DISCUSSION

Kazuhisa Miyoshi

In many electrical and electronic devices, electrical resistance of an interface is important in determining the electrical, the mechanical, and the economic viability of a particular tribological system. In addition to the study on the functioning of electrical contacts, electrical resistance measurements of metallic interface are considered and used to study the real area of contact between metals, both stationary and sliding surfaces. For this reason a great deal of effort attempted by the authors to gain further insight in the complex phenomena of friction and electrical resistance is a very welcome contribution to the field of tribology.

The difficulty with friction, wear and electrical resistance studies is that in most practical situations the conditions at and below the sliding interface are very complex. Apart from those operating in outerspace, in high vacuum, or at elevated temperatures, the friction may vary relatively little from one environment to another, while the wear may vary by factors of a thousand or more. In this connection, the following questions may be raised:

1. Have the authors systematically observed the formation, transfer, or release of wear fragments (metallic fragments and/or oxide fragments) in this study? Do the authors intend to investigate the effect of wear fragments themselves on the friction, wear, and electrical resistance and noise in air, argon, and carbon dioxide environments?
2. What degree of surface contamination and thin oxide films can markedly affect electrical resistance and noise during sliding?
3. Do the authors think that the influence of work-hardening or work-softening (i.e., formation of deformed layers on the wear surfaces due to the shearing process) can be seen on electrical resistance and noise?

Authors' Closure

The authors wholeheartedly concur with the observations made by Kazuhisa Miyoshi regarding the importance of the electrical contact resistance and electrical noise for the performance of electronic devices as well as for a tool for the study of interfaces at rest or in relative motion. They similarly agree with his assessment of the great complexity of the interfacial processes during friction and wear, as also that, not infrequently, the magnitudes of the coefficient of friction and of the wear rate bear no known relation to each other. Since much of the authors' work is concerned with gaining fundamental understanding, they concentrate on correlated measurements and observations of an as wide range of entities as possible. It is for this reason that in the present paper interconnections are sought between the electrical resistance, the electrical noise, the coefficient of friction, and the time of exposure to different ambient gases, both for stick-slip and continuously sliding couples. We believe that the results justify this approach in that more detailed conclusions could be drawn than would have been possible with any of the measurements by themselves, or with a smaller set of correlated measurements.

Even so, it will be desirable to still add to the arsenal of correlated investigative methods brought to bear in such studies. In fact, in our laboratory a novel apparatus is nearing comple-

tion in which single contact spots can be studied by means of the crossed-rods geometry and, if desired, using foil samples which are amenable to interments and/or post-hoc microscopical investigation, especially through TEM and SEM electron microscopy [26]. Furthermore, in order to permit studies relevant to behavior in space, the hoop apparatus is presently being modified to permit operation at reduced pressures, down to a low-level vacuum, probably of some $10^{-3}$ Torr. Finally, measurements are increasingly supported by correlated computations of the flash temperature, (e.g., references [27 and 28]).

The very limited evidence available so far on the question of tribology at elevated temperature indicates that the critical parameter is the momentary temperature at the contact spots. So far it appears as if it is immaterial whether the contact spot temperature is controlled via the ambient temperature, e.g., in an oven, or through input of friction and Joule heat at low ambient temperature. However, much more research will have to be done, and is planned.

As to the specific points raised by K. Miyoshi, the following responses:

1. We have not yet made systematic investigations of the formation, transfer or release of wear fragments beyond those reported in reference [17]. In that study no attempt was made to determine the electrical resistance at the same time that the wear occurs, but it is known that this resistance is very low, i.e., in the order of some tenths of milliohms. This is not surprising since metallic wear fragments were formed and wear was rather fast. In the hoop apparatus, and as reported in the present paper (see middle of point 4 of the "Summary and Discussion"), it is observed that wear raises the electrical resistance as well as the noise level. Specifically, if after some sliding time a clean paper tissue is pressed against the wear track, a dark smudge is transferred to the tissue paper and the noise drops discontinuously. More work in this important area of research is planned for the future.

2. Even very thin surface layers can do markedly influence the contact resistance and noise. Thus the thickness of the oxide layer causing the much higher resistance and noise in air as compared to argon and carbon dioxide (Fig. 1) was estimated at about 60 Å, whereas the surface films in argon and CO₂ were probably only about 5 Å thick (see middle of left column under Fig. 2).

3. We do not believe that one can detect the effect of workhardening in the subsurface layers on contact resistance: Those layers are rarely thicker than 0.1 mm and the electrical resistivity is typically raised by less than a factor of two between the annealed and most severely workhardened state. The correlated film resistivities would thus appear to be in the order of $10^{-10}$ Ω m², at most. In general, the effect would be through the constriction resistance, raising it in proportion with the increase of electrical resistivity through workhardening. In the present paper constriction resistance is negligible on account of the large number of contact spots, in any event.

Additional References