N70- 19318

NASA TECHNICAL MEMORANDUM

NASA TM X- 52748

NASA TM X-52748

CASE FILE COPY

FRICTION AND WEAR INTERDISCIPLINARY WORKSHOP

NASA Lewis Research Center
Cleveland, Ohio
November 19-21, 1968

FRICTION AND WEAR INTERDISCIPLINARY WORKSHOP

NASA Lewis Research Center
Cleveland, Ohio
November 19-21, 1968

Edited by

E. E. Bisson, NASA Lewis Research Center
P. M. Ku, Southwest Research Institute

STEERING COMMITTEE

P. M. Ku, Southwest Research Institute (Chairman)
G. S. Ansell, Rensselaer Polytechnic Institute
E. E. Bisson, National Aeronautics and Space Administration
G. C. Deutsch, National Aeronautics and Space Administration
D. G. Flom, General Electric Company
E. E. Klaus, Pennsylvania State University
E. C. McKannan, National Aeronautics and Space Administration
M. C. Shaw, Carnegie-Mellon University
R. P. Shevchenko, Pratt and Whitney Aircraft

CONTENTS

INTRODUCTION

P. M. Ku
Southwest Research Institute
San Antonio, Texas

E. E. Bisson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

E-5496

In an effort to further the advances in the complex and interdisciplinary subject of lubrication, the National Aeronautics and Space Administration inaugurated in 1967 an interdisciplinary lubrication symposium series. The first meeting of this series, a symposium entitled Interdisciplinary Approach to Friction and Wear, was held in San Antonio, Texas, on November 28-30, 1967. Ninety persons (approximately 25% basic scientists, 50% lubrication research engineers, and 25% design and development engineers) participated in this invitational meeting. The program featured a series of lectures and discussions, devoted to a critical appraisal of the level of understanding and the needed research in the area of sliding friction and wear under unlubricated and boundary-lubrication conditions.

It was noted during the San Antonio meeting* that the majority of the participants felt that many key problems in friction and wear (both

* Ku, P. M.: Closing Remarks. Interdisciplinary Approach to Friction and Wear, P. M. Ku, ed., NASA Spec. Publ. SP-181, 1968, pp 479-486.

theoretical and practical) warranted further in-depth discussion and that such discussion could more profitably be conducted in an informal manner. Accordingly, on the recommendation of the Steering Committee, an Interdisciplinary Workshop on Friction and Wear was held on the grounds of NASA Lewis Research Center, Cleveland, Ohio, on November 19-21, 1968.

The Workshop was attended by 79 participants, composed approximately of 10% basic scientists, 60% lubrication research engineers, and 30% design and development engineers. The conduct of the Workshop was as follows:

On the morning of the first day, all participants met in a general session to hear a welcoming address by E. J. Manganiello, Deputy Director of NASA Lewis Research Center. Following this address, six members of the Steering Committee introduced a number of key problems in six broad areas which appeared to merit special attention. These problems were selected by the Steering Committee in advance, merely to serve as a starting point for later discussions. It was emphasized, however, that the various Working Groups should feel free to depart from the suggested agenda in the light of their own interests and experience.

For the next one and one-half days, the participants were divided into six Working Groups, all comprising as nearly as possible the same distribution of basic scientists, lubrication research engineers, and design and development engineers. The Groups met separately to consider the suggested problems, with the request to emphasize where critical under-standing was lacking and how the problems might possibly be attacked. The six Steering Committee members who made the initial presentations served as the Group Leaders.

The six Working Groups and their broad assigned areas were:

I. Surfaces and Surface Interactions.

II. Unlubricated and lubricated wear.

III. Boundary lubrication and wear.

IV. Aerospace lubrication.

V. Lubrication, friction, and wear under gross plastic deformation.

VI. Extreme-temperature lubrication.

The entire third day was devoted to a final general session, during which the six Group Leaders presented the reports from each of the Groups. This was followed by general discussions from the floor.

This volume presents the six reports prepared by the Group Leaders after the meeting, as well as a summary of the proceedings of the final general session prepared, also after the meeting, by the present writers who served as chairmen of the Workshop and also editors of this volume.

The writers acknowledge their appreciation of the enthusiastic participation of all those who attended the Workshop, and particularly the time and effort expended by the Group Leaders. Last but not least, the courtesy extended by NASA Lewis Research Center in hosting the Workshop is sincerely appreciated.

SURFACES AND SURFACE INTERACTIONS

P. M. Ku
Southwest Research Institute
San Antonio, Texas

Editors' Note: The members of Working Group I were G. S. Ansell (Group Leader), M. Antler, E. D. Brown, H. J. Dawe, C. Dayson, G. C. Deutsch, R. S. Fein, H. C. Hoffman, R. A. Lad, F. F. Ling, E. I. Shobert, T. Spalvins, T. N. Strom, R. A. Wilde, and J. Zuk. This report was prepared by P. M. Ku, based upon the verbal report presented by G. S. Ansell during the final general session.

The suggested topics for discussion by this Group were as follows:

1. Definition of a "solid surface".

2. Characterization of solid surfaces (physical, chemical):

   a. Not in contact.

   b. In static contact.

   c. In moving contact.

3. Application of modern instrumental techniques to:

   a. Characterize solid surfaces in moving contact.

   b. Characterize surface interactions (physical, chemical).

4. "Unlubricated friction"—How does it take place?

5. "Unlubricated wear"—How does it take place?

6. How to bridge the gap between the basic "micro" approach and the practical "macro" approach in friction and wear studies?

All of these topics were touched upon during the working session.

It was felt that the definition of a "solid surface" could be approached in two ways. One way would be to refer to the external layer, starting at that depth where the surface discontinuity first modifies the bulk properties, and including any physically or chemically bound layers which may be present. The alternative would be to define by characterization.

The characterization of a single solid surface should include: (a) topography, which involves gross features such as overall size and shape; more detailed features such as waviness, machining marks, and asperities; and atomic-scale structure such as steps and ledges; (b) chemical composition, which involves identification as to element, concentration, and location; and environmental relationship; (c) atomic arrangement, which involves crystal structure, orientation, defect structure, and local distortion; and (d) surface properties, which include physical, rheological, and chemical properties.

The characterization of two solid surfaces in static contact should include not only the above features, but also: (a) relative orientation, (b) state of stress, (c) interpenetration of the surfaces, and (d) distribution of contacts and the free space between the surfaces.

In dealing with two solid surfaces in relative motion, still other factors should be considered. These include: (a) thermal gradient and transfer, (b) mass gradient and transfer, and (c) changes in all above-mentioned features with respect to time.

Referring to experimentation, the Group noted that apart from the various instrumental techniques already identified at the San Antonio Symposium, the scanning microscopy and gas analysis techniques might also warrant consideration. These available techniques were, unfortunately, mostly not used by the friction and wear investigators. It was also emphasized that the experimental configuration should be such as to permit the surfaces to be examined repeatedly in the course of a test without their being disturbed in any way.

With reference to unlubricated friction, the Group took cognizance of the two divergent models discussed at the San Antonio Symposium and felt that neither was satisfactory because they both ignored the realities of the surface structure with no linkage to fundamental properties.

The Group was not satisfied with the current views on unlubricated wear for basically the same reasons.

In order to further the understanding of friction and wear, the Group felt that an attempt should be made to link the gross behavior to the characterized surface. The concensus was that the surface can be characterized but requires the application of instrumental techniques not generally used in this field, and that friction and wear phenomena may be understood on the basis of characterized surfaces by employing models which permit critical experimentation.

UNLUBRICATED AND LUBRICATED WEAR

D. G. Flom
General Electric Company
Valley Forge Space Technology Center
Philadelphia, Pennsylvania

Editors' Note: This report from Working Group II was transmitted by D. G. Flom, Group Leader. Other members of the Group were J. K. Appeldoorn, J. J. Bikerman, P. H. Bowen, D. H. Buckley, R. Courtel, H. E. Evans, R. L. Hammel, R. L. Johnson, A. J. Lemanski, W. E. Littmann, C. J. Pentlicki, C. N. Rowe, G. Salomon, and D. W. Wisander.

The discussions of this Group were aimed initially at the following seven items:

1. Distinction between "unlubricated" and "lubricated" wear.
2. Classification of wear.
3. Physics and chemistry of wear.
4. How to bridge the gap between the basic "micro" approach and the practical "macro" approach in friction and wear studies.
5. The utility of mathematical models of wear.
6. Fretting.
7. Oscillatory motion (i. e. , large amplitude).

For reasons which will become apparent, these items were not taken up in order. Also, Items 6 and 7 were not covered at all, not because of lack of importance but rather because it did not appear wise to cut off the enthusiastic discussion of the other topics.

Initial attempts to draw a distinction between "unlubricated" and "lubricated" wear indicated that this could be done more easily if Item 2 on

Classification were discussed first. To facilitate this task, it was decided to check the terms pertaining to wear in the Report of the Research Group on Wear of Engineering Materials of OECD (Organization for Economic Co-operation and Development) entitled "Friction, Wear, and Lubrication. Terms and Definitions". Agreement on these terms would make subsequent communication much easier. Checking of the list was done with particular emphasis given to the following terms:

Abrasion	Normal wear
Adhesive wear	Oxidative wear
Cavitation erosion	Pitting
Corrosive wear	Ploughing
Electrical pitting	Scoring
Erosion	Scratching
False brinnelling	Scuffing
Fatigue wear	Seizure
Fluid erosion	Severe wear
Fretting	Smearing
Fretting corrosion	Spalling
Galling	Thermal wear
Impingement erosion	Transition wear effects
Initial pitting	Unlubricated sliding
Lubrication	Wear
Mechanical wear	Wear rate
Mechano-chemical wear	Wear resistance
Mild wear	Wedge formation

It was agreed that the definitions of these terms in the OECD List were by and large good, even though they were primarily macroscopically-oriented. There were very few objections to the definitions, and it was agreed that those who did object should submit their preferred definitions to R. L. Johnson, NASA-Lewis, a member of the OECD Sub-Group.

It was felt also that the OECD activity in this area was important and should be continued, including a continual updating of the List of Definitions.

Other methods of classifying wear could have been adopted but this was not considered necessary for the present discussion. It was recognized that a number of different wear mechanisms can operate concurrently and there is no reason to consider them mutually exclusive.

In considering the distinction between "unlubricated" and "lubricated" wear, the Group decided to change the terminology from "wear" to "conditions" so as not to exclude friction from the discussion. It was then concluded that both an engineering distinction and a scientific distinction would be desirable. In the engineering context, "unlubricated" conditions are those in which no lubricant (oil, solid lubricant, etc) has been added to the system. Conversely, "lubricated" conditions are those in which a lubricant <u>has</u> been added intentionally. An example of lubricated sliding is one in which a thick hydrodynamic film can be developed, even under conditions of low speed and low load.

A scientific distinction between "unlubricated" and "lubricated" conditions does not serve as useful a purpose because of the usual presence of films on nominally "clean" surfaces. These films can often provide some lubricant action. Thus, it is preferable to recognize the continuous gradation between "unlubricated" and "lubricated" conditions.

A different type of distinction should be added, namely, that between a "coolant" and a "liquid lubricant". From a research standpoint, this is desirable because a coolant can be useful for conducting away the heat in an "unlubricated" experiment. From a practical standpoint, a coolant serves the obviously useful function of heat conduction in extremely high temperature applications. An example of a useful application of "coolants" is that of helicopter transmission systems.

