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Electrical Contacts 1983

Part I Proceedings of the Twenty-Ninth Annual Meeting of the HOLM CONFERENCE ON ELECTRICAL CONTACTS

Part II Title word index and author index for Proceedings of the first twenty-nine Holm Conferences on Electrical Contacts and the first eleven International Conferences on Electric Contact Phenomena

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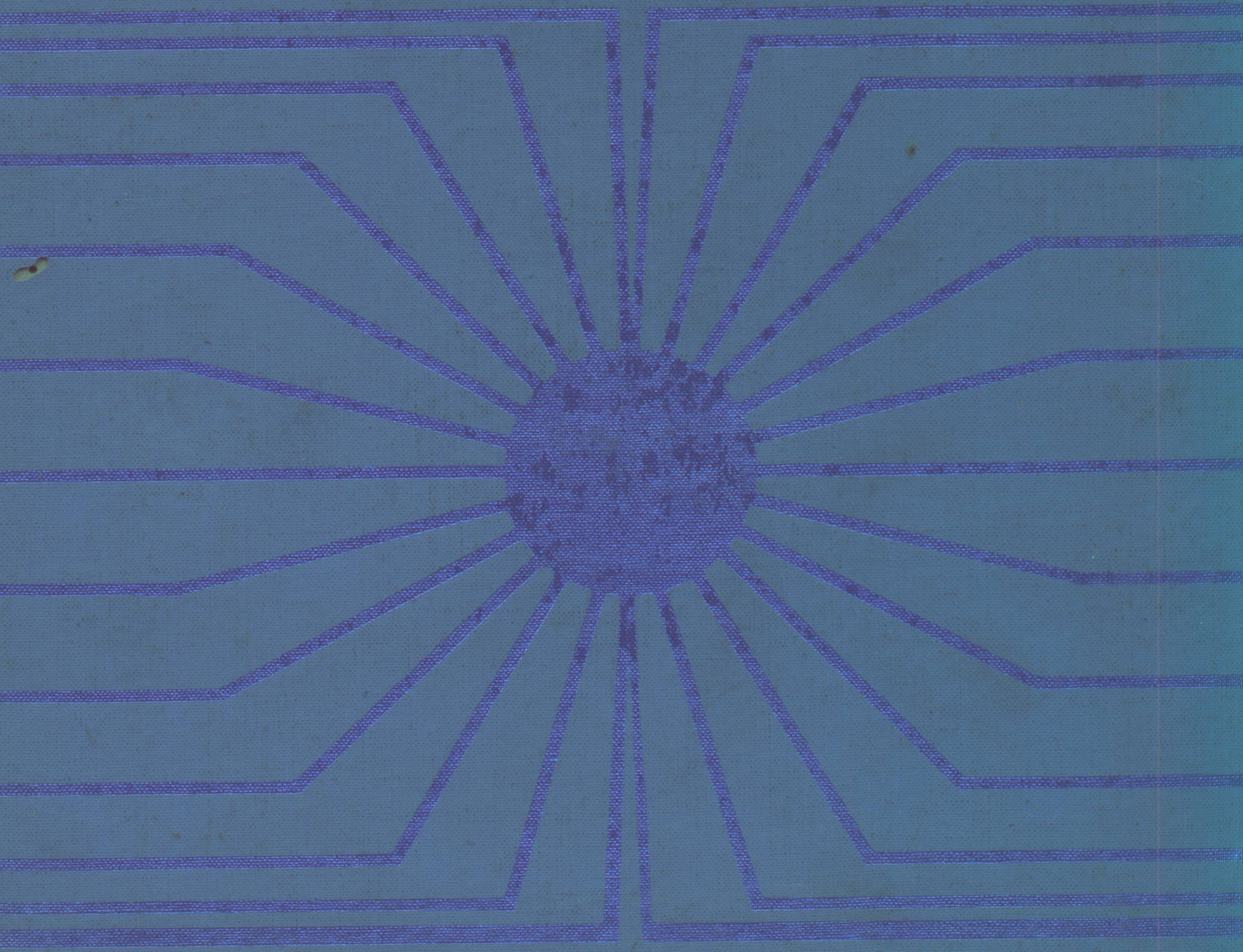

