has been verified by following the temperature at a point near the block surface and separating the surfaces immediately after a typical fluctuation. The surface profile was then measured and a depression of maximum depth $0.7 \cdot 10^{-3}$ in. was observed, the radius being about 0.2 in. The latter value is twice the corresponding value (120 ft./sec) in Table I but the constraint exercised by the surrounding metal would cause the depression to be shallower and of greater radius than the wear volume. It must also be remarked that the heat input over the area is probably not uniform and the values of a in Table I would be larger if a linear or parabolic distribution of heat input was assumed.

APPROXIMATE ANALYSIS

So little is known with any certainty about the friction deformation process, that it is impossible to give more than a rudimentary analysis of the growth process of such points of contact. The following assumptions will be made to obtain a solution, though the latter can only be expected to be grossly approximate.

(1) That the height (λ) of the centre of the contact area above the surface level is $\alpha \int_0^\infty T \mathrm{d}x$ where T is the temperature at a distance x from the surface on the normal passing through the centre of the area of contact. α is the coefficient of linear expansion.

(2) That the heat input is constant and uniformly distributed over a constant area.

Under these conditions λ is given by

$$\lambda = \frac{\alpha Q}{4\pi k}\left[\frac{4\kappa t}{a^2}\left(1-\exp(-a^2/\kappa t)\right) + \left(-Ei\left(-\frac{a^2}{4\kappa t}\right)\right)\right] \tag{1}$$

where κ is the thermal diffusivity, t the time and $-Ei(-z)$ is defined by

$$-Ei(-z) = \int_z^\infty \frac{e^{-y}}{y}\,\mathrm{d}y$$

and is tabulated elsewhere[2].

If we measure the total wear rate W as a velocity (the rate of recession of the surface) the amount linearly worn from the point in one cycle will be

$$w = \frac{WAt_c}{n\pi a^2} \tag{2}$$

where t_c is the duration of the cycle, A is the total area of apparent contact and n is the average number of points of contact at any one time.

It will be seen that a and t only occur in the combination t/a^2 in eqns. (1) and

(2). Further, it is evident that when $t=t_c$, $\lambda=w$ so that the intersection of eqns. (1) and (2) gives the value of t_c/a^2 and w.

APPLICATION TO AVAILABLE DATA

The value of n is taken as 2 since at least 2 points are necessary for static equilibrium.

Table II shows the values of $4\kappa t_c/a^2$, w and t_c as functions of speed. Comparison with Fig. 1 shows that t_c agrees well with the length of the rising portion of the curve.

As previously stated, the expansion and wear process gives rise to depressions in the surface and it should be possible to correlate the observed depth of these depressions with the value of w. The surface profiles showed a depth of $0.7 \cdot 10^{-3}$ in. (120 ft./sec) to $0.5 \cdot 10^{-3}$ in. (20 ft./sec). If the surrounding surface is taken as the mean surface level, this measurement agrees well with Table II.

TABLE II

Speed (ft./sec)	$\frac{4\kappa t_c}{a^2}$	t_c *(sec)*	$w \times 10^3$ *(in.)*
120	20	1.9	1.65
55	44	2.6	1.67
35	58	2.56	1.36
20	144	4.72	1.33

TABLE III

Speed (ft./sec)	*Actual wear rate* $\times 10^6$, *measured (in./sec)*	*Wear rate* $\times 10^6$ *estimated from frequency of peaks (in./sec)*
120	11.7	12.5
55	5.4	5.1
35	3.3	3.4
20	1.3	1.5

Since each cycle reduces the level of the surface by w, the wear rate should correspond to the frequency of temperature peaks at a given point. The number of peaks recorded on the 0.061 in. depth thermocouple in a period of 1000 sec, which exceeded the height of the maximum peak on the 0.109 in. thermocouple, was measured. The theory of heat conduction defines the area within which the centres of the relevant contact areas must fall, it being assumed that smaller peaks are caused by similar contacts at a greater distance from the themocouple. The wear rate calculated from these measurements is compared in Table III with the directly-measured wear rate.

A statistical error is inherent in the estimated value since the individual point may not begin and end the test at the same height relative to the mean level of the surface.

It would certainly appear that the thermal distortion mode is responsible for most of the wear in the system.

It very often happens that a temperature peak is closely followed by a subsidiary peak (see Fig. 1). Also, those thermocouples situated beneath points advanced in the direction of sliding, often show a peak shortly after those "upstream". It is proposed that these phenomena may be caused by a build up of metal due to the tangential stress[3] and/or the accumulation of wear particles[4].

CONCLUSIONS

The thermal distortion of the sliding surfaces appears to offer a plausible explanation for observed temperature fluctuations and is in reasonable agreement with certain numerical checks. Some reservations, however, must be maintained about the quantitative predictions in view of the imperfect knowledge of the heat-generation process and the assumptions necessary to achieve a solution. It is hoped to carry out more fundamental experimental work to confirm and refine the theory.

If we accept the basic mechanism of the process two consequences follow immediately.

(1) That the friction and wear characteristics of two flat surfaces are determined by the behaviour of a small number of areas of contact (probably equal in number to the degrees of freedom of the system) caused by thermal distortion of the surface. One would expect these characteristics to be influenced by thermal expansion coefficients as well as the mechanical properties at high temperatures.

(2) That the large-scale surface roughness is determined by the combined action of thermal expansion and wear. This offers an explanation for the fact that sliding surfaces eventually adopt a surface roughness which is independent of the initial conditions.

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