The Group turned its attention next to the utility of mathematical models of wear. Several equations have been developed in the past for relating wear to experimental conditions and to material properties. Perhaps the simplest of these is the linear equation due to Archard:

$$\frac{V}{L} = K \frac{W}{3H} \qquad (1)$$

where V is the volume of wear, L is the distance of sliding, W is the load, H is the hardness of the softer of the two materials in contact, and K is a constant of proportionality. This equation (referred to hereinafter as the K-equation) applies only for very limited conditions, e. g. , mild adhesive wear where the wear particles do not act as an abrasive leading to catastrophic wear. Chemical effects are not inherent in this equation. Furthermore, the constant K must be determined by experiment and cannot yet be developed from first principles. K is usually interpreted as a probability that a given encounter will lead to a wear particle; alternatively, it can be considered as the fraction of total number of encounters a given asperity must undergo before it forms a wear particle. The equation is useful for interpolation but <u>not</u> for prediction of wear under new conditions or for new material combinations.

C. N. Rowe's modified K-equation has the form

$$\frac{V}{L} = K_m \alpha \frac{W}{P_m} (1 + \beta f^2)^{1/2} \tag{2}$$

where K_m is a new wear coefficient, P_m is flow pressure, f is the coefficient of friction, and α and β are constants for a given set of materials and conditions. This equation allows the introduction of additional material properties; but at the expense of introducing some nonlinearity. The effect of the lubricant is included in the α term. K_m can be interpreted to include metallurgical properties and fracture mechanics and P_m can be modified so as to include strain-hardening effects, the latter probably being very important in the relative wear properties of different materials. Also, there can be little argument with the opinion that wear is frequently only a form of fracture and that new insight into wear mechanisms will probably come through the application of fracture mechanics. Rowe's modified K-equation appears to be a good starting point for work in this area. The recommendation of the Group is that future investigators devote attention to clarifying the nature of K_m (i. e., include fracture mechanics and attempt a derivation from first principles) and also P_m (i. e., include strain-hardening). Even in Rowe's modified form, it is important to note again that one should <u>not</u> use the K-equation outside of the mild wear regime. Also, investigators who do use the equation should report the boundary conditions or limits of use for their experiments.

Other models of wear have been proposed and these deserve evaluation by other working groups and investigators. These are the models suggested by Rabinowicz, by Kragelski, and by the research group at IBM. Where possible, the equations associated with these models should be applied to newly-generated data and the degree of fit reported.

While equations of the type just discussed are useful in relating wear to material properties, it is apparent that to learn more about the mechanisms of wear it is necessary to adopt also an atomistic, or at least a microscopic, approach. Recent work in the physics and chemistry of wear has confirmed that wear on an atomistic scale can be observed. By this is meant the transfer of material as atoms from one surface to another. Nishikawa has used field-ion microscopy to measure transfer of tungsten to aluminum in a tungsten-aluminum mechanical contact in vacuum. More recently, Buckley has brought copper into contact with single-crystal nickel under light load in vacuum and has observed transfer of copper to the nickel. He has used low-energy electron diffraction (LEED) techniques and has observed that the copper shows up at interstitial sites in the nickel lattice. Further studies of this type should be pursued regardless of any difficulty in applying the results immediately to practical wear problems.

In the same category are sliding experiments on single crystals. Such studies illustrate the fact that deformation and plastic flow can occur at distances far removed from the apparent area of contact and also that different friction and deformation results can be obtained when sliding in different directions on a given single crystal face. These effects are obscured in a polycrystalline material and modified by the presence of grain boundaries; but there is no reason to believe that the same processes do not take place also within individual grains. Courtel has found in single crystal studies that friction measurements themselves can serve as good indicators of the presence or lack of surface films.

The study of fracture and adhesion as an approach to the mechanism of wear has already been mentioned. Keller is pursuing this line and is utilizing the results of Milner and Rowe as supporting evidence.

An important fact to bear in mind is that solid-to-solid contact is not needed for wear to occur. Since force can be transmitted through a fluid lubricant, it is necessary only that such force have a directional component which will result in fracture and detachment of wear particles. There is ample evidence for this extending from ambient pressures of 10^{-5} torr to full hydrodynamic lubrication. It appears that metal-to-metal contact may have been overemphasized in wear investigations in the past.

The Group felt that several recommendations could be made (in addition to those already mentioned) to help guide future wear investigations and make the results more generally applicable. One of these recommendations is to specify the heat flow conditions for the experimental configuration used in a given study. Heat dissipation is of extreme importance. Discrepancies in a recent round-robin wear study using the same test materials were attributed ultimately to different heat flow conditions in the different experimental configurations.

Surface roughness and composition should also be specified even though the difficulty of always doing this is recognized, particularly with respect to composition. It is desirable to measure roughness both before and after an experimental run; but the engineering purpose must also be kept in mind. For some applications, e.g., precision ball bearings, smooth surfaces are more important than for other applications.

In a broader sense, there is a prime need for complete control of parameters and conditions as well as the specification of these in experimental wear studies. For example, the atmosphere, moisture content, temperature conditions, and — this is very important — how these parameters were measured should always be specified. One of the biggest interdisciplinary deficiencies in wear studies is incomplete characterization. A classic example of this is illustrated by the different ways in which researchers view the same experiment. The lubricant investigator knows in great detail the composition and structure of his oil; but when asked about the metal used he may answer: "it's some kind of steel". The metallurgist, on the other hand, knows precisely what kind of metal or alloy he is using; but when asked about the lubricant he is liable to say: "it came out of this bottle". Obviously, such situations need correcting.

In connection with experimental control, it is also recommended that the mechanical stability of instruments be specified, i.e., resonant frequencies, tolerances, etc. It is a known fact that even wear machines wear out and that experimental results may be dependent on the state of deterioration of the test apparatus.

The Group felt that caution should be exercised in the use of standardized wear tests, particularly for research purposes. While useful for acceptance tests and for screening materials, there is a danger in placing undue emphasis on standard tests when there is a more urgent need for critical experiments to answer specific questions. The rapid progress made in experimental techniques during the past few years has opened up the spectrum of approaches available to the researcher. For example, the stereo scanning electron microscope has provided exciting new information in other fields, such as composites, and the use of this technique in wear studies is to be encouraged.

As the investigations of friction and wear progress, new facets are continually uncovered. Relaxation and vibration effects (both normal and tangential) in sliding friction and wear may be important, independent of instrumentation (work of Rocard). This may be especially significant in fretting, a subject which was not covered in the discussions of this Group, but which was felt nevertheless to be of general importance.

BOUNDARY LUBRICATION AND WEAR

E. E. Klaus
Pennsylvania State University
University Park, Pennsylvania

Editors' Note: This report from Working Group III was transmitted by E. E. Klaus, Group Leader. Other members of the Group were G. P. Allen, W. J. Anderson, D. Godfrey, W. R. Jones, J. Maltz, C. A. Moyer, R. S. Owens, D. Ramadanoff, J. B. Rittenhouse, H. M. Schiefer, and R. B. Waterhouse.

The agenda included the following items:

1. Definition of "boundary lubrication".
2. Transition from elastohydrodynamic lubrication to boundary lubrication.
3. Physics and chemistry of boundary lubrication.
4. Classification of wear; wear behavior.
5. Physics and chemistry of wear.
6. Effect of environment (such as oxygen, moisture, etc) on boundary lubrication and wear.
7. Electrical resistance measurement in boundary lubrication.

The interdisciplinary nature of this Group is indicated by the seven disciplines (chemistry, chemical engineering, electrical engineering, materials engineering, mechanical engineering, metallurgy, physics) represented. It was generally agreed that chemistry in the form of chemical reactions between the bearing surface and components of the lubricant and/or atmosphere plays an important role in boundary lubrication and most forms of wear.

A definition of boundary lubrication was derived from a discussion of present as well as classical research in the field. Boundary lubrication is the condition where the nature of the sliding interface influences friction and wear. This definition places "mixed lubrication" in the general category of boundary lubrication. That is, all of the ZN/P curve to the left of the elastohydrodynamic region as shown in figure 1 is covered by this definition.

There was considerable discussion of the continuous nature of the phenomena studied in lubrication and the discontinuous nature of definitions. This probably results from the empirical approach to lubrication from the several disciplines involved. Examples of empirical boundaries that do not exist as discrete locations on the ZN/P curve are hydrodynamic to EHD and mixed lubrication to classical boundary lubrication. Another example is microslip and sliding. In this case, to a molecule on the surface at an appropriate point in time, it makes little difference what you call it. These are the general problems associated with the maturation of a technical field in the change from empirical to theoretical or macroscopic to microscopic considerations.

Wear classification was considered from several viewpoints. First, there appear to be three fundamental processes involved in wear (mechanical, thermal, and chemical). Another way of classifying wear forms is shown in table 1.

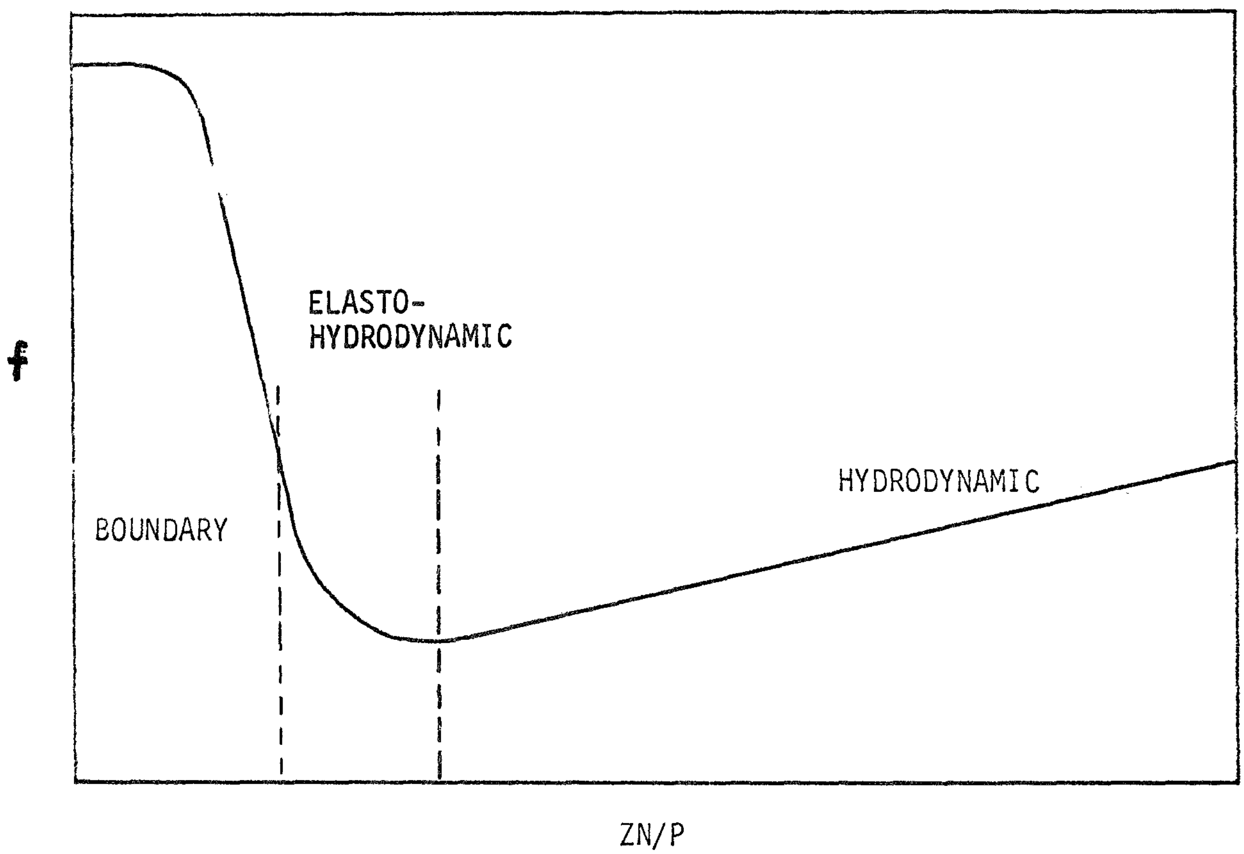


Figure 1. — Effect of viscosity on the coefficient of friction. f = coefficient of friction, N = rotational speed, Z = effective viscosity, P = unit projected load.

