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**INTEGRATED FUNDAMENTAL RESEARCH
ON CURRENT COLLECTION**

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INTEGRATED FUNDAMENTAL RESEARCH ON CURRENT COLLECTION

Reporting Period February 1989 to September 1992

INTRODUCTION

The aim of our research has been to add to basic understanding in the area of current collection with particular emphasis on topics likely to benefit practical objectives. Under sponsorship of this contract twenty three papers were published in the international literature, as listed in the last section. Additionally, thirteen invited lectures and eleven contributed lectures on various aspects of this research were delivered at Universities, Research Laboratories and International Conferences by the Principal Investigator and co-workers. Last not least, development of a novel metal fiber material for sliding electrical contacts has been continued with much success. This is expected to become very useful for making metal fiber brushes for homopolar motors/generators as well as for EML armatures. By any objective measure, the results of this program have been valuable.

PRINCIPAL RESEARCH TOPICS AND RESULTS

Studies on the Behavior of Adsorbed Layers and Lubricants on Sliding Interfaces (Nos.1,4,6,10,12,13,14,16)

From research in our own laboratory (see No.19 in the reference section) it had been known for more than fifteen years that under "clean" conditions in the atmosphere, there are two monolayers of water between the contact spots of sliding metals. The importance of these layers for inhibiting cold-

welding and thereby disastrous wear rates had been clearly recognized, as also the fact that those two monolayers of water provide the theoretically lowest possible film resistivity for sliding contacts, namely $\sigma = 10^{-12} \Omega.m^2$. It had therefore been clear for many years past that the maintenance of those two monolayers of adsorbed water are critical for the good performance of unlubricated sliding metal contacts. However, it was seemingly mysterious how these could be present so reliably, provided only that adequate moisture levels were maintained and chemical attack by other gases, e.g. of oxygen on copper was avoided, seeing that the thickness of adsorbed moisture on the free surfaces varies widely with humidity.

The research of these past three years has answered that question: If adsorbed fluid films are squeezed out under pressure, they order into parallel layers once their thickness is reduced below several nanometers. From then on, increasing pressure squeezes the fluid layers out stepwise. Now, all but the last two layers are expelled by pressures prevailing at typical contact spots, i.e. comparable to that of the hardness of the softer of the two contacting materials, while those last two layers cannot be expelled even at very much larger pressures.

Refs. 1, 6, 10, 12, 13, 14 and 16 present the above facts and discuss numerous related effects of adsorbed moisture on the behavior of sliding contacts. Specifically examined were, among others, (i) the contribution to sliding friction made by the adsorbed moisture layers as a function of load and sliding speed, (ii) the small, gradual increase of the film thickness at contact spots with sliding speed which yet results in a significant increase of the film resistivity σ and thus the contact resistance and (iii) stick-slip, which is a quite frequent by-product of those layers.

Publication 4 concerns graphite lubrication of metals. That is critical, of course, for the widely used electrical brushes made of compacted mixed metal and graphite powders. The functioning of that

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graphite lubrication, too, strongly depends on moisture. That is known since WW II, because electrical brushes made of graphite "dust" and become abrasive, unless a minimum of moisture is available, which became a serious problem in high-flying aircraft and in space applications. Yet the mechanism by which moisture facilitates graphite lubrication was unknown. #4 documents that this comes about through adsorption films at the basal planes of graphite (as well on metals in accordance with the previous paragraph) as follows:

The adsorbed moisture lowers the surface free energy of the basal plane of graphite so that it becomes shearable at stresses typically lower than the shear strength of the lubricated metals, while without adsorbed moisture the stress necessary to shear the graphite is substantially higher than for the metals. Further, adsorbed moisture films on graphite and on metal bond together so that the graphite adheres to the metal. In the presence of adsorbed moisture, therefore, the contact spots of metals are protected by graphite layers which in the course of sliding shear into ever thinner lamellae, much like a pack of playing cards. Only when thus the graphite layer at any particular contact spot has become very thin will the underlying metal shear, too. Thereby fresh metal surface becomes exposed to which fresh graphite adheres and the process repeats. The result are "pads" of very thin alternating layers of graphite and metal which form the bulk of the wear debris that can be collected and from the analysis of which the above process was inferred. In the absence of moisture, however, the graphite is harder than the metal and does not cling to it but abrades it. A certain amount of metal abrasion takes place in any event through graphite particles which accidentally become embedded in the metal surface with their basal plane nearly normal to the interface. These act much like the cutting tool in a lathe and produce characteristic slivers of metal wear debris. - A summary of this work is also contained in ref.19, an invited paper on the occasion of the Holm Achievement Award to the Principal Investigator.

