20 Lauer, J. L., and Peterkin, M. E., "Infrared Emission Spectra of Elastohydrodynamic Contacts," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 98, 1976, pp. 230–235.

21 Ausherman, V. K., Naqaraj, H. S., Sanborn, D. M., and Winer, W. O., "Infrared Temperature Mapping in Elastohydrodynamic Lubrication," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 98, 1976, p. 236.

22 Kannel, J. W., Zuqaro, F. F., and Dow, T. A., "A Method for Measuring Surface Temperature Between Rolling/Sliding Steel Cylinders," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 100, 1978, pp. 110–114.

23 Abdel Ghany, A. A., "Elastohydrodynamic Behavior of Rolling Contact Surfaces," Ph. D. thesis, Cairo University, Faculty of Engineering, 1983.

24 Mokhtar, M. O. A., and Abdel Ghany, A. A., "Developed Experimental and Measuring Techniques for Elastohydrodynamic Investigations," (to be published).

25 Mokhtar, M.O.A., and Abdel Ghany, A. A., "Elastohydrodynamic Behavior of Rolling Elliptical Contacts: Part II: Oil Film Thickness and Contact Profile," a complimentary paper to be presented in same ASME/ASLE conference, Paper No. 84-Trib-25.

26 Hertz, H., "Contact of Elastic Solids," English translation in *Miscellaneous Papers*, Macmillan Company, London, England, 1896, pp. 146–183.

27 Murch, L. E., and Wilson, W. R. D., "A Thermal Elastohydrodynamic Inlet Zone Analysis," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 97, 1975, pp. 212–216.

28 Herrebrugh, K., "Elastohydrodynamic Squeeze Films Between Two Cylinders in Normal Approach," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 92, 1970, pp. 292–302.

29 Chiu, Y. P., "An Analysis and Prediction of Lubricant Film Starvation in Rolling Contact Systems," *Trans. ASLE*, Vol. 17, No. 1, 1974, pp. 22–35.

30 Kannel, J. W., Zugaro, F. F., and Dow, T. A., "A Method For Measuring Surface Temperature Between Rolling/Sliding Steel Cylinders," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 100, Jan. 1978, pp. 110–114.

31 Dowson, D., and Higginson, G. R., *Elastohydrodynamic Lubrication*, Pergamon Press, Oxford, 1966.

32 Cheng, H. S., "A Numerical Solution of the Elastohydrodynamic Film Thickness in an Elliptical Contact," ASME JOURNAL OF LUBRICATION TECHNOLOGY, Vol. 92, 1970, pp. 155–162.

DISCUSSION

M.M.A. Safa and P. B. Macpherson[1]

The authors should be congratulated for their attempt at studying the EHD elliptical contact, using thin film microtransducers, at such highly loaded conditions. The achievement of 5.6 μm width transducers using a masking technique is also praiseworthy. However, the length of the transducers used is not mentioned in the publication. This point is of considerable interest in studying the point or elliptical contact as a long transducer would average out the pressure along the major axis of the ellipse where, unlike line contact, the pressure would vary substantially. It might be of interest to know that the discussers have developed a technique by which these thin film transducers are made up to a size of 2 × 5 μm (further reduction is also possible), using a laser milling technique. This technique obviates the need of any mask and can produce transducers with very small gaps between them.

One of the most interesting features of the pressure profiles presented by the authors suggests that the primary peak pressure within the contact could exceed the maximum Hertzian pressure by a substantial amount. In our experience of studying line contact in a disk machine [33] we found the measured primary peak pressure to be close to the calculated maximum Hertzian pressure. Thus it was decided by the discussers to set up a simple EHD circular contact experiment and check whether the same holds for point contact. The sliding EHD contact was formed between a rotating steel ball of 2.54 cm in diameter and a fixed glass plate under load (the discussers happen to be working with the rig to study squeeze film lubrication process using thin film micro transducers). A 10 μm × 10 μm calibrated transducer, fabricated on the glass plate, was slowly passed through the contact zone, while being observed through a microscope. The signal generated by the transducer was recorded in a digital storage oscilloscope. The result shows the maximum recorded pressure within the contact to be about 10 percent less than the maximum Hertzian pressure calculated for the geometry and the materials involved. However, this simple experiment is not directly comparable to the authors results. It would still be interesting to know how the authors have calibrated their pressure transducers or the pressure profiles and whether the temperature coefficient of the pressure transducers was relatively high.