Table 1. — Wear Classification by Fundamental Processes Involved

Wear classification	Fundamental process involved
Corrosive	Chemical
Evaporative	Thermal
Adhesive	Mechanical (modified by chemical)
Abrasive	Mechanical (modified by chemical)
Erosive	Mechanical (modified by chemical)
Fatigue	Mechanical (modified by chemical)

The definition of erosion (erosive wear) by this Group differs from that of the OECD definition in one important detail. The OECD definition indicates that "erosive wear is loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles". This Group feels the definition should end after the word "fluid". This definition would then fit erosion as used by this Group in describing cavitation.

Cavitation, fretting, and electrical discharge were where other wear forms considered to be mixtures of the fundamental classes in table 1.

Fretting contains the aspects of both adhesion and fatigue. Some recent work reported by Waterhouse involves fretting studies with electrolytes as lubricants. Fretting can be controlled in these studies by providing mildly corrosive lubricants. Godfrey also reported on the use of additives with mildly corrosive action to reduce fretting.

Cavitation involves both fatigue and erosion as fundamental wear forms. Chemical corrosion also appears to play a role in some types of cavitation damage. Cavitation is caused by a sudden reduction in pressure in the liquid phase. This removes soluble gas or vaporizes volatile components to form a low pressure gas bubble. When the pressure is again increased in the course of the fluid flow process the bubble implodes. One current explanation is that the damaging shock wave is created by a liquid jet set up by the collapse of the bubble. This energy source can also supply the heat necessary for a chemical corrosion reaction as well as the eroding force to wipe a boundary film off of the solid surface. Replacing gas solubility with a volatile liquid component like water or its equivalent in an organic liquid reduces the damaging effect of the cavitation. In general, the lower the volatility of the volatile component, the less damaging the cavitation. The relative importance of this phenomenon in affecting boundary lubrication is yet to be demonstrated.

Particulate debris plays a role in most cases of wear. The size and shape as well as the physical and chemical properties determine the role these particles will play in further wear under boundary or EHD conditions. Generally, spherical particles with little tendency to adhere to the bearing surface may result in little wear even in cases where the particle diameter exceeds minimum clearance for the boundary film.

The chemistry of boundary lubrication was discussed in some detail. Reaction rate and its relation to wear and boundary lubrication were discussed. The majority felt that the optimum rate of reaction is controlled by the severity of the interfacial loading conditions.

Some members of the Group felt that the thickness of the boundary film resulting from the reaction rate, rather than the rate itself, should be considered the important factor.

Three factors were considered in the discussion of reaction rate in boundary lubrication. One was the possibility that the clean metal surface formed under a lubricant is acting as a catalyst to provide for chemical reactions with a lowering of the activation energy. A second possibility is the increased temperature at the bearing surface due to frictional heating which could provide for a relatively high reaction rate. The third possibility is the increased reaction rate resulting from the high local temperature combined with a large reactive surface area provided by continuing interfacial wear. The third possibility appeared to be favored by the Group.

The effectiveness of oxygen and water as lubricity additives was illustrated with the data on figure 2.

In this discussion it was stressed by numerous examples including O_2, H_2O, acid phosphites, organic acids, and other corrosive lubricity additives that an optimum concentration would produce minimum wear for a given set of conditions. The optimum may be the minimum additive to produce the minimum corrosion rate to prevent seizure.

Data from many forms of analysis of surface films on insoluble material formation in boundary lubrication experiments show the presence of insoluble material formed by the environment typical of boundary conditions. There appears to be enough data to suggest that the specific materials produced vary considerably with lubricant, additive package, metal surface, atmosphere, and test conditions. In some cases "friction polymer" produced appears to aid the lubrication of the bearing. In other

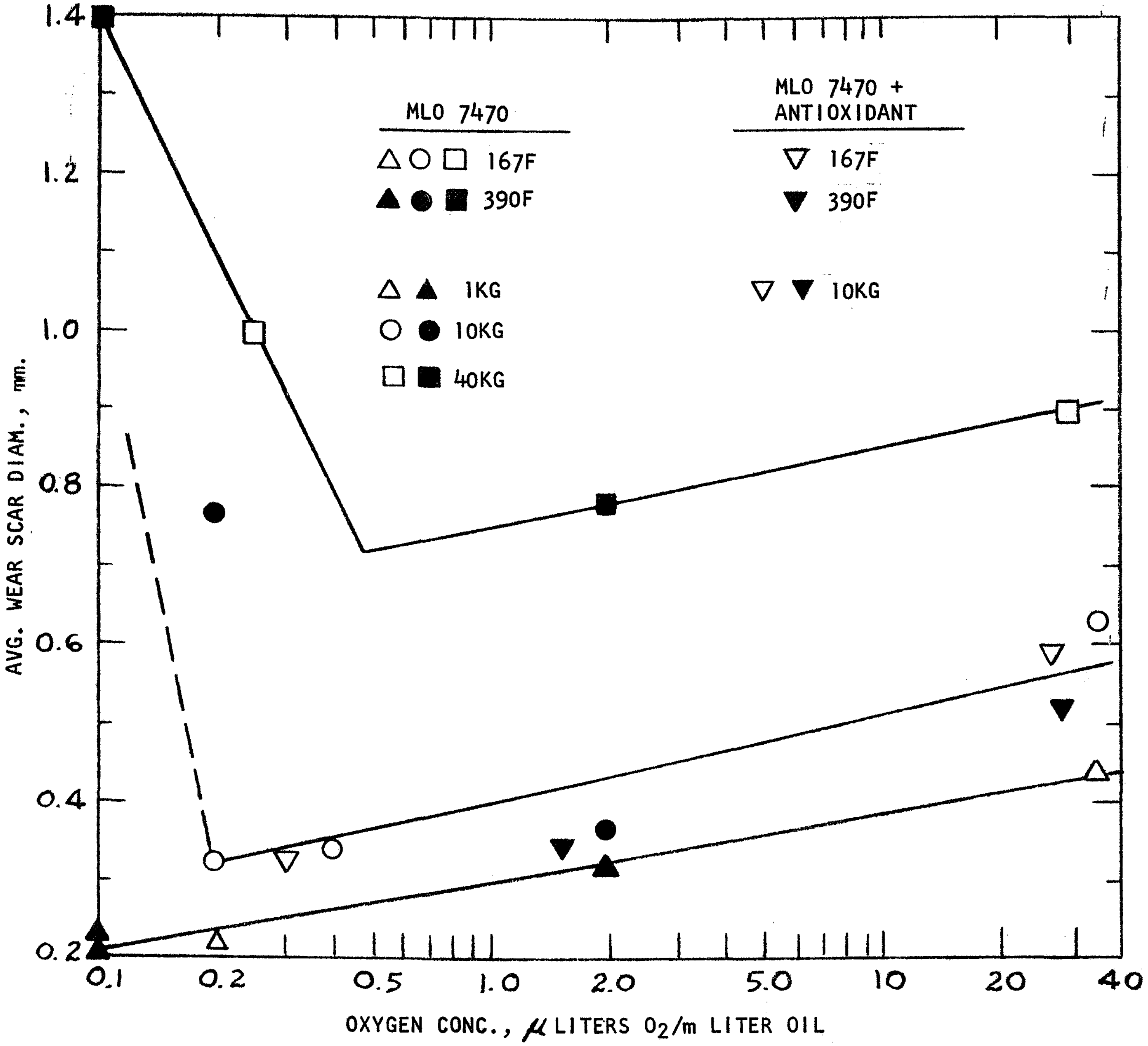


Figure 2. - Effect of dissolved oxygen on the wear behavior of a mineral oil. Tests conducted in a Shell 4-ball wear tester in which the atmosphere above the test fluid can be controlled at test temperatures indicated. The test fluid was a super-refined paraffinic neutral (MLO 7470).

cases the poorer the lubricant the more the solid material produced. It appears to the Group that the different nature of the debris may be responsible for the apparent difference in effectiveness of such material in boundary lubrication.

The use of electrical resistance measurement techniques in boundary lubrication was discussed. This technique has been used effectively to separate EHD from the boundary condition. The use of such techniques to categorize boundary lubrication in a quantitative manner appears to this Group to be an overextension of the present capabilities.

In summary, the Group is convinced that chemical reaction does play a broad and important role in boundary lubrication and most forms of wear. In all of the areas covered by the discussion, further work of a mechanistic nature could be undertaken with good prospects for advancing lubrication theory.

AEROSPACE LUBRICATION

E. C. McKannan
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama

Editors' Note: This report from Working Group IV was transmitted by E. C. McKannan, Group Leader. Other members of the Group were A. J. Babecki, W. A. Brainard, D. E. Brewe, W. F. Hady, D. V. Keller, J. S. Przybyszewski, E. A. Saibel, J. J. Sherlock, W. H. Teimer, and R. G. Wilmoth.

The Group was asked to consider the following items:

1. Definition of a "clean surface".

2. How to obtain a clean surface; how to verify the cleanliness?

3. Application of modern instrumental techniques to the in-situ observation of surface interactions in high vacuum.

4. Role of the lubricant and its effect on adhesion, friction, and wear in high vacuum.

5. Materials compatibility.

6. Design and lubrication considerations for mechanical components for high-vacuum service such as bearings, gears, and seals.

However, in view of the limited time available, the Group decided to focus its attention on practical aspects of lubrication in the space environment.

Emphasis was placed on the effects of the vacuum parameter: (a) limitation of heat transfer to conduction, only, with the implication that heat generation must be minimized, and (b) the volatilization, evaporation, sublimation, desorption, and outgassing of materials with the implication that low molecular weight materials, such as lubricating oils, often cannot be used.

Clean Surfaces

It was decided that a more precise definition of an absolutely (atomically) clean surface was not necessary for the remainder of the discussion and probably not attainable in the time available. Therefore, the definition given in the San Antonio Symposium was accepted:

> "A clean surface is an abrupt termination of the bulk crystal lattice with a reorientation of atoms shifting the unit cell. All foreign atoms such as oxides or adsorbed gases are excluded leaving unsaturated bonds on the surface atoms."

However, it was decided that we should be concerned with clean surfaces from the engineering standpoint, or surfaces which are chemically cleaned relative to the intended commercial application. This decision was based on the information that actual spacecraft have "dirty" surfaces and gaseous environment with a pressure greater than the ambient pressure of their position in space. Also, it was indicated that a typical monolayer of contaminant may re-adsorb on a surface in 10^{-6} torr-seconds. With this in mind, spacecraft lubrication engineers have the same interest in atomically clean surfaces as all other lubrication engineers: i.e., for the theoretical understanding of adhesion mechanisms. Cold welding in space does not appear to be the vital problem it was once thought to be.

