DISCUSSION

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The question of temperature at the contact interface in a sliding system is an extremely important one and, as the authors have pointed out, the measurement of such temperatures is extremely difficult. Generally, only a rough estimate of the true surface temperature can be made. Numerous attempts in the past have resulted in only varying degrees of success.

The experimental arrangement which the authors have used represents a unique approach. It must be realized, of course, that the experiment has been designed to provide for two-dimensional heat flow and this must be kept in mind if the results are to be applied to a practical sliding case in which the heat flow is three-dimensional. Also, as the authors pointed out, the temperatures which they determine are not necessarily those at the contacting asperities but rather represent an average value. I should like to ask the authors if they have calculated the apparent pressure in their contact and whether or not this approaches the yield pressures of the contact materials. In other words, I question whether the apparent area of contact and the real area of contact are identical.

It is somewhat surprising that a temperature difference across the interface is obtained. In previous analyses an interface temperature common to both solids has been assumed. On the other hand, one can think of several reasons why there might be a temperature difference in the two materials in the close vicinity of the contact. For example, a given area on the disk slider is heated only intermittently and at a rate depending on the speed of rotation of the slider. On the other hand, the rider is essentially in constant contact and can be considered to be heated continuously. In view of this fact it is somewhat surprising that the authors obtain a constant temperature throughout the contact area for the slider and yet a variation in temperature throughout the contact area for the rider. If the temperature distribution along the rider contact does not vary with successive passes of the disk, either a waviness in that surface is indicated or the presence of surface films which can modify considerably the conduction of heat into that surface. Did the authors use new surfaces for each of the three loads reported or were these results obtained with the same run-in surfaces? I note that the temperature distribution as given by Fig. 6 is different for each of the three loads.

Another question is whether or not the authors have compared their results with previous surface temperature calculations such as those of Jaeger [4],[5] Blok [5], and Archard [6]. It is realized, of course, that those calculations include speed as one of the variables and this has been kept constant purposely in the present work.

Finally, I should like to mention a technique which might be used to check independently the temperature reached at the contact interface. This is based on the findings of Bowden and Williamson [7], and Greenwood and Williamson [8], in which the passage of current through a solid contact constriction results in temperatures which can be correlated with structural transitions taking place in the contact material. The latter transitions are determined by microscopic examination of the cross-sectioned contact after passage of the current. It is true, of course, that the temperatures reached are greater than the ones given by Ling and Simkins. Nevertheless, it may be possible by suitable choice of metals and alloys and also by the rubbing conditions to produce surface temperatures high enough for certain phase transitions to occur. This can provide a check, therefore, on the temperatures as determined by the combined experimental and theoretical analyses as described by the authors.

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[5] Numbers in brackets designate Additional References at end of this discussion.

Additional References

4 J. C. Jaeger, *Proceedings Royal Society* N.S.W., vol. 56, 1942, p. 203.

5 H. Blok, General Discussion on Lubrication, London, *Institution of Mechanical Engineering*, vol. 2, 1937, p. 222.

6 J. F. Archard, *Wear*, vol. 2, 1959, p. 438.

7 F. P. Bowden and J. B. P. Williamson, *Proceedings Royal Society*, vol. A246, 1958, p. 1.

8 J. A. Greenwood and J. B. P. Williamson, *Proceedings Royal Society*, vol. A246, 1958, p. 13.

Authors' Closure

The authors wish to thank Dr. Flom for his thoughtful discussion. The suggestion to render further checks by correlation between temperatures and structural transitions of the contacting materials is an inviting one; while the authors are aware of this possibility, they have not yet attempted such a task.

Perhaps the authors have introduced an unnecessary ambiguity by mentioning the yield pressure. What is important to the success of the experiment is that the contacts should be at least a line contact on the macroscopic scale in the direction of the axis of the disk. Whether there is one line or more should be revealed indirectly by the nature of temperature distributions. One of the distinguishing features of the approach is to let the heat input be arbitrary within the framework of two-dimensionality; and the solution of the heat equation appropriate to this condition is used. It should be noted that no other assumptions were made for the purpose at hand. To answer Dr. Flom's first question now, within the macroscopic scale and on the one or more line contacts, the apparent area and the real area of contact are identical.

Since the presentation of this paper, a new paper has been written upon further experimental work which resulted in more refined data and further analysis on the probable temperatures at the asperity tips.[6] On the macroscopic scale the cause of the temperature jump is established as the following: Heat is generated on one or both of the surfaces in sliding contact and not at the interface exactly. Depending on the capacity of the sliding members to remove heat, a function of geometries, and so forth, heat must be transferred from one surface to the other in general. Since the surfaces are not smooth and contacts are not continuous on the microscopic scale, there is a thermal resistance to this transfer of heat and hence the jump on the macroscopic scale. Thus the conjecture advanced in the paper about heat having to move from one surface to the other by convection and radiation is quantitatively established.