ELECTRICAL CONTACTS - 1983

PROCEEDINGS

of the

TWENTY-NINTH MEETING

of the

HOLM CONFERENCE ON ELECTRICAL CONTACTS

The purpose of the Conference is to provide a forum for the presentation and discussion of practical information on the latest developments in the field of electrical contacts. The technical papers cover a broad span of interest ranging from practical application of contacts to contact theory. The technical content of the Conference is focused on eight major application areas:

Electronic Connectors
Circuit-Breaker Contacts
Contacts for Industrial Controls
Vacuum Interrupter Contacts
Relays
Aluminum Wire Connections
Slip Rings and Commutators
High-Current Brushes

The several contact properties emphasized are:

Lubrication
Wear
Arc Erosion
Corrosion and Contamination
Design
Manufacturing Processes
Reliability and Testing

Also included in this volume are indices of proceedings of the first twenty-nine Holm Conferences on Electrical Contacts and of the first eleven International Conferences on Electric Contact Phenomena as follows:

Chronological Listing of Papers

Author Index

Title-Word Index

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TWENTY-NINTH ANNUAL MEETING

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FOREWORD

- Part I -

The Twenty-Ninth Annual Meeting of the Holm Conference on Electrical Contacts, which meets from September 26-28, 1983, comprises three days of technical paper presentations with discussion, and two panel sessions.

The Conference proper includes nine sessions of volunteered and screened papers in the general areas: electronic connectors, circuit-breaker contacts, contacts for industrial controls, vacuum interrupter contacts, relays, aluminum wire connections, slip rings and commutators, and high-current brushes.

Opportunity is provided in each session for questions and discussion of individual papers, and for general discussion.

Included in this volume are the reviewed and edited papers of all twenty-seven speakers and one panelist. The papers are arranged in the order in which they are presented. One must recognize that questions, answers, discussions, and especially the panel sessions constitute in substantial measure the value of the Conference and that these proceedings, assembled before the Conference, cannot include them.

The Conference custom, instituted in 1972, of presenting the Ragnar Holm Scientific Achievement Award to an outstanding scientist and contributor to the field of Electrical Contacts, is continued this year. The 1983 Awardee is introduced on page x, together with a brief description of the award; and the Awardee's Address appears beginning on page 1 of this Volume.

Nominations for the Award for future years should be sent with supporting statement, biography and list of publications to the Holm Conference Director.

Illinois Institute of Technology is grateful to the Conference Program Committee, and Authors and Co-Authors, and the Session Chairmen and Co-Chairmen as well as Panel Discussion Organizers and Panelist for their valuable contributions to the Conference and for the authors' permission to include their writings in this volume.

- Part II -

Part II of this volume presents in 150 pages three indices to the Proceedings of the first twenty-nine Holm Conferences on Electrical Contacts and of the first eleven International Conferences on Electric Contact Phenomena.

The first index is a chronological listing of all of the papers in the order in which they appeared.

The second is an author index, and the third is a title-word index for all of the papers appearing in all of the volumes listed above.

Illinois Institute of Technology
Chicago, Illinois 60616
September 26, 1983

Ralph E. Armington
Conference Director

THE 1983 RAGNAR HOLM SCIENTIFIC ACHIEVEMENT AWARD

The 1983 recipient of the Ragnar Holm Scientific Achievement Award is Dr. Ernest Rabinowicz. Dr. Rabinowicz thus becomes the eleventh laureate of the Holm Award in recognition of his work on surface phenomena and interactions that contribute to an understanding of electrical contact performance.

The Ragnar Holm Scientific Achievement Award derives its significance and prestige from the scientist whose name it carries. The contributions of Dr. Ragnar Holm to electric contact theory and application are renowned the world over. The Award, created in 1971 by the Steering Committee of the Holm Conference honors the memory of the founder of modern electrical contact science by recognition of an outstanding scientist or engineer in the field of electrical contacts or related technologies.

The Award is granted annually, provided a worthy candidate is found. Nominations for the Award accompanied by a statement of reasons for the choice, a biography and a list of publications and achievements, may be made in writing to the Conference Director. Selections for the nominees are made by the Holm Award Committee based upon years of contributions to the technology, the importance of the nominees' work, their achievements and their degrees of practice.