At this point we were reminded that a surface does not even have to be exposed to high vacuum to attain adhesion to another surface. In a roll bonding study made in air at room temperature, Milner and Rowe* attained adhesion equal to 100% of the bulk strength in aluminum by compression rolling two sandwiched sheets together causing the oxides to diffuse into the bulk. No adhesive bond was attained until 40% deformation was reached. With increasing deformation the shear strength of the adhesive bond rapidly approached the bulk strength of the aluminum. Individual asperities on bearing surfaces may well reach these large deformations.

Returning for a moment to atomically clean surfaces, the Group felt somewhat obliged to react to the question of how to obtain atomically clean surfaces in the laboratory. In contradiction to statements made in the San Antonio Symposium, it is possible though difficult and tedious to attain atomically clean surfaces in the laboratory. Several researchers have employed a sequence of chemical cleaning, degassing by vacuum bake-out, ion bombardment with spectrographically pure argon, and re-annealing to get the surface back to the initial metallurgical condition. This has been done on pure materials taking great care to eliminate impurities in the bulk of the material and on other surfaces in the vacuum chamber. Whether or not atomically clean surfaces can be obtained on engineering alloys is still questionable.

---

* British Welding Journal

Extending this line of thought to that of measuring or characterizing an atomically clean surface, two methods were discussed. The first, combining LEED to indicate lattice structure with Auger spectroscopy to measure the composition is being used. The second, combining a laser beam to desorb surface material and mass spectrometry to measure the composition is suggested. It was emphasized that so-called surface tension measurements could not be used to indicate the level of cleanliness because the corresponding "surface-tension" properties of the various surface contaminants have not been defined.

Returning to clean surfaces from the engineering point of view, the Group expressed a great need for further research in the measurement of surface wetting. This has applicability to brazing, soldering, painting, and coating with oils or DFL's. The possible correlation of several properties with wetting were considered. Work function (possibly using the contact potential) or a coefficient of friction measurement were considered to be most amenable to packaging for use in the field; of course, surface finish would also have to be involved. It was noted that surface defects (micro-cracks), in addition to being involved in the Rehbinder hardness change, may affect surface wetting. This too needs to be investigated carefully. Cleanliness from an engineering standpoint can be related to wetting for a specific surface and wetting agent.

Compatibility

Compatibility of bearing materials for use in vacuum was considered from two points of view: (a) outgassing, which would cause degradation of the material in its function as a bearing, or which would contaminate adjacent surfaces, and (b) material combinations for use on unlubricated contacting surfaces.

An example of the latter case was a leaded-phosphor bronze rider on a 4340 steel cam which could not be lubricated for fear of contaminating adjacent optics. Other combinations of both dissimilar composition and hardness are sought to eliminate galling (or adhesion) in unlubricated contact. The use of sulfur-containing, free-machining steels was suggested as a source of sulfur for lubrication in the same manner as teflon-bronze compositions (DU) or oil-filled bronze (oilite).

In a discussion of reinforced teflon bearing materials, problems with strength and exposed glass were examined. It was suggested that high-strength graphite filaments (thermal) should be investigated as a replacement for the glass filament in these applications.

In the discussion on wear rates of graphitic seals and bearings in the cryogenic liquids, it was observed that wear rates increase when going from LOX, to LH_2, to LN_2 without good explanations. It was suggested that at these temperatures the wear process could be dominated by adsorption kinetics and that the work of C. N. Rowe on heats of adsorption should be applicable.

Wear-In

The practice of wear-in was examined with emphasis on statistical failure analysis, reliability prediction, and elimination of sports or infant mortality components, and reducing the coefficient of friction. Other reasons for wear-in included: (a) smooth burrs and roughness, (b) work harden the surface, (c) set tolerances, (d) glaze DFL surface, (e) clean out initial wear debris, and (f) check on wear patterns.

No recommendation for changing these practices was made.

Electrical Field Effects

It was recommended that the use of electrical fields to selectively polarize bearing surfaces for control of the lubrication and wear processes ought to be re-examined. This was considered in light of the information that spacecraft carry a high electrostatic charge, of reports of cathodic wear in brush-slip ring application, and of reports of damage to aircraft engine bearings attributed to electrostatic discharges across dielectric lubricating films. Variations in both metal surfaces and lubricants should be investigated with a view to increasing the reaction of polar materials for boundary lubrication. Furthermore, conductive fluids should be investigated for generating separating forces on bearing surfaces by means of magnetohydrodynamic lubrication.

Conclusions

It is obvious that, while focusing on a single environmental problem, this interdisciplinary Group ranged in thinking from fundamental mechanisms, laboratory experiments, measurement of process variables, selection of improved bearing material, and application of new effects. In summary, our recommendations for further study involve:

1. Wetting phenomena in practical applications:
    a. Field measurements.
    b. Correlations with use conditions.
2. Cryogenic adsorption kinetics for an explanation of the behavior of carbon seals and bearings in cryogenic fluids.
3. Graphite filament reinforcement replacing glass filaments in bearing components.
4. Electric field effects on bearings to separate surfaces and to reduce wear.

LUBRICATION, FRICTION, AND WEAR UNDER GROSS PLASTIC DEFORMATION

M. C. Shaw
Carnegie-Mellon University
Pittsburgh, Pennsylvania

Editors' Note: This report from Working Group V was transmitted by M. C. Shaw, Group Leader. Other members of the Group were R. L. Adamczak, H. S. Cheng, H. M. Davis, R. L. Furaso, K. C. Ludema, A. T. Male, C. H. Savage, H. E. Sliney, M. A. Swikert, and J. B. P. Williamson.

The assignment of Group V was to probe the general area of lubrication, friction, and wear under gross plastic deformation. This was to include the following items:

1. Friction and wear behavior under gross plastic deformation versus the normal range of asperity interaction.
2. Role of lubrication.
3. Modern instrumentation techniques for the measurement and observation of friction and wear phenomena in the gross plastic range.
4. Design and lubrication considerations in metalworking processes such as abrasion, extrusion, cutting, etc.

Identification of Area of Interest

For many years the field of lubrication has been classified as follows:

1. Hydrodynamic lubrication (complete separation of sliding surfaces by liquid film).

2. Boundary lubrication (separation of sliding surfaces by physically adsorbed film).

3. Extreme boundary lubrication (separation of sliding surfaces by chemically attached layer).

4. Sliding of clean surfaces.

More recently elastohydrodynamic lubrication has been added to this list. Elastohydrodynamic lubrication is to be distinguished from ordinary hydrodynamic lubrication in that

1. The surfaces deform and change their geometry under load.

2. The pressure developed in the bearing is so high that the viscosity of the lubricant is influenced.

The foregoing mode of classification concerns the character of the separating lubricant and the macroscopic geometry of the load supporting surfaces.

In order to highlight the subject to be discussed here, it is useful to classify load supporting surfaces somewhat differently as follows:

1. Surfaces that are uniformly loaded on a microscale (hydrodynamic lubrication).

2. Surfaces with asperities in elastic contact.

3. Surfaces with asperities in independent plastic contact.

4. Surfaces with interacting asperities in plastic contact.

Items 2 to 4 are associated with boundary lubrication.

Most of the research on friction and wear in the past has been done on lightly loaded sliders which perform under conditions 2 and 3. There are, however, many practical applications which involve heavily loaded sliders operating under condition 4.

Archard's theory of wear (ref. 1) for lightly loaded sliders results in the following equation

$$\frac{V}{L} = KA_R \tag{1}$$

where V = volume worn away,

L = length of sliding contact,

K = a constant for a given pair of metals, geometry, and lubrication situation, and

A_R = the real area of contact as distinguished from the apparent area, A .

This equation indicates that wear rate is independent of the apparent area of contact.

Burwell and Strang (ref. 2) presented wear data for a stationary hemispherical pin rubbing on a rotating disc that was in agreement with equation 1 up to a particular value of unit load, $\frac{P}{A}$. If

$$A_R = \frac{P}{H} \tag{2}$$

where P = load on slider, and

H = hardness of pin,

then from equations 1 and 2

$$\frac{V}{LP} = \frac{K}{H} \tag{3}$$

When Burwell and Strang plotted $\frac{V}{LP}$ against $\frac{P}{A}$, as in figure 1, the curve was a horizontal straight line to a value of $P/A = H/3$. Equation 3 is for lightly loaded sliders (conditions 2 and 3 above) for which $\frac{K}{H}$ will be a constant and hence $\frac{V}{LP}$ will be constant as long as the hemispherical slider is lightly loaded.

When $\frac{P}{A}$ reaches the value H/3, the wear rate, $\frac{V}{LP}$, rises abruptly. This is due to the fact that the uniaxial bulk flow stress of the material beneath the sphere, γ, corresponds closely to $\frac{H}{3}$ and the onset of plastic flow beneath a spherical indenter occurs at a mean stress, $\frac{P}{A}$, of about 1.1γ. Thus, when $\frac{P}{A} = \frac{H}{3}$ plastic flow beneath the surface commences. This in turn causes the real area of contact to become more uniformly distributed and the individual asperities to interact, which causes an increase in the flow stress due to the size effect. The real area of contact then increases and this gives rise to an increase in the wear rate, since from equation 1, $\frac{V}{LP}$ will increase rapidly, at constant P, if A_R increases. As $\frac{P}{A}$ is further increased more and more subsurface flow occurs (until $\frac{P}{A} = H$), and thus A_R will increase at an increase rate with P/A beginning at the point where P/A is about equal to H/3.

The Burwell and Strang experiment is probably the best known example of behavior under gross plastic flow (condition 4).

A lightly loaded slider may now be defined as one for which $P/A < H/3$ where H is the hardness of the softer member of the sliding pair.

Shaw (ref. 3) has indicated the transition from independent asperity behavior to complete interaction by figure 2. The circles mark the plastic regions beneath asperities. When the load becomes high enough, the plastic zones interact and the entire subsurface becomes plastic. The real area of contact increases more rapidly with P when this occurs. This corresponds to $P/A = H/3$ in the Burwell and Strang experiment.

Amonton's Law (coefficient of friction independent of P) holds for lightly loaded sliders but not for heavily loaded ones, since A_R is then no

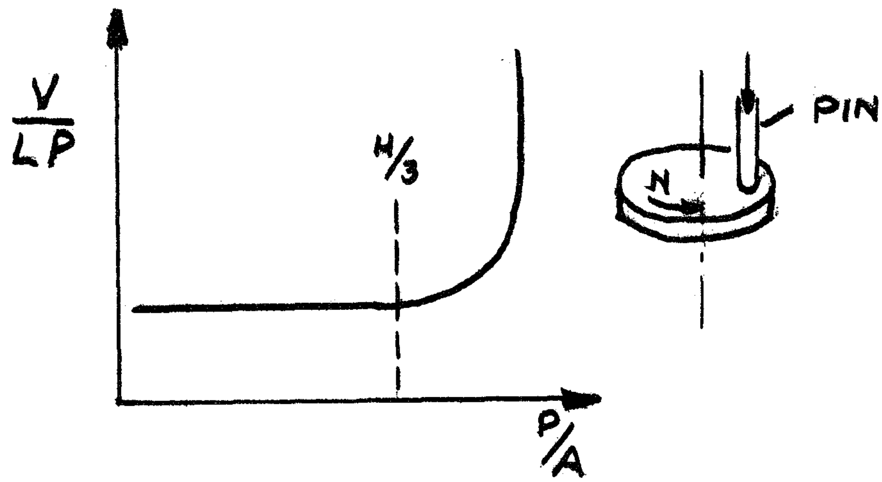


Figure 1. — Wear characteristics for steel hemisphere sliding on hard steel disc using an inert fluid lubricant (Burwell and Strang, ref. 2).