It is not really surprising to find that the surface temperature of a disk is essentially constant on physical grounds. For the Peclet number, which is the ratio of the sliding velocity to the velocity of dissipation of heat so to speak, is high and "all" the heat has to be removed from the peripheral in this mechanical model. To be sure, the authors mentioned that the temperature is constant within some 3 percent. Table 3 shows quantitatively that small percentage which was neglected for another calculation which should be of interest at this point (also see Fig. 2, reference [3], for more detail): Equations (8) and (9) are matched at the interface for $N = 32{,}700$ with $U \equiv 2\pi hT/q_0$. U_0 was found to be 471×10^{-4}.

Finally, it is to be noted that the heat-transfer theory within the body is known since the pioneering work of Fourier (1812), Poisson (1823), Duhamel (1832), and others, but the solutions of boundary value problems using the heat equation have been accumulating with the passage of time; in particular, the solutions used for the present geometries are new within the last year [3]. As to Jaeger's solution [4], it is a different form of parts of Blok's solution [5] of the heat equation which deals with a

[6] F. F. Ling and S. L. Pu, "Probable Interface Temperatures of Solids in Sliding Contact," *Proceedings of a Conference on the Fundamental Mechanisms of Solid Friction*, to appear as special issues of *WEAR*.

Table 3 $(U - U_0)$ versus angular position within the contact zone

Angular position[a]	U-U_0
$-\pi/18$	5.5×10^{-4}
$-\pi/24$	6.0
$-\pi/36$	3.5
$-\pi/72$	1.5
0	0.2
$\pi/72$	−1.5
$\pi/36$	−2.8
$\pi/24$	−5.5
$\pi/18$	−8.4

[a] Positive $\pi/18$ denotes the leading edge.

band source moving along a semi-infinite solid. As such, the solution does not apply in the present case since the boundary conditions are different. First of all it assumes that the material is at ambient temperature before coming to the contact zone; this is not the case for bodies which become repeatedly heated. To illustrate this point, the two-dimensional heat conduction theory with respect to a constant moving frame is ($\partial^2T/\partial x^2$ being negligible for high Peclet number)

$$\partial^2T/\partial z^2 = k^{-1}\partial T/\partial(x/V) \qquad (10)$$

where T is the temperature above a constant ambient, x is the coordinate parallel to the surface, z is perpendicular to it, k is the thermal diffusivity, and V is the velocity of movement of the frame. From theory of equation of the type (10), as $z \to 0$, i.e., on the surface, Ling has shown [1] that

$$T = \begin{cases} (k/\pi V)^{1/2}K^{-1} \displaystyle\int_{-l}^{x} q(x')(x - x')^{-1/2}dx' & (-l \leq x \leq l) \\ 0 & (-l < x) \end{cases} \qquad (11)$$

where K is the thermal conductivity and q is the heat distribution between $-l \leq x \leq l$. Now for $q = q_0 =$ constant, equation (2) integrates into

$$T = \begin{cases} 0 & (-\infty < x < -l) \\ q_0(k/\pi V)^{1/2}(2K)^{-1}(x + l)^{1/2} & (-l \leq x \leq l) \\ q_0(k/\pi V)^{1/2}(2K)^{-1}[(x + l)^{1/2} - (x - l)^{1/2}] & (l < x < \infty) \end{cases} \qquad (12)$$

This is the same as Blok's 1937 results which took several pages to derive and compute numerically; of course Professor Blok will agree that Ling has the advantage of the passage of 22 years between the appearance of the papers.

As to the rest of Blok's pioneering work the assumption of no temperature jump at one point is made; certain improvements have been made in 1957.[7]

The difference between the 1957 paper and Archard's 1959 paper [6] is that Archard has made the available solution more readily usable by:

(*a*) Breaking up the solutions to small and large Peclet number; and

(*b*) Calculating areas of contact on the basis of elastic and plastic mode of deformation.

As such he showed simple formulas for various combinations of (*a*) and (*b*). The fact remains, however, that basically the underlying solutions used were for the semi-infinite solid (both the stationary and the moving one) heat input on both surfaces are constants and that the temperatures are matched at one point only.

[7] F. F. Ling and E. Saibel, "Thermal Aspects of Galling of Dry Metallic Surfaces in Sliding Contact," *WEAR*, vol. 1, 1957, pp. 80–91.