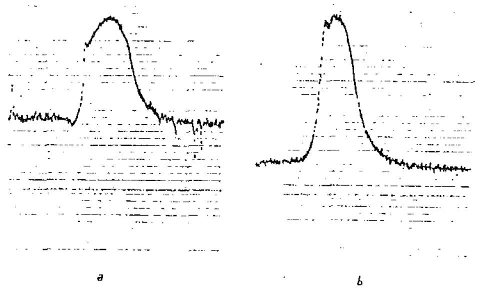

Fig. D1 Effect of temperature rise within the contact on unannealed pressure transducer. Trace (a) at higher load and pure rolling condition, (b) low load and sliding condition.

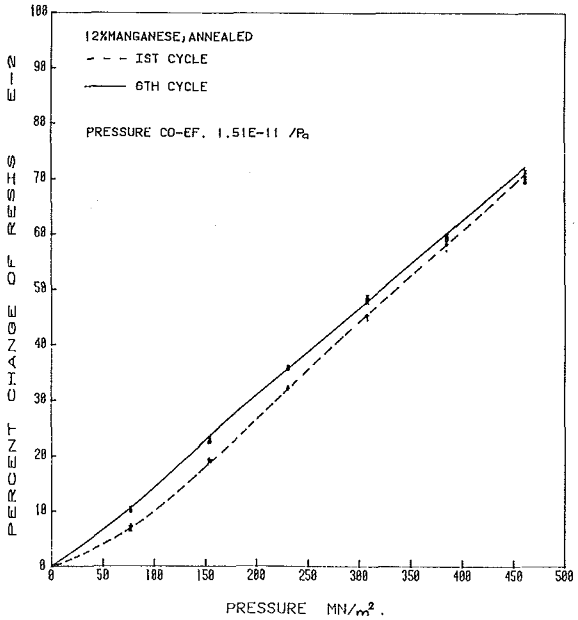

Fig. D2 Pressure coefficient of resistivity of thin film of manganin; first few pressurisation cycles

It is of interest to compare some of the results obtained by the discussers, in studying line contact, with those of the authors. The pressure profiles recorded by the authors suggest similar problems to those encountered by the discussers in their early stages of development of the microtransducers, namely high temperature sensitivity of the deposited manganin film and change in the material property of manganin in thin film form, which gives rise to an effect similar to negative pressure at the inlet or the exit zone of the present profiles.

Figure D1. shows two pressure profiles recorded by the discussers with one of their early devices. The traces were recorded under similar loads, however, trace "*b*" was recorded under sliding conditions. This caused a higher temperature rise within the contact which, in turn, produced a much larger signal level than in trace "*a*" which was recorded under pure rolling conditions. It was found that manganin

---

[1] Westland Helicopter Ltd., Yeovil, Somerset, England.

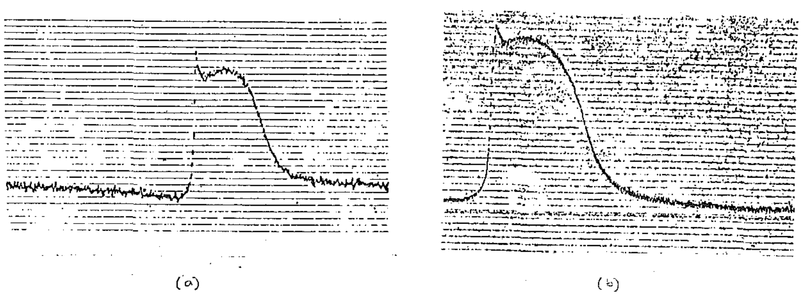

Fig. D3 Effect of zero level shift on the exit side is apparent in trace 'a' which was recorded with an unannealed transducer. Trace 'b', recorded with a different transducer, does not show that shift.