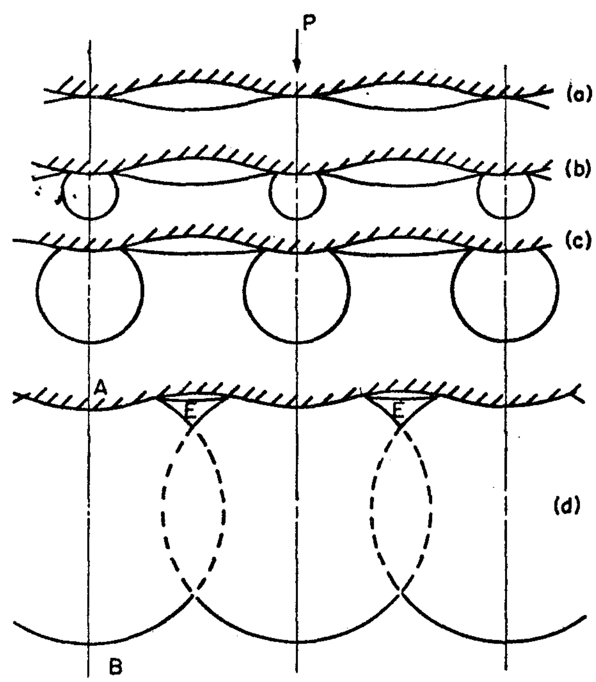


Figure 2. — Plane slider under progressively increasing load P. Upper surface is hard, lower surface is soft (Shaw, ref. 3).

longer equal to P/H as indicated in equation 2 which only holds for lightly loaded sliders.

Figure 3 shows experimental data for heavily loaded sliders where the entire subsurface is flowing plastically. In this plot the shear stress, τ, on the slider is shown plotted against the normal stress, σ (both measured in terms of the apparent area of contact, A). The coefficient of friction is $\frac{\tau}{\sigma}$ and this is seen to decrease with increased load (increased σ) for points beyond A. From this plot it is clear that Amonton's law does not hold for heavily loaded sliders.

Figure 4 interprets figure 3 in terms of the value of A_R relative to A. Here three regimes of sliding are identified. In region I, $A_R \ll A$ and asperities act independently. This is the regime of the lightly loaded slider. In region II, $A_R < A$, the asperities are interacting and the entire subsurface is plastic. Region III is the hypothetical case where $A_R = A$. This would correspond to the 45° shear plane for a simple compression specimen before fracture. For this situation the flow stress τ on the 45° plane is independent of the normal stress on this plane and hence the τ vs. σ line is horizontal.

In region III the curve has been drawn to connect the straight line characteristic corresponding to Amonton's law in region I with the horizontal line of region III. The experimental data of figure 3 substantiates the shape of the curve drawn in figure 4.

Williamson (ref. 5) has obtained results that indicate the transition from regions I to II. An aluminum specimen with bead-blasted surface was encased in a steel container and loaded by a polished flat piston that closely fitted the steel container. As load was applied the surface asperities were flattened but did not disappear. Figure 5a shows the change in the number of plateaus

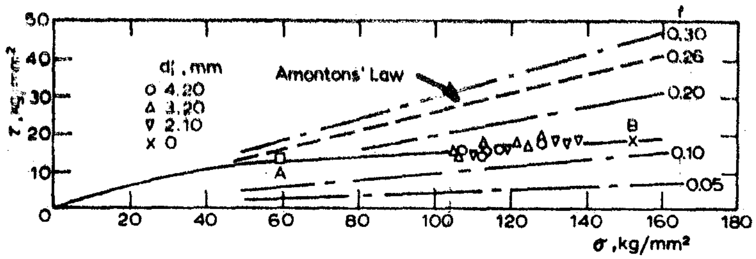


Figure 3. — Variation of τ with σ for 1/2-in. dia. Brinell ball tested in torsion against mild steel specimen. Diameter d is size of central hole beneath sphere. Point A is for subplastic load (Shaw, Ber, and Manin, ref. 4).

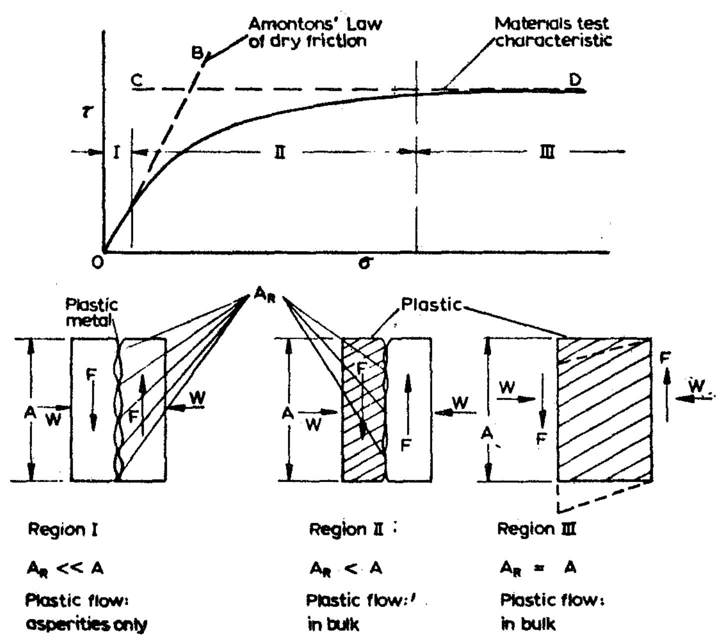


Figure 4. — Three regimes of surface contact (Shaw, ref. 4).

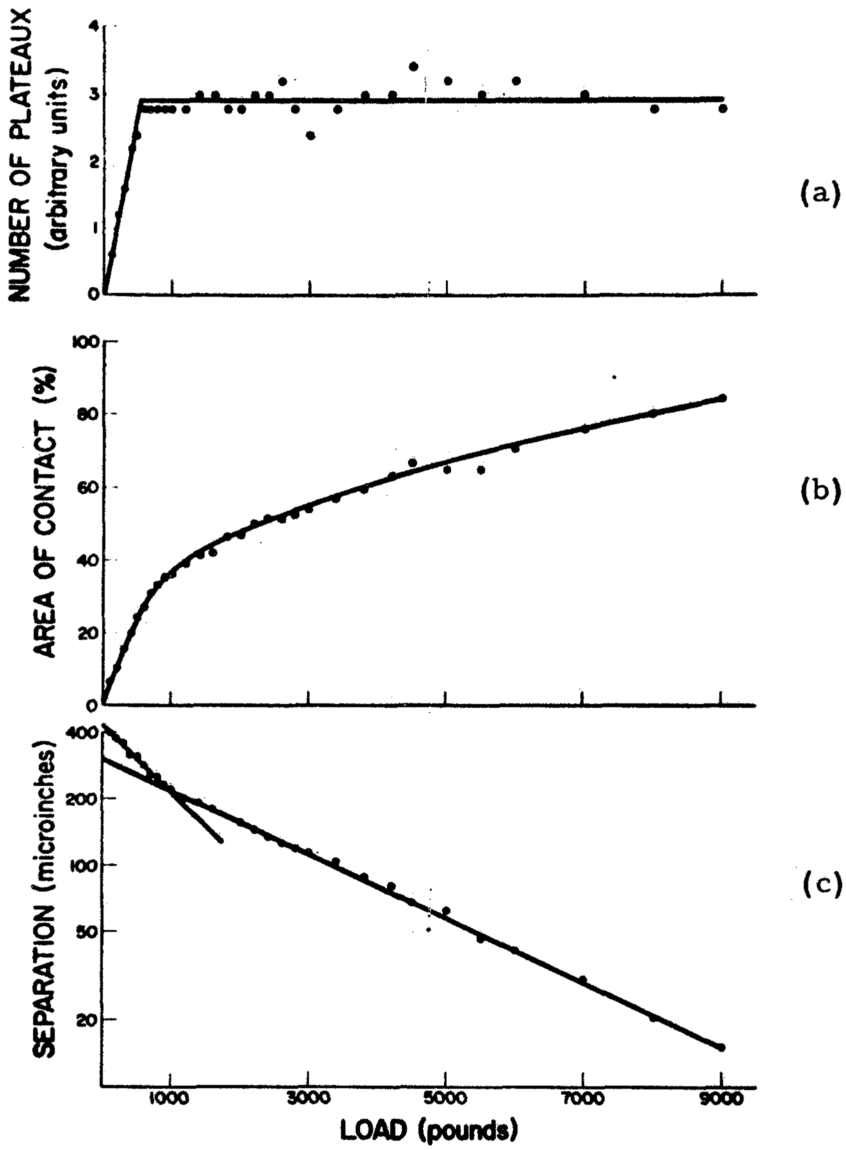


Figure 5. — Behavior of contacting surfaces under very high pressure (Williamson, ref. 5).

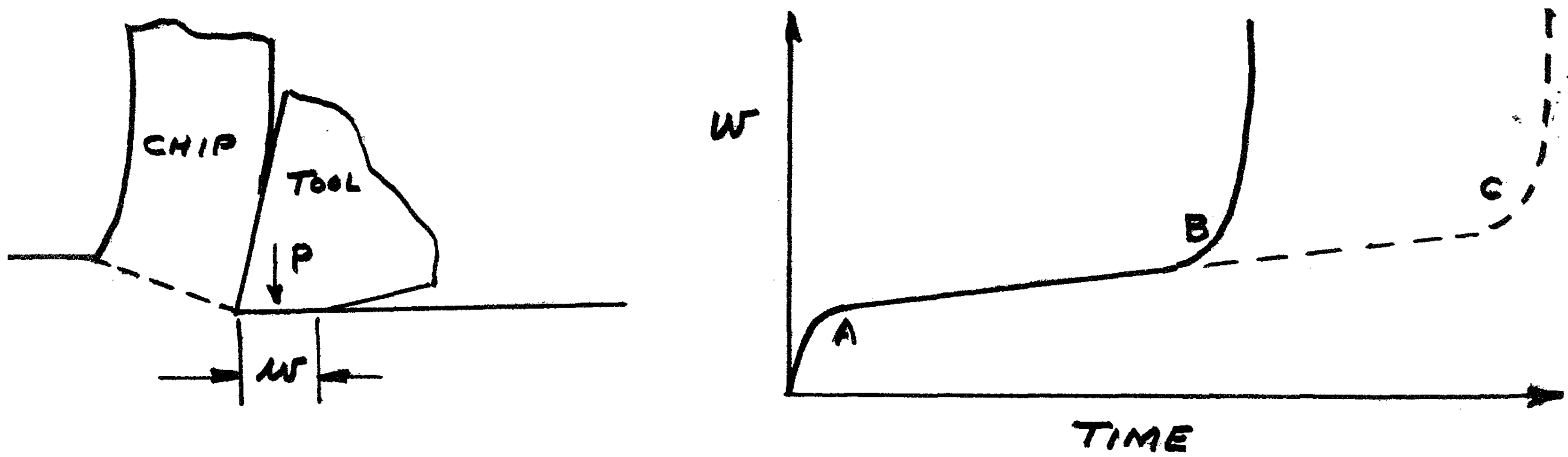
with load. At first the number increases linearly with load and then remains constant with further increase in load. Figure 5b shows the variation in area of contact with load and this curve is seen to have a knee at about the same load as that where the previous one ceased to rise. Figure 5c shows the variation in separation of two surfaces versus load. Again, there is an abrupt change in the slope of this curve at a load of about 900 pounds which corresponds to the force required for bulk plastic flow of the specimen.