Studies on the Sub-Surface Deformation of Materials at Sliding Interfaces (Nos.2,3,5,7,8,15,17,18,20,21,23)

An extremely important aspect of sliding electrical contacts is wear. Even the best electrical brushes in regard to electrical performance will not be acceptable if their wear life is too short, and this is a particular challenge for metal fiber brushes, the focus of interest in this project, since they are unlubricated. A better theoretical understanding of the processes which give rise to unlubricated wear is therefore urgently needed. Central here is the generally accepted fact that wear under such conditions arises from sub-surface deformations at and about the contact spots. Our own research has shown that to a first approximation and certainly before the formation of any particular tribo-surface films, this sub-surface deformation is the same as that which takes place in bulk under similar conditions of stress and strain. In fact, based on this insight one may deduce the distribution of sub-surface stresses in worn samples from the microstructure (see reference No. 2).

From the above set of circumstances derives the interest in this project for expanding the understanding of correlations between microstructure and plastic deformation in general (Nos. 3, 15, 17), and in particular for multi-slip and large deformations (Nos.7, 8, 18, 20), as well as for high strain rates (No.5), since these conditions are characteristic for the sub-surface strains of tribological samples. Another correlated interest is in the involvement of very thin layers of contaminants which may become trapped at the contact spots, e.g. of adsorbed water or oxygen. According to a quite recent discovery (Nos.21 and 23), such layers can greatly add to the strength of a material but also cause worksoftening, i.e. an instability. It may be noted here that the numerous publications referred to in the present section have not added significantly to the cost of the project but are more of a kind of bonus since almost no salary support was involved.

Studies on Optimal Running of Electrical Brushes (Nos.9,11,19,22)

For the practical success of electrical brushes a number of conditions have to be met. The impact of theory in achieving success in meeting some of these is contained in paper No.19. First and foremost, electrical brushes should be non-toxic, have low electrical bulk and contact resistance, have adequate wear life, and be applicable at low enough loads that they do not damage the slip-ring and do not cause large amounts of friction heat. Depending on conditions they should have resistance to incidental contamination of the running surfaces, adapt to reversal of running direction, be capable to be run at high speeds and/or be capable of running on commutators.

A wide range of tests with detailed data collection and preferably extending over days or weeks is required to assess those various aspects of brush performance. Papers 9, 11 and 22 relate to such testing. Specifically, No.11 describes a system for long-term brush testing in controlled atmospheres, including pre-programmed changes of speed and current strength, with automatic data collection on resistance and wear. A considerable part of the whole effort under this project has been spent on developing that system of which we now have two mildly different versions in our laboratory. These testers are invaluable and without them much of our work would have been virtually impossible. Albeit, Paper No.9, which establishes the ability of metal fiber brushes to perform satisfactorily under commutation, required a different experimental set-up and was practically completed before the start of the present project.

In No.22 the automated testing equipment together with a newly developed mister by David Makel was used to determine the optimal conditions for the application of moisture, requisite for the double molecular layer of adsorbed water discussed in the first part of this section. Wear rates were

lowered to what now appears to be a theoretical minimum at the least for copper on copper. It appears to arise through ion migration caused by the current, but more research is needed for verification. Prospects are bright that further lowering of wear rates without significant loss of electrical performance is possible by the use of other metals in lieu of copper.

Development of a New Metal Fiber Material For Sliding Electrical Contacts

A major part of the funding was expended on the development of an improved metal fiber brush material. This effort had begun much earlier and was concurrently supported by the David Taylor Research Center, Annapolis. It has not yet been published, partly because it is not yet complete and partly because it may have commercial applications. Even so, at this stage success seems assured in overcoming a previous serious limitation of metal fiber brushes, namely what we have dubbed "the mink toothbrush problem". It is this:

For lowest possible electrical resistance and wear rates, metal fibers should be very thin, e.g. 20 μ m, while the optimal aspect ratio of length to thickness is about 100 and the optimal packing fraction of fibers is about 20%, all as described in our earlier patents ("An Electric Brush and Method of Making", D. Kuhlmann-Wilsdorf, C.M. Adkins, and H.G.F. Wilsdorf, U.S. Patent #4,415,635, November 15, 1983; "A Versatile Electrical Fiber Brush and Method of Making", D. Kuhlmann-Wilsdorf, U.S. Patent #4,358,699, Nov.9, 1982). However, the length of the fibrous part of such brushes if constructed painter's style is evidently only a few millimeters, and even minor wear will cause their performance to deteriorate sharply. It was therefore decided to make metal fiber brushes in which fibers of the desired dimensions are statistically interconnected among near-neighbors. Using rods of such material for

brushes, microscopically at the running surface the wanted electrical and wear behavior is obtained but macroscopically the fiber material can have any arbitrary length and be worn through any arbitrary distance without change in the local behavior. We are glad to report that we are now able to make some such material and that among others it could be enormously useful for EML armatures.

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