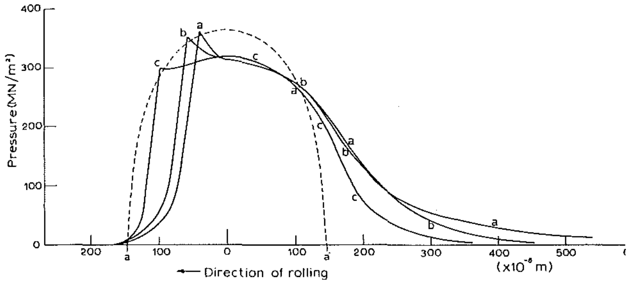

Fig. D4 Pressure profiles recorded with 10μm device, using oil2, at a fixed load of 0.0834 MN/m and surface velocities of (*a*) 0.75, (*b*) 1.73, and (*c*) 3.6 m/s

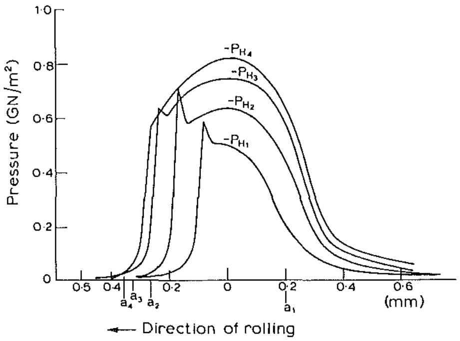

Fig. D5 Pressure profiles recorded with 10μm device, using oil2, at a surface velocity of 3.7 m/s and loads of (*a*) 0.167, (*b*) 0.278, (*c*) 0.417, and (*d*) 0.5 MN/m

film deposited by flash evaporation could have a temperature coefficient of resistivity as high as $2 \times 10^{-3}/°C$. This can be reduced to a value of up to $5 \times 10^{-5}/°C$ by proper flash evaporation (using minute particles under steady feed) in high clean vacuum and then annealing. Annealing also improved the resistivity of the manganin film from 150 to about 60 μrcm (bulk value 44 μrcm). The pressure coefficient of resistivity of manganin (in the bulk form $\sim 3.5 \times 10^{-11}$/Pa) also changes in the thin film form, however, properly flash evaporated film retains the linearity as can be seen in Fig. D2. The test was carried out in a specially designed hydrostatic pressure vessel. The pressure coefficient of thin film manganin was found to vary from deposition to deposition. The variation generally remained within the range of 0.3 to 0.5 of the bulk value.

Figure D3 presents two pressure profiles recorded with two different transducers. Zero level shift is apparent at the exit side of trace "*a*." which recovers back to proper zero level with a short distance. The reason for this zero level shift is not clear, one possible reason could be the shear stress sensitivity of some deposited manganin film. Again proper flash evaporation and subsequent annealing help to remove this effect as can be seeen in Fig. D3. b.

The pressure profiles presented by the authors in Fig. 5 at skew angle zero show the presence of the secondary pressure peak. However, even at high load the secondary pressure peak tends to merge with the primary pressure peak. One would expect the secondary peak to move toward the exit side and become distinct from the primary peak at the high load and moderate surface velocity and viscosity operating condition used by the authors. In Fig. D4 a set of pressure profiles recorded by the discussers at a fixed load is presented. This set shows the movement of the secondary peak and the change in the inlet pressure development zone with surface velocity.

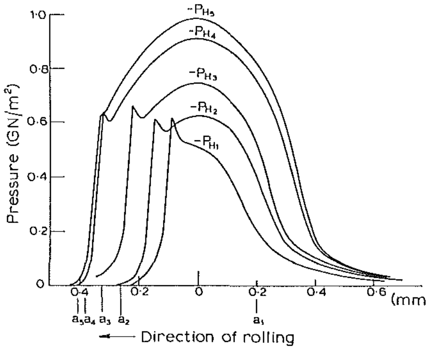

Fig. D6 Pressure profiles recorded with 10μm device, using oil2, fixed surface velocity of 5.4 m/s and loads of (*a*) 0.167, (*b*) 0.278, (*c*) 0.417, (*d*) 0.58, (*e*) 0.667 MN/m

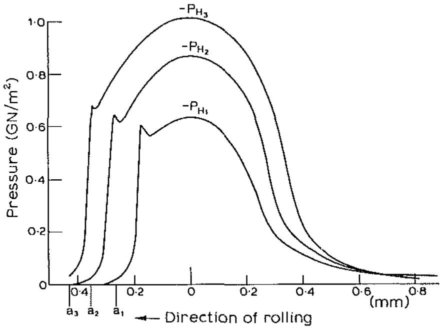

Fig. D7 Pressure profiles recorded with 10μm device, using oil2, at a surface velocity of 7.4 m/s and loads of (*a*) 0.228, (*b*) 0.5, and (*d*) 0.723 MN/m