The first award was made at the Sixth International Conference on Electric Contact Phenomena in 1972 in conjunction with the Eighteenth Annual Holm Seminar. The Awardees have been:

1972	Professor Frank Llewellyn-Jones
1973	Dr. Albert Keil
1974	Dr. Erle I. Shobert II
1975	Professor Kunio Mano
1976	Harold N. Wagar
1977	Dr. Wilfred E. Campbell
1978	Henry W. Turner and Dr. Clara P. Turner
1980	Dr. Morton Antler
1981	Dr. J. B. P. Williamson
1982	Dr. Werner Rieder

Ernest Rabinowicz, the Award Recipient this year, received the B. A. in Physics and PhD in Physical Chemistry from Cambridge University, England in 1947 and 1950 respectively. Since then, up to the present time, he has been affiliated with the Massachusetts Institute of Technology, currently as Professor of Mechanical Engineering at their Surface Laboratory.

He has authored two books and over 120 papers in the general scientific areas of surfaces in contact, including friction and wear, surface energy, lubrication, fretting, mechanics of polishing, adhesion, etc., using such aids as radioisotopes and exoelectrons. From this background, he has contributed to our better fundamental understanding of how various materials properties relate to contact performance.

He has been involved with specific contact problems with slip rings, relationships between frictional fluctuations and electrical noise, applications of precious metal to edge card connectors, and optimum adaptation of various metals for slip ring use through an understanding of their special crystal structure.

He is a Fellow of the American Society of Lubrication Engineers and of the Physical Society of London, and is a member of the American Society of Mechanical Enginers and the American Physical Society. He is also a Registered Professional Engineer in the Commonwealth of Massachusetts.

RAGNAR HOLM SCIENTIFIC ACHIEVEMENT AWARD

1983 RECIPIENT

DR. ERNEST RABINOWICZ

PART I

CONTENTS

FROM PANEL DISCUSSION ON
APPLICATION OF SURFACE ANALYTICAL TECHNIQUES FOR CONTACT EVALUATION

ADDRESS OF THE ELEVENTH RECIPIENT OF THE RAGNAR HOLM SCIENTIFIC ACHIEVEMENT AWARD

Ernest Rabinowicz
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Mr. Chairman, Colleagues:

I should like to thank the Award Committee for thinking me worthy of following the distinguished line of Holm lecturers. I feel especially honored because a large fraction of my work has not been in electric contacts, but in other areas of tribology.

As Dr. Antler mentioned in his address of 1980, (and I regard his remarks as authoritative), it is customary for the Ragnar Holm lecturer to offer personal remembrances of Dr. Holm (1). I first met Dr. Holm in Chicago in 1952, at a conference on friction and lubrication (2). I still remember that I wondered who that slight, slender, elderly gentlemen was, who was asking all those questions and who was obviously exceptionally well informed; and when someone mentioned his name I suddenly realized, with considerable shock, that it was Ragnar Holm. For some illogical reason, I had assumed that the author of Electric Contacts (3), which I had read with interest and awe some years earlier, would be a more substantial figure.

Later, we corresponded from time to time, and I am delighted that an illustration from one of my papers got into the final edition of his book (4), as did a lengthy discussion of why Dr. Holm disagreed with a key finding of my doctoral dissertation (5).

While making these general remarks about Ragnar Holm, I should like to make the point that all of us know that he did distinguished work in the field of electric contacts. Some of us know of his fine work in other areas of tribology, especially in the theory of friction and wear. Few of us know of his pioneering work in surface physics. Thus, in his Nobel Prize Lecture of a few years ago, Leo Esaki pointed out that Ragnar Holm was the first to observe and interpret the important phenomenon of tunneling currents (6).

Before I begin the technical part of my talk I would like to thank my colleagues and former students who have worked with me on my various electrical contact studies, namely G. S. Reichenbach, R. G. Foster, A. R. Pogeler, R. Smelser, R. Papetti, N. Ohmae, S. A. Barber, S. S. Man, P. C. Chan, Z. Rozenfeld, S. W. Webber, D. A. Stephenson and J. M. Tanner.

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THE IMPORTANCE OF ELECTRICAL CONTACTS IN TRIBOLOGY

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ABSTRACT

The field of electrical contacts is narrow, and its literature is highly specialized. There is a danger that such fields fall behind the general level of technology. Some key tribological ideas and discoveries of the past are examined, to see to what extent the discovery originated in the electric contacts field and then spread to the rest of tribology, and to what extent the opposite happened.

In the case of the adhesive theory of friction, the first formulation for the basic equation for the friction coefficient came from electric contacts, and soon thereafter researchers in metal cutting and surface chemistry re-discovered the same relationship.