It therefore appears as though the abrupt change in behavior in curves 5a, b, and c corresponds to a transition from the action of region I to that of region II. In region I the real area of contact increases linearly with load (Amonton's law) and the surfaces come rapidly together. In region II the rate of increase in real area with load decreases as the surfaces approach each other.

It appears apparent that different rules of behavior pertain for heavily loaded sliders than for lightly loaded sliders, just as different rules of behavior pertain to elastohydrodynamic bearings as for ordinary hydrodynamic bearings.

We might distinguish behavior for region II type sliding from that of lightly loaded sliders (region I) by referring to the former as sliding under <u>fully plastic support</u> (FPS), whereas the latter would correspond to sliding under <u>independent asperity support</u> (IAS).

An example might be cited at this point to stress the importance of recognizing the onset of sliding under conditions involving gross subsurface flow. When metal is cut a wear land, w, develops gradually on the clearance face of the tool (fig. 6a). If the size of the wear land, w, is plotted against time, a curve such as that of figure 6b results. This curve has a



(a) (b)

Figure 6. — Development of wear land on metal cutting tool.

rapid rise at the beginning and at the end of tool life, with a more gradual rate of wear in between.

For the freshly sharpened tool, w will be very small and $\frac{P}{A}$ will be large and greater than $\frac{H}{3}$ where H is the hardness of the "work". Thus at the outset sliding on the tool flank is under conditions of gross plastic flow and the wear rate will be high.

After a time, $\frac{P}{A} < \frac{H}{3}$, and sliding on the tool flank corresponds to that of a lightly loaded slider and the tool wear rate is low (A to B in fig. 6b). As w increases, the temperature will rise (as $\sqrt{w}$ for a given load P), as will the load, P . Thus, H will decrease due to the temperature rise and $\frac{P}{A}$ will increase if P increases more rapidly than A (A = wb where b is the width of cut). Subsequently, $\frac{P}{A} > \frac{H}{3}$, subsurface flow will again occur and the wear rate will increase rapidly. Point B marks the practical limit of tool life.

It should be noted that the increase in wear rate at B does not indicate that the tool is softening (as commonly assumed); but instead that the "work" is softening. The tool is, of course, a much more refractory material than the work.

It has recently been found that tool life may be significantly improved when machining a stainless steel by introducing additives which make the workpiece more refractory. This new material has about the same wear rate as the old, but may be used to a wear land corresponding to C instead of that at B in figure 6 before the condition of catastrophic wear is reached.

This example illustrates the importance of understanding the difference in wear characteristics for heavily and lightly loaded sliders.

Asperity Mechanics

In the experiment of Williamson previously described, it was found that the load on the piston to cause the unconstrained aluminum specimen to flow in bulk was 900 pounds. However, when a load four times this value was applied to the piston, it was found that the real area of contact had reached a value of only 50% of the apparent area. Thus, even though the mean stress on the asperities was eight times that corresponding to the uniaxial bulk flow stress, the asperities were still half present.

Moore (ref. 6) had drawn attention to this phenomenon earlier by pressing a hard cylinder into a soft copper surface having small parallel grooves (.025 mm apart x 20° included angle) machined in the surface. He found that even though the subsurface flowed extensively the grooves were still substantially present.

In seeking an explanation for this anomoly, it is necessary to consider the mechanics of asperity deformation. Since asperities are very blunt, the deformation of an asperity by a smooth surface is similar to the formation of a brinell impression (fig. 7).

When a split specimen having a grid in its meridional plane is deformed by a sphere placed on the split the plastic region beneath the surface may be clearly distinguished from the elastic region. The elastic-plastic boundary must satisfy the elastic solution for a loaded punch, since the elastic-plastic boundary will be a line of constant shear stress by the Tresca flow criterion of plasticity. Figure 8 shows lines of constant shear stress, M, for a Hertzian load distribution on a punch of diameter 2a. One of these lines is the elastic-plastic boundary. Which one must be determined by considering another convenient load distribution on the punch (a concentrated load) and making the two solutions consistent with the

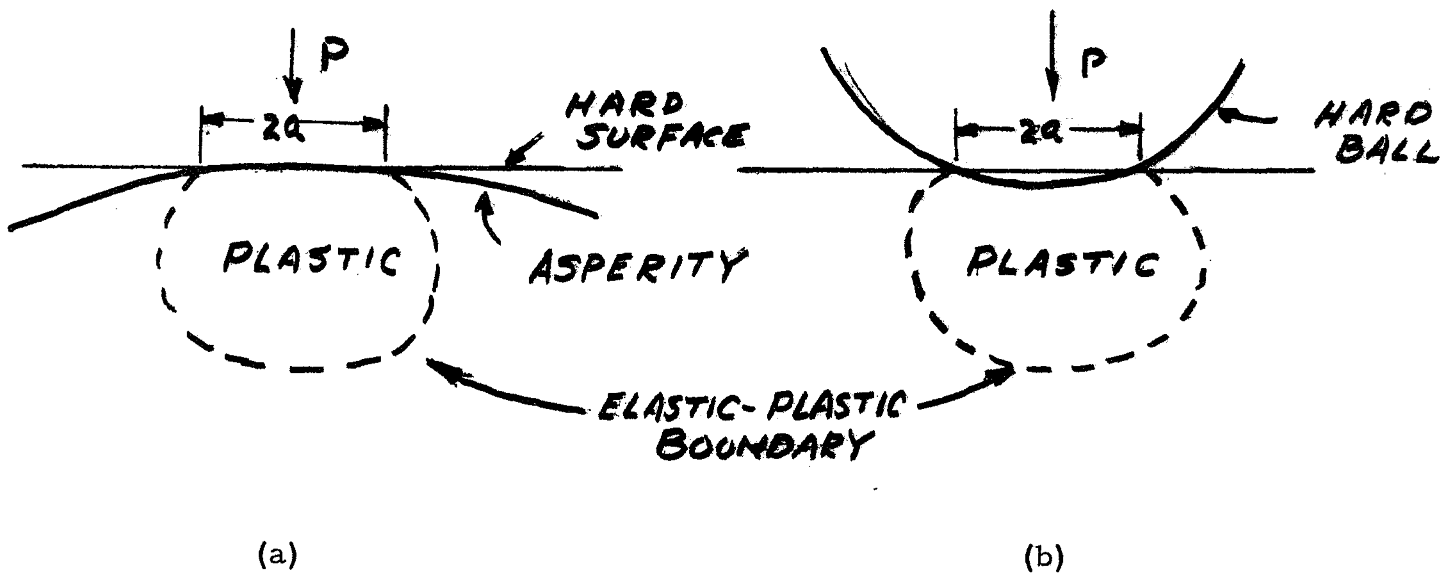


Figure 7. — Similarity of asperity: (a) asperity deformation. (b) Brinell test.

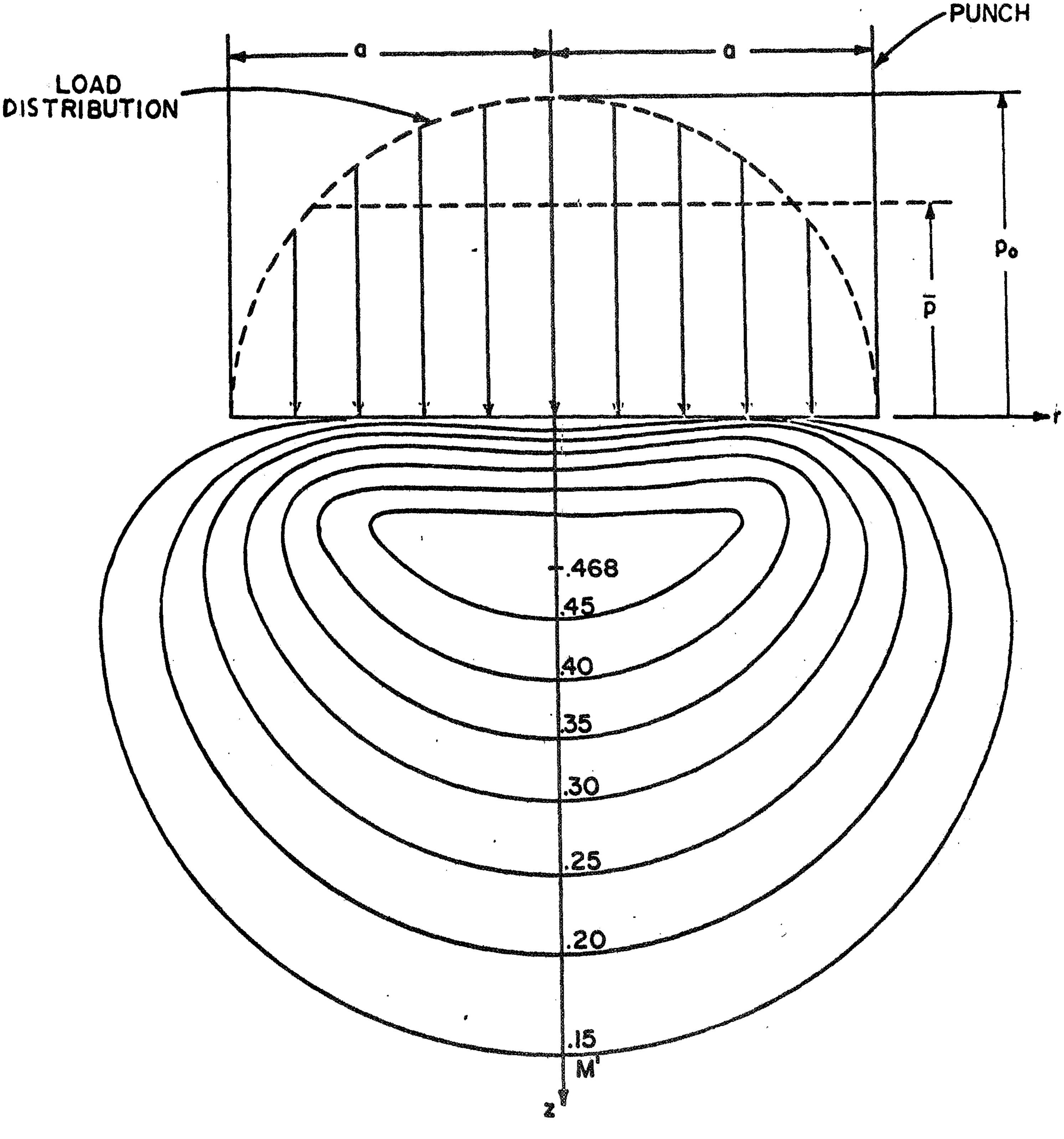


Figure 8. — Lines of constant sheer stress, M, for a Hertzian load distribution on a spherical punch loaded to the point that the diameter of contact is 2a. (Shaw and DeSalvo, ref. 7).

principle of St. Vennant. When this is done the mean load having a flat spot of diameter 2a on a circular asperity is found to be 3γ, where γ is the uniaxial compressive flow stress of the metal (ref. 7).