In Figs. D5, D6, D7, three sets of pressure profiles are presented. Combined, these sets show the effect of load and surface velocity on the pressure profiles in general. In studying the height of the secondary pressure peaks from these experimentally obtained traces, one must remember that it is limited by the finite width of the transducer and the frequency response of the electronic circuitry involved. In general it was found that the secondary peak moves towards the exit side with increased load and reduced surface velocity, and it also becomes narrower. As a result, the finite width transducer could not resolve the secondary peak at 5 mn/m load and 3.7 m/s surface velocity, but as the velocity is increased to 5.4 m/s the same device could resolve the peak at

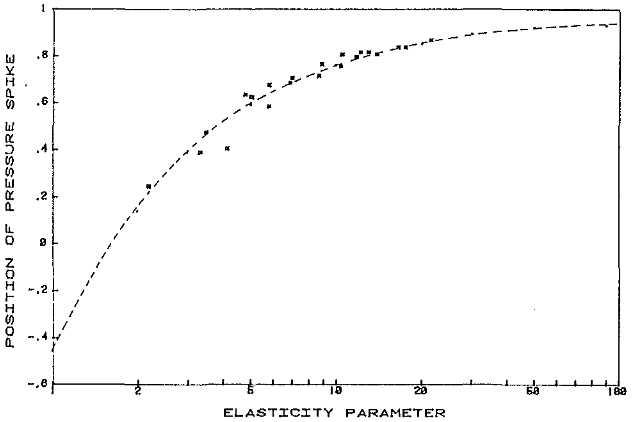

Fig. D8 Variation of the relative position of secondary pressure peak, x/a, with logarithm of nondimensional quantity g, oil2

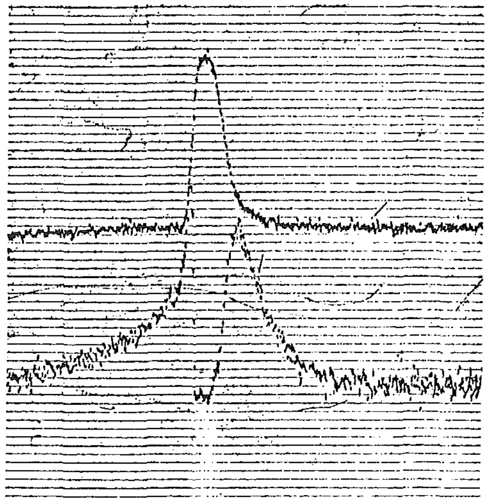

Fig. D9 Signal generated by a set of synchronized pressure and temperature transducers

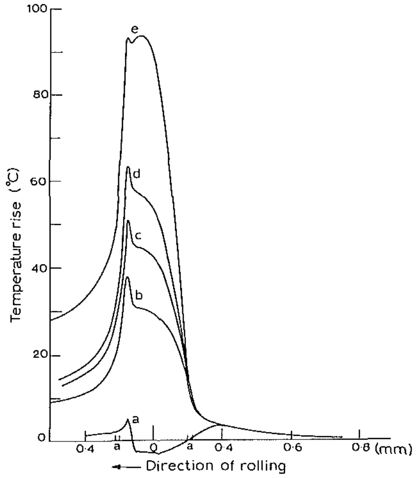

Fig. D10 Temperature profiles at a fixed load of 0.222 MN/m (*a*) pure rolling at 4 m/s, (*b*) partial sliding 4:3.06 m/s, (*c*) partial sliding 4:2.5 m/s, (*d*) partial sliding 4:2 m/s, (*e*) partial sliding 4:0.62 m/s

even 0.58 MN/m load. In Fig. D8 the position of the secondary peak is presented against the nondimensional parameters g3 and, as can be seen, the pattern follows K. L. Johnsons [34] prediction wall.

The temperature transducers fabricated by the authors seems to have worked well. However, on the exit side the temperature decayed to ambient even when there is still some detectable pressure remaining. In our experience with line contact we observed that on the exit side temperature decays slowly over a long distance by which time the contact pressure becomes undetectable.