In the case of the equation for the adhesive wear rate, the original equation was discovered in the electric contact field, but using an unrealistic model, and the derivation using the findings of wear researchers came seven years later.

The discovery that graphite needs moisture in order to slide with a low wear rate originated in a problem involving graphite electric motor brushes. Many other solids are now known whose friction and wear properties are moisture - dependent.

The fact that the surfaces of some solids, for example tin, can be the site for the growth of needle - like 'whiskers' originated in the electrical contacts industry. Such 'whiskers' are nearly dislocation - free and have exceptional mechanical strength. Occasionally in air bearings, whiskers cause other tribological problems.

Friction polymer, a solid formed by the catalytic polymerization of organic vapor molecules on a solid surface, was first found on relay switches. Currently, this same process is associated with the deterioration of automotive lubricants and the malfunction of magnetic memory devices.

Wedges or prows growing on sliding surfaces were not discovered in an electric contacts context, but most of the study of these features, which can lead to short-circuits in electric systems, has been in an electrical contacts context.

Although some developments, like fluorine based lubricants and metallurgical compatibility, originated elsewhere and then moved to electric contacts, it is clear that very often in the past the electric contacts community pioneered new ideas and discoveries. It is hypothesized that in contrast with other areas of tribology, electric contacts failures are frequent, readily identifiable, and their cost readily determinable. Accordingly, organizations involved with electric contacts have for a long time maintained continuous research programs in this area.

I. INTRODUCTION

For my technical presentation I have decided not to review my own work and the many other studies of sliding electrical contacts. That would be going over ground ably covered in other Holm lectures (1,2). Rather, I would like to discuss a more general topic, namely the interaction between the narrow technical field of electric contacts and the wider field of tribology of which it is a part.

The first point to make is that the field of electric contacts is not only narrow, but also sharply delineated. People who work on electric contacts tend not to study other tribological problems, whereas there is much more cross-mobility in the areas of friction, wear and lubrication. The literature is also very narrow. Most of it is contained in a very small number of monographs, and the proceedings of the annual Holm conferences, supplemented every few years by the proceedings of an international conference of the same scope.

This isolation of the electric contacts community leads to inbreeding when it comes to the citation, in published papers, of earlier work. To illustrate this, Table I compares the references cited in the proceedings of two recent conferences of rather similar type. One was the last Holm conference, held in Chicago a year ago (3). The other was a 'Wear of Materials' conference (the fourth of what promises to become a well-established series of alternate - year meetings). This took place in Washington in April of this year (4).

A count shows that authors of the Wear of Materials conference cited papers given in previous conferences in the same series 6% of the time. That seems a reasonable ratio. However, authors of the Holm conference cited papers published in earlier Holm conferences 25% of the time, am obvious indication of the specialized nature of the field.

When a field is speciallized and inbred, there is a tendency for it to become a quiet backwater, falling further and further behind the rest of technology. The question I wish to pursue is whether this has happened to electric contacts, and in particular to examine the extent to which new results have emerged from electrical contacts to stimulate and fertilize other areas of tribology, or if this has not happened, we must assume that the movement has been in the other direction. The half a dozen examples chosen refer to topics with which I have had at least some involvement, and which were first reported in the literature some 25 to 50 years ago, so that we can evaluate them with some perspective. Others would surely have drawn up a very different list.

II. THE ADHESIVE THEORY OF FRICTION

The modern analysis of friction is based on three propositions, one qualitative and two quantitative.

a. When two surfaces are pressed together, they come into surface-atom to surface-atom contact at a number of small regions called junctions. The sum of the areas of the junctions is the real area of contact A_r (Figure 1). The normal load is transmitted by the junctions and the friction force is the force required to shear the junctions. The rest of the apparent area of contact A_a carries no normal force and offers no resistance to shear.

b. The junctions are produced by plastic flow of the asperities under the normal load L. The plastic strength of the softer material at the interface is its hardness p, and thus we have for the

Table I. Distribution of Citations

Conference proceedings	Wear of Materials, 1983	Electrical Contacts, 1982
Number of citations	1283	191
Citations to earlier conferences with the same title	77	65
Ratio	6.0%	25.4%