If we consider an array of asperities, partly flattened (fig. 9), the mean stress on each flat area will be 3Υ. In figure 9 a coordination number of 6 has been assumed for the asperity arrangement (each asperity has 6 nearest neighbors). The asperities should flatten until the total load on all asperities will be just sufficient to cause the subsurface to flow plastically (i.e., until the stress in the subsurface = 1.1Υ). From the plan view of figure 9,it is evident that the area of two asperity flats (shaded) is equivalent to area BCDEFG. The subsurface should therefore flow when

$$3\Upsilon(2)(\pi a^2) = 6\{\tfrac{1}{2}\,[2(a+b)]^2 \sin 60°\}1.1\Upsilon \tag{4}$$

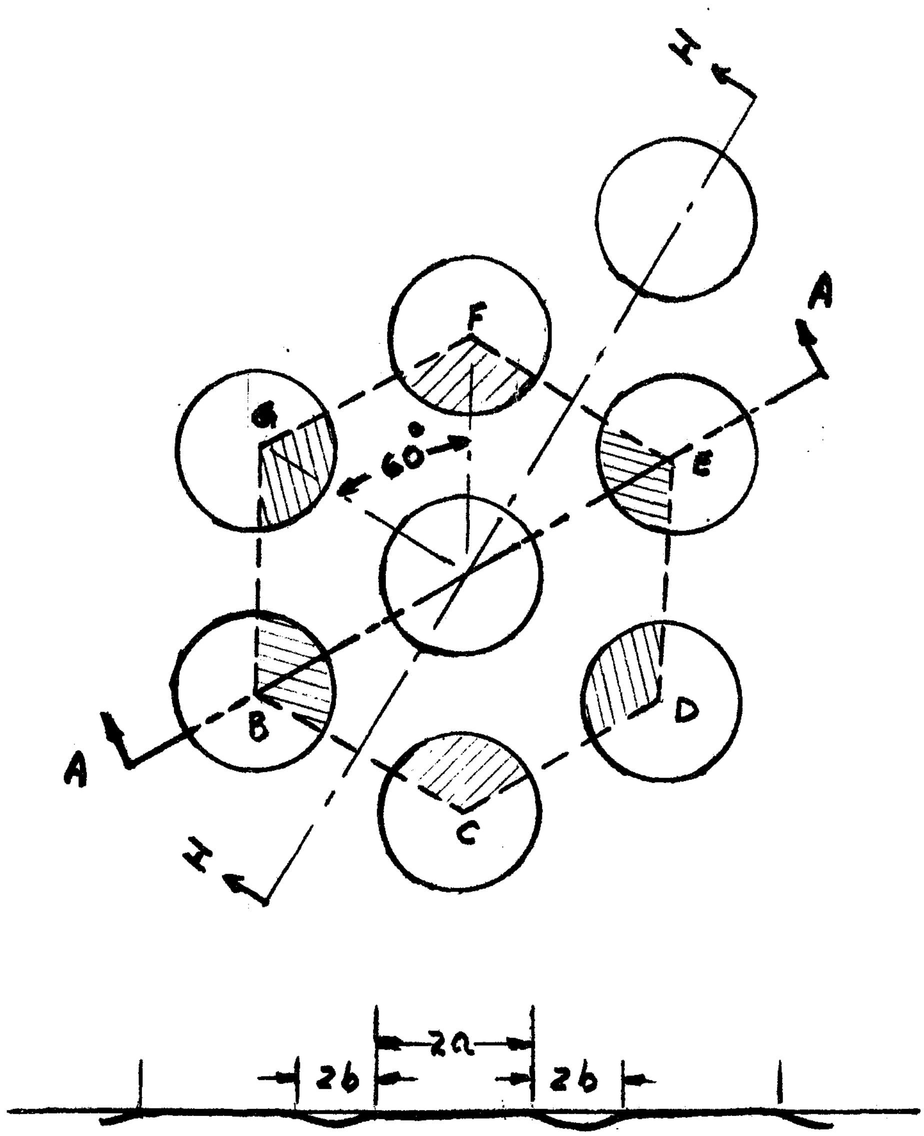
or

$$\frac{b}{a} = 0.28$$

Thus, three dimensional asperities when viewed in section AA should be flattened to the point where $b/a = 0.28$. This will be the ratio of $\frac{\text{distance between flats}}{\text{extent of flats}}$ for a section AA in figure 9. However, if the section considered were HH then the half distance between flats, b, would be 2(.866)(.28a) or b/a would be 0.485 instead of 0.28. In general, the spacing of asperities will not be uniform,but will be randomly distributed between 2b = 2(.280a) and 2(.485a). It appears reasonable to assume that,on the average,

$$\frac{b}{a} = \frac{.280 + .485}{2} = 0.38$$

for a representative section.



SECTION AA

Figure 9. — Array of asperities having coordination number 6 (Shaw, ref. 8).

This is in general agreement with the observations of Williamson and of Moore.

However, in an experiment performed in preparation for this Workshop at Carnegie-Mellon University, some parallel grooves having a spacing of about 0.1 inch and an included angle of 60° were produced in a soft steel surface. When these grooves were pressed with either a cylinder or a ball the grooves very nearly completely disappeared. This result is in complete disagreement with those of Williamson and Moore. It is suspected that the size of the grooves is significant here; but further study is required to completely explain these contradictory results.

It is of interest to note that the Moore effect has been found in the case of plasticine and with indium. When a 10-32 screw is rolled across a flat plasticine surface very shallow grooves may be produced which are not pressed out when a steel ball or cylinder is forced a long way into the surface relative to the depth of the grooves (ref. 8). Only the tops of the grooves are flattened. Williamson (ref. 9) has done a similar experiment with indium which, of course, has a strain recrystallization temperature below room temperature. The fact that this effect may be demonstrated on such a wide variety of materials suggests that it is not controlled by material structure or deformation mode; but that it is controlled by the geometry of the system and the distribution of stresses.

A quantity called the plasticity index, ϕ, has been proposed by Greenwood and Williamson (ref. 10) to determine when asperities should behave elastically and when plastically. This nondimensional quantity is

$$\phi = \frac{E}{H}\sqrt{\frac{\alpha}{\beta}} \tag{5}$$

where E = Young's modulus of elasticity,

H = hardness of metal,

α = standard deviation of asperity height distribution, and

β = radius of curvature of the highest asperities

By considering a statistical array of asperities, it may be shown that only about 2% of the asperities will be deformed sufficiently to go plastic when ϕ is equal to one. Thus $\phi = 1$ may be taken to indicate the onset of plastic flow. In most practical cases ϕ is either large or small relative to one. The quantity ϕ may therefore be used in the manner of a Reynolds number to determine when asperities act predominantly elastic ($\phi < 1$) or predominantly plastic ($\phi > 1$).

For example, the asperities of a ball bearing will have a ϕ of about 1/50 and hence they will behave elastically, while the asperities of a loaded turned surface will characteristically be about 20 and hence the asperities on such a surface will behave plastically.

The plasticity index is seen to consist of two parts: (a) a material part, $\frac{E}{H}$, and (b) a geometrical part, $\sqrt{\frac{\alpha}{\beta}}$. It is of interest to note that ϕ is independent of the applied load.

The plasticity index may decrease with wear if conditions are such as to cause a smoothing (lower α, larger β) of the surface with time. This normally involves limiting the path length of wear debris, which will tend to cause surface roughening if allowed to roll up and grow.

The lowest wear rate undoubtedly is associated with a value of $\phi < 1$ as in the case of a ball bearing. If ϕ should increase there will be an increase in attritious wear since larger junctions will pertain and this will primarily increase K in equation 1. There will also be an increase in the rate of wear, $\frac{V}{L}$, with increase in applied load due to an increase in A_R (equation 1). An abrupt increase in wear will occur when the subsurface goes plastic, which from equation 4 will occur approximately when

$$\frac{A_R}{A} = \frac{2\pi a^2}{6\{\frac{1}{2}[2(a + b)]^2 .866\}} \tag{6}$$

where $\frac{b}{a} = 0.28$

or when $\frac{A_R}{A} = 0.37$

Role of Fine Structure

Asperities are very small relative to the sizes of ordinary materials test specimens and therefore we should not assume that asperity properties are the same or even close to those for materials in bulk.

Such items as grain boundaries, phase differences, structural defects of all sorts (including impurities, microcracks, and missing atoms), surface layers (oxides due to the reaction of surfaces with air; sulfides, chlorides, phosphides, etc. due to reaction of surfaces with lubricants; adsorbed films of organic alcohols, acids and oxyacids, ketones, aldehydes, etc.) and residual stress fields distributed on a micro basis all tend to make the properties of materials inhomogeneous. Therefore the behavior is apt to vary widely from point to point.

In general, materials become stronger when the loaded specimen volume gets smaller, not only with regard to fracture, but also relative to flow. This is due to the fact that the probability of encountering a stress concentration of a given magnitude decreases with a decrease in the effective volume of the specimen.

It has been shown that such structural influences play an extremely important role in a number of practical applications. In fine grinding the energy required to remove a unit volume of metal is 30 times that required in ordinary cutting operations, since in fine grinding the shear strength of the metal removed approaches the theoretical shear strength value ($\frac{G}{2\pi}$ where G = shear modulus) due to the absence of stress concentrations which promote dislocation formation in the size range pertaining (ref. 11). Similar size effects have been shown to hold in materials testing (ref. 12), in hardness testing (ref. 13), and in comminution (ref. 14). Brittleness is a property that has no meaning unless the loaded specimen size is specified. For example, marble is perfectly ductile when loaded by a microhardness indenter but perfectly brittle when subjected to an ordinary macrohardness test. The probability of finding a large flaw in the loaded zone is so great in the ordinary test that the material fails in brittle fracture immediately the load is applied. However, in the microhardness test the probability of finding a critical flaw in the loaded zone approaches zero and the material may be indented to a substantial depth without the slightest indication of crack formation. V. Weiss of the Department of Metallurgy at Syracuse University has recently published papers associated with the size effect in materials testing.

The behavior of a hard oxide on a soft substrate is extremely important to the performance of electrical contacts. Details of behavior in actual contacts is provided by studying a large plasticine to simulate a brittle oxide coating (ref. 15). When load is applied the action takes place in three stages:

1. Radial crack formation.
2. Circumferential crack formation.
3. Gross flow and crazing.

The difference between lubricated (vasoline spread on shellac) and unlubricated shellac-coated asperities operating in pairs is most interesting. When no lubricant is present, cracks formed on one asperity transfer to the other and "metal-to-metal" contact results. When a lubricant is present, the cracks in one surface in general do not line up with those in the other and there is less bonding.

The adhesion of contacts appears to occur at periodically spaced distances on contacting oxidized asperities — at those points where the periodically spaced cracks line up.

It was suggested that the Lisegang phenomenon in geology which accounts for the banding observed in natural agates might provide another source of inhomogeneity, namely, one that would appear in surface films. This phenomenon may be demonstrated (Prof. Kahlweit of Göttingen) by placing a drop of $AgNO_3$ solution on a sheet of gelatin containing $KCrO_4$ in the gelatin. The Ag ion diffuses through the gelatin causing a periodic precipitation of $AgCrO_4$. It is conceivable that banded surface films might arise from a mechanism such as this. A gold film containing 2% indium exhibits such a banded structure.

A recent publication of Prof. Halling of Manchester is concerned with some new asperity model studies.

It was suggested that the Moore experiment might be a convenient one to provide information on size effects and the role of the many inhomogeneities that may occur on a micro scale.

A note of caution was sounded concerning inferences drawn from the shapes of wear particles. Wear particles are generated as plates which are rolled up into cylinders as they pass between two sliding surfaces. Only by removing wear particles as soon as they are generated is it possible to study their initial size and shape. Experiments involving a slider on a frequently replaced screen are capable of revealing the characteristics of freshly generated wear particles.

The possibility of wear particles being generated when asperities are <u>unloaded</u> instead of when being loaded was suggested by the recent discovery that metal beneath an indenter flows plastically twice. Once (downward) upon application of the load and a second time (upward plastic flow) over a smaller volume when the load is removed (ref. 7).