We developed a technique of fabricating synchronised pressure/temperature and pressure/oil film thickness transducers with an alignment accuracy of less than a few microns. Fig. D9 shows a pressure and a temperature profile produced by such a set of transducers undergoing pure rolling condition. We used titanium as temperature sensor as it has the advantage of extremely good adhesion. The temperature transducer however is also sensitive to pressure and as a result the signal generated by the temperature transducer shows the combined effect of temperature and pressure. Thus at the point where the pressure effect becomes more prominent the profile shows the change in direction. The pressure effect could, however, be corrected by using the accompanying pressure transducer signal and knowing the pressure coefficient resistency of titanium transducers. The advantage of titanium shows up in sliding condition, as these devices could withstand large slide to roll ratio under large load and thinner oil film. Figure D10 shows a set of temperature profiles recorded under various slide to roll ratio. The trace under pure rolling after correction indicates a temperature of about 15°C. The apparent formation of the secondary pressure peaks in this set of temperature traces occurs due to the interactic between rapid pressure drops.

Description of Oils Used

Oil	Type	Viscosity at Temp.	Pressure Viscosity Coefficient
1. SAE 90	Mineral	0.0168Pa.s at 99°C 0.231 Pa.s at 38°C	$2\times10\,\text{Pa}^{-1}$
2. Special Mixture	Mineral	0.0125Pa.s at 99°C	$3.05\times10\,\text{Pa}^{-1}$
3. AST0555	Diester	0.00125Pa.s at 99°C 0.039 Pa.s at 30°C	$0.95\times10\,\text{Pa}^{-1}$

Additional References

33 Safa, M. M. A., "Elastohydrodynamic Studies Using Thin Film Transducers," PhD thesis, London University, 1982.

34 Johnson, K. L., *Journal of Mechanical Engineering Science*, Vol. 12, 1970.

J. W. Kannel[2]

It was great fun to see Mokhtar and Abdel's papers on EHD contacts and to remember the days when EHD research was the in thing. Not much has been done in the last few years and it is encouraging to see some renewed interest in the area. The paper covers many aspects of the old EHD discussions including discussion of the existence of the pressure spike and discussions of the validity of the X-ray data in contrast to theories. In general, it would seem that the authors data tend to confirm that X-ray measurements, capacitance measurements, and properly most theories all tend to agree with each other with the admittance that data scatter is reasonable in these kinds of study.

I am not particularly impressed with the author's pressure data. In general, our pressure data at load levels much in excess of 1.2 GPa tend to agree with the Hertzian pressure distribution much better than the authors. I suspect that the author's technique tends to cause an unnatural perturbation to the pressures at the transducer contact. Would the authors comment on this? Specifically, have the authors made surface profile measurements of the surfaces containing the transducers to ascertain that the transducers are not overly perturbing the surface shape?

---

[2] Battelle Columbus Laboratories, Columbus, Ohio 43201.

Unfortunately, the authors do not present detailed discussions of the temperature measurements. Temperature studies may be the last frontier in EHD and much work is needed to understand the role of thermal effects on the lubrication process. The authors say their measurements agree well with the measurements at Battelle. Could they be a a little more specific? How well do the two sets of measurements agree and under what conditions? Could the authors comment on their interpretation of temperature data with regards the EHD process?

Authors' Closure

The authors appreciate the generous comments and discussions of Dr. Safa and Dr. Macpherson about the EHD measuring techniques and results herein presented.

As regards the calibration of the manganin pressure transducer, it has been found that the use of preassigned pressure electric resistivity coefficient is unreliable, as the discussors also claimed, as it may vary from deposition to another. Hence, direct correlation between the applied load and the attained pressure trace was computed for each test results. The integration of the pressure traces, as proposed earlier [15], was related to the applied load on the disks. This had been carefully executed by numerical computations to predict the pressure ellipsoid from the attained pressure traces. Then, by integrating the pressure along the measured contact area and equating the resultant force to the actual applied one, the exact pressure scale could be assigned. Careful attention has been given to the exact determination of the points terminating the pressure wave and the corresponding extent of the contact. However, the near Hertzian pressure values attained by the discussors may be attributed the extended pressure profile prior to oil inlet and possibly due to the difference in tests configurations.

The authors would like also to thank Dr. Kannel for his interest and comments on the present work.

Dr. Kannel and his respectful colleagues had performed some interesting EHD measurements [15, 17, 22]. Although their experimental studies were confined to line contact situations, the general features of pressure profiles are in qualitative agreement with the present findings under elliptical contacts. Meanwhile, the authors were fully aware of possible surface perturbations. The problem of perturbation, which would be more liable in case of surface coating of rolling disks with the evaporated manganin band as described earlier [15], has been solved by the authors by depositing the transducer band in a narrow slit on disk surface.

As regards temperature measurements and thermal effects on EHD regimes, the authors agree well with Dr. Kannel that this subject is still in need for further work.