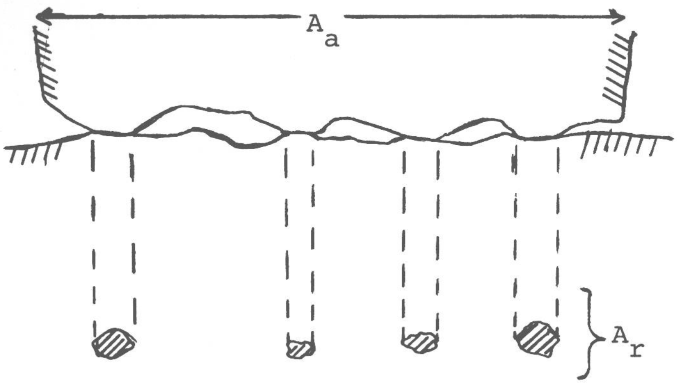

Figure 1. Schematic illustration of an interface, showing apparent area of contact A_a and real area of contact A_r

real area of contact

$$A_r = L/p \qquad 1$$

c. In the unlubricated case, the stress required to shear a junction is the plastic shear strength s of the softer material at the interface, and thus we have for the friction force F

$$F = sA_r \qquad 2$$

Combining equations 1 and 2 gives for the friction coefficient f

$$f = \frac{F}{L} = \frac{s.A_r}{p.A_r} = \frac{s}{p} \qquad 3$$

The friction coefficient, being the quotient of two plastic strength parameters of the softer of the two contacting materials, tends to be a constant.

This mode of analysis was arrived at around the year 1940 by three groups of research workers, namely the physicist Holm (5), the mechanical engineers Ernst and Merchant (6), and the surface chemists Bowden and Tabor (7). Clearly, Holm whose work was first published in 1938 got there first, since the other workers presented their work two and four years later. However, Holm's model is the least well worked out, since he applies it only to concentrated contact situations (like crossed cylinders), rather than to extended surfaces. Hence he does not really discuss proposition (a).

III. THE THEORY OF ADHESIVE WEAR

As is well known, the quantitative analysis of the various forms of wear got off to a very late start, mainly because most research workers did not know that wear was a scientific phenonenon to be analysed, but rather thought it was an unfortunate fact of life.

In the first English edition of his monograph (8), Ragnar Holm has the equation

$$\text{wear volume} = \frac{\text{constant x load x distance}}{\text{hardness}} \qquad 4$$

He derives this by an argument based on layers of surface atoms of the two contacting materials encountering each other and then sliding past each other. Every once in a while this process leads to transfer of an atom.

Some years later, Archard (9) as part of an analysis of the sliding process derived the same equation using a model of the encounter of asperities on the two surfaces, producing large junctions. Occasionally these encounters lead to the formation of a large wear particle. This model, which leads to eqn 4 except for a factor of 3 in the denominator, is worked out with some elegance, and it is shown that the equation is true for all sizes of junctions and of wear particles.

The equation is generally called Archard's equation, after the person who first set up an accurate model of the wear problem and then solved it. Not unnaturally, Holm felt that the credit for this important equation should have gone to him.

Assigning credit in this case is a very difficult and perplexing problem. Holm's model that wear occurs primarily by the removal of individual atoms is clearly incorrect, but since (as Archard showed) the same equation results irrespective of the wear particle size, Holm arrives at the correct result. Furthermore, he published the first wear coefficient tables (10), and they are still useful.

In any case it is clear that in regard to the fundamental equations of friction and adhesive wear, the basic equations were generated in the electrical contact field and moved from there to the rest of tribology, not the other way round.

IV. EFFECT OF MOISTURE ON CARBON BRUSHES

One of the earliest ways in which work with electric contacts contributed to tribology in general was the discovery by Savage (11), soon confirmed by Campbell & Kozak (12), that graphite brushes in electrical motors operating in a low humidity environment, as in airplanes flying at great heights, gave excessive wear. Savage's explanation was that water molecules adsorbed on the graphite crystal are required to produce good cleavage fracture of the graphite, leading to the formation of thin graphite sheets. These sheets, adhering more or less horizontally oriented to the sliding surfaces, are essential in giving low wear. This explanation, I believe, is generally accepted to-day.

Two further comments are in order. Graphite of course has many tribological uses other than as an electrical brush material. The necessity for moisture therefore affects such important components as graphite seals, graphite-based bearings, and graphite-containing solid lubricant films. For example, I recently encountered a case involving failure of a graphite bearing in a high-temperature, dry nitrogen environment.

Many other cases have been identified in which some minimum humidity is required to give low friction and wear (13).

In some situations, for example in magnetic memories like tapes and disks, both very high and very low humidities must be avoided (Figure 2), the former because it can lead to stiction and the latter, as we have seen, because it can produce high wear.

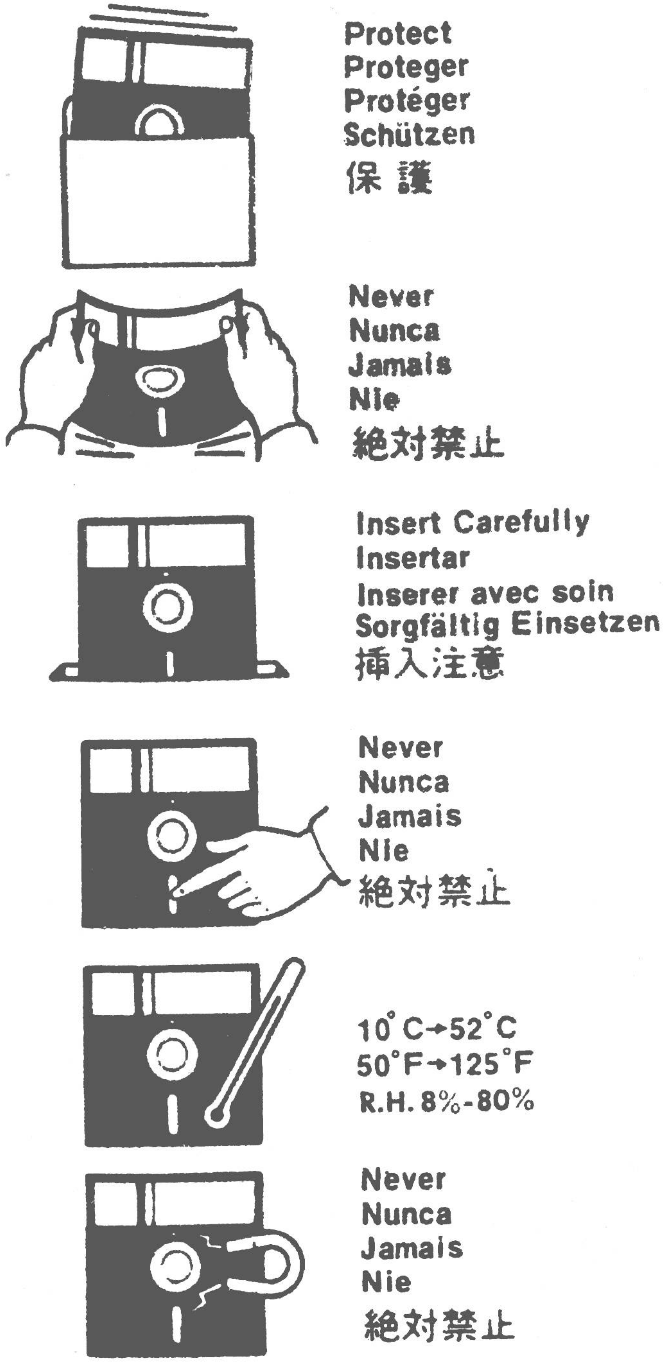

Figure 2. Instructions given by a manufacturer of floppy disks. The relative humidity should be in the range 8% - 80%

In graphite-based slip rings, the harmful effect of insufficient moisture is generally overcome by the use of special additives such as halogenated hydrocarbons.

V. THE FORMATION OF METAL 'WHISKERS'

It was discovered in the 1940's by electronics engineers that, as they were miniaturizing their equipment, they encountered mysterious short circuits. This was traced to the formation and growth of fine wires or whiskers on the surfaces of various metals, especially tin (14). In 1952, Herring and Galt discovered an even more remarkable fact, namely that tin whiskers were dislocation - free. Like others, I tried to incorporate this high strength into models of the friction and wear processes (16).

In retrospect, it is surprising how little impact whiskers have had in materials engineering. Few solid composites, for example, are strengthened by whiskers incorporated into their structure. Of course, whiskers are still a possible source of problems associated with the use of tin as an electric contact material, but it seems that by the appropriate choice of tin - based alloys the formation of whiskers can be prevented (17).

Recently, reports have surfaced of another problem area in tribology in which whiskers are being encountered.

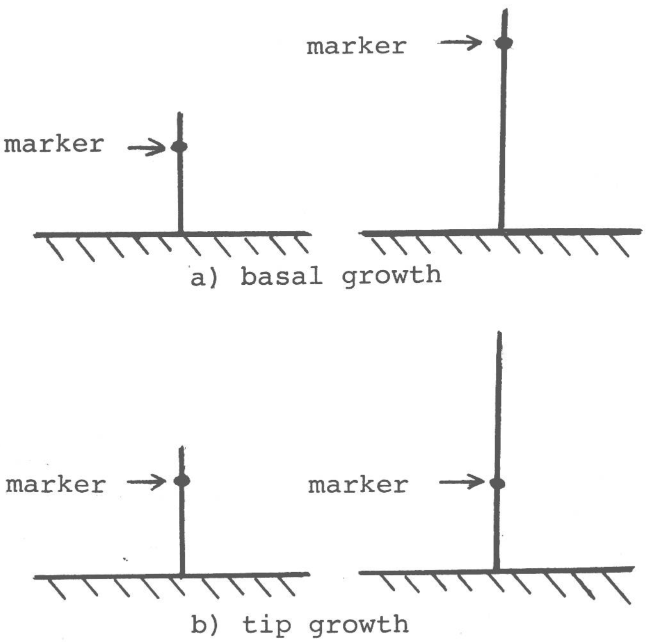

Figure 3. Schematic illustration of basal and tip growth of whiskers. To make the nature of the growth visible, a marker has been applied to the whisker.

These whiskers are formed on the ceramic heads of magnetic recording systems, and are quite awkward because they are much larger than the air gap between the magnetic head and the disk, and hence they can cause failures. These whiskers are formed appartently by tip growth, namely by the migration of very small wear particles or even single molecules from the face of the head to the trailing edge and then to the tip of the whisker.

VI. FRICTIONAL POLYMER FORMATION

Hermance and Egan (18) were the first to report the formation of organic deposits in the vicinity of sliding electrical contacts, specifically relay switches. They postulated that the deposits were formed as result of the polymerization of organic vapor molecules in the local atmosphere, the noble metal acting as catalyst. A sizeable literature discussing the formation and properties of these polymers has been produced (19-21), and this fully supports Hermance and Egan's conjecture.

Friction polymers are formed on other materials, for example steels (22). This suggests that during the operation of automobile engines polymerization of relatively small organic molecules in the lubricating oil occurs at steel surfaces scraped clean as result of sliding. The large molecules produced by polymerization are soluble in the lubricating oil at elevated temperatures, and often deposit as a varnish-like deposit in the cooler parts of the engine, such as the sump.

Recently I have encountered friction polymers as deposits on the ceramic heads of floppy disk computer memories. It is not clear in this case whether the source of the organic matter is the atmosphere or the disk surface.

Calculations suggest that the efficiencies of various solids as sites for polymerization differ greatly. On noble metals 10 to 100% of sites scraped clean by sliding produce frictional polymer, while for ceramics the comparable proportion is .01% - .1%, and for steel surfaces it appears to be .1% to 1%.

VII. FORMATION OF 'WEDGES' AND 'PROWS'

This is a case where the initial discovery was not made in an electrical contacts context, but most of the later work is associated with electrical contact components. Cocks (23) was the first to observe that in sliding a copper pin on a copper cylinder, a copper wear particle generally formed on the pin and grew by the accretion of further material, eventually forming a large 'wedge', which periodically was knocked off the surface, only to be replaced by another. Later work by Antler (24) and Rabinowicz (25) has described this process as occurring in noble metals used in slip rings, and discussions of the mechanism suggest that 'noses' can occur whenever there are strong adhesive forces between the sliding surfaces. Figure 4 shows one of these nose - like prows.

When these wedges came off electrical contact surfaces, they typically have the form of long relatively thin slivers. Lengths exceeding 1 millimeter are by no means uncommon. Not infrequently, the slivers are able to short-circuit electrical circuits. I know of an airplane crash which may have occurred because of this effect.

VII. DISCUSSION

When I started my evaluation of the literature, the aim was to judge the status of electric contacts as a branch of tribology. The outcome of the inquiry has been that electric contacts has in fact been a leader, an area from which time and time again good new data and good new ideas have come, to nourish tribology as a whole.