The role of hydrogen in causing steel surfaces coated with ceramic to flake was cited as a possible cause of wear. Moisture in the slip applied to the clean metal surface decomposes on firing to give atomic hydrogen which will diffuse through the steel. This hydrogen will tend to collect at points of stress concentration and in the case of a ceramic coated steel surface may generate sufficient local pressure to cause flaking of the ceramic. A paper on hydrogen embrittlement by R. A. Oriane of the U. S. Steel Fundamental Laboratory soon to be published by AIME is of interest in this connection, as is the work of the DuPont Savannah river group on the orientation of hydride nodules in stressed metals due to the tendency for hydrogen to precipitate perpendicular to a tensile field and perpendicular to a compressive field in zircaloy and titanium alloys (ref. 16).

Surface Geometry

Different details of geometry of finished surfaces are of interest for different purposes. The slopes of the tops of asperities are of greatest interest in friction and wear. The geometry at the bottoms of asperities appears to be of greatest interest relative to strength and the Rehbinder effect, while the entire profile appears important relative to adhesion, plating, and perhaps catalysis.

In studying the slopes at the tips of asperities for friction and wear applications, it was suggested that Weibull extreme value statistics may be of value in providing a better estimate of the slopes of the highest points than may be obtained by working with the mean asperity slope of a band 10% of the peak-to-valley distance down from the highest peak. By use of a Weibull plot the 10% and 90% rank slopes may readily be obtained as well as the median (50%) rank value. The slope of the Weibull plot together with the mean slope of the highest 10% peaks should better characterize surfaces produced in different ways for use in friction and wear applications than use of the mean value alone.

Kramer Effect and the Role of Electrons Emitted from Surfaces

The Kramer effect involves the emission of electrons from a freshly scratched, cut, or broken surface. These electrons may be detected by a Geiger counter and caused to activate a loud speaker. A recently completed PhD thesis at Delft (ref. 17) written in the Dutch language was abstracted by

Dr. Salomon. This study was concerned with the production of images produced on photographic plates by the emission of electrons from a surface. The electrons emitted are photoelectrons and their emission is stimulated by irradiation of the surface by ultraviolet light. The emission of photoelectrons depends not only on irradiation, but also on the rate of oxidation of the surface, which may be controlled by use of methane as a cover gas which increases sensitivity. The details of surface texture seen on the photographic plate result from the different rates of electron emission at different points on the surface.

It would appear that the flow of electrons that would come from a freshly scratched asperity as it oxidizes could have an important influence on bond formation between asperities making contact and on surface chemical reactions. This subject is therefore of importance to those interested in wear and is particularly applicable to the wear of heavily loaded sliders where more new surface will be generated as a result of an increased wear rate.

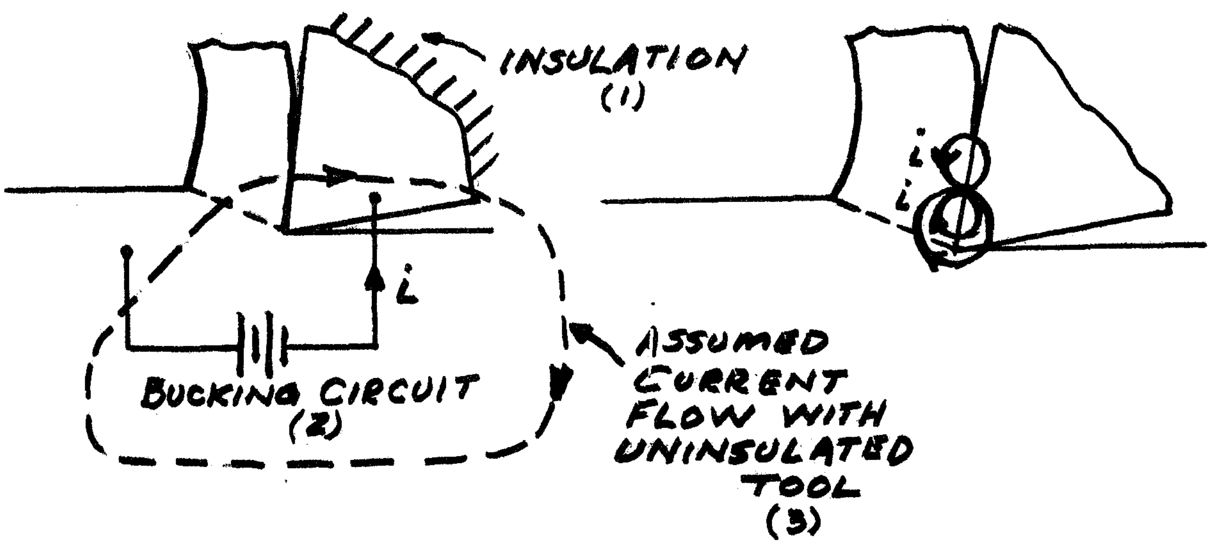
The enormous influence that the generation of fresh surfaces has on surface reactions is dramatically illustrated by the mechanical activation process (ref. 18) in which organometallic reactions that will not go under ordinary laboratory conditions may be readily carried out by cutting the metal under the surface of liquid reactants. For example, when magnesium is cut in the presence of phenyl chloride and ethyl ether (solvent), the corresponding Grignard reagent (phenylmagnesiumchloride) is produced even though this reaction cannot be induced in the ordinary glass apparatus of the organic chemist. The electrons emitted from the freshly cut surface undoubtedly figure in these reactions, although the increased electron mobility at the freshly cut surface is augmented by local autoclave conditions in the zone of reaction (pressures up to the flow stress of the deforming magnesium and local temperatures of several hundred degrees on the surface of the deforming metal).

Over the years there have been many claims and counter claims concerning the role of the heavy thermoelectric currents that are generated when a tungsten carbide tool cuts steel (ref. 19). The current flow in these cases is from chip to tool and it is claimed that wear may be reduced if this current flow may be prevented by (a) insulating the tool from the system, or (b) by introducing a counter emf that reduces the current flow to zero (fig. 10a). Great claims have been made for this method of preventing tool wear; but these have generally not been substantiated.

It would appear that the explanation for this anomoly lies in the fact that, in general, the heavy thermoelectric currents are eddy currents as shown in figure 10b. Insulating the tool or applying a counter emf will have little influence on these eddy currents.

Occasionally, the path resistance may be less through the machine and "work" than for the path of an eddy current, which would be the case if a semi-conducting oxide were developed between chip and tool. In such instances it would be possible to alter the current flow by tool insulation or by use of a bucking circuit. It is probable that in such cases good results have been obtained and reported in the literature using these techniques. However, it is believed that, in general, the situation is as shown in figure 10b. The only thing that will reduce the extremely high current flow here is the formation of an insulating oxide film that greatly increases the electrical resistance between chip and tool.

Recently there have been a number of reports of greatly improved tool life (from 2 to 10 times) due to the formation of a stationary oxide film on the surface of titanium carbide containing tools. This oxide has been shown to be due to the build up of inclusions in the steel resulting from special deoxidation techniques (ferrosilicon and calcium oxide) (refs. 20-22).



(a) (b)

Figure 10. — Current flow in metal cutting situations.

Alternatively, it may be induced by use of special oxide forming lubricants such as a 4% soda water solution (ref. 23). While these oxide films have generally been thought to act as a diffusion barrier to prevent the loss of carbon from the WC crystals in the tool face to the austenitic layer on the rapidly moving chip face, it is also possible that the oxide is preventing the large eddy currents that will be present in the absence of an insulating film.

The complete absence of crater wear for ceramic tools could be due to the absence of eddy currents with a tool material that is electrically nonconducting.

It appears worth giving some thought as to how photochemical and thermoelectric electron flow might be prevented or reversed, in those cases where the electrons flow in such a direction as to weaken the slider. Possible solutions might be found in the suitable choice of composite slider materials or by new methods of rendering sliding surfaces nonconducting.

Future Experiments

More experiments are needed in which friction and wear characteristics are studied under conditions of gross subsurface flow. An example of one such experimental system will be given.

It would be of interest to run both friction and wear experiments under conditions of gross subsurface flow with variable constraint. A method of doing this is suggested in figure 11. Here a specimen of height h would be rotated against two hard spheres subjected to a load P. Load P would be increased in each case until a brinell impression of diameter, 2a, was produced (where $2a/D = 0.4$). The mean load on the interface between sphere and rotating specimen would be a function of h/2a and specimens of different thickness should be tested ($h/2a = 1$ to 10). The mean stress, $\overline{p}$, on the interface should be Y when $\frac{h}{2a} \cong 1$ and should be about $3Y$ when

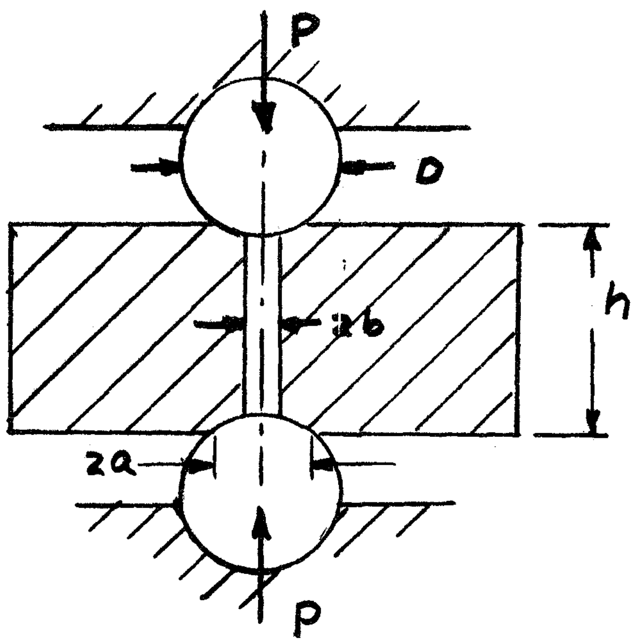


Figure 11. — Proposed friction and wear test under conditions of subsurface plastic flow with different degrees of constraint.

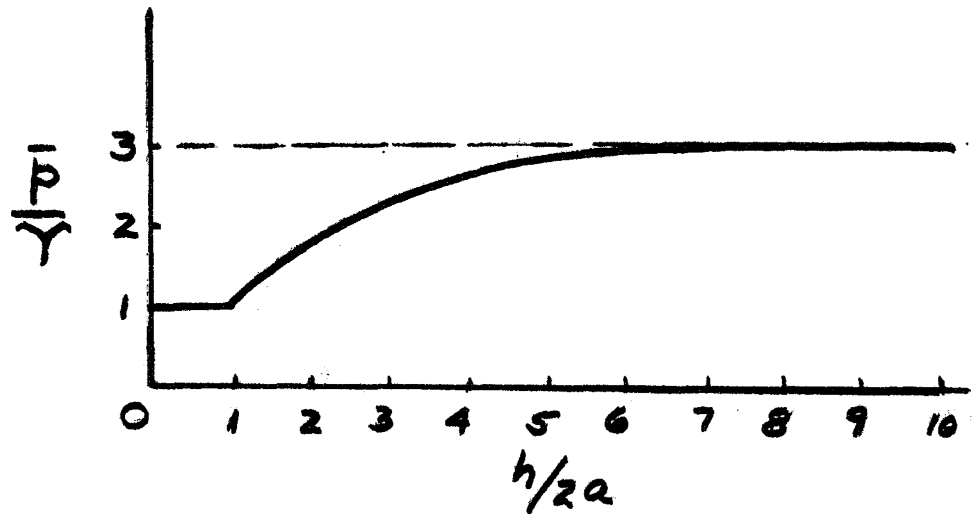


Figure 12. — Variation of constraint factor $\overline{p}/\gamma$ with h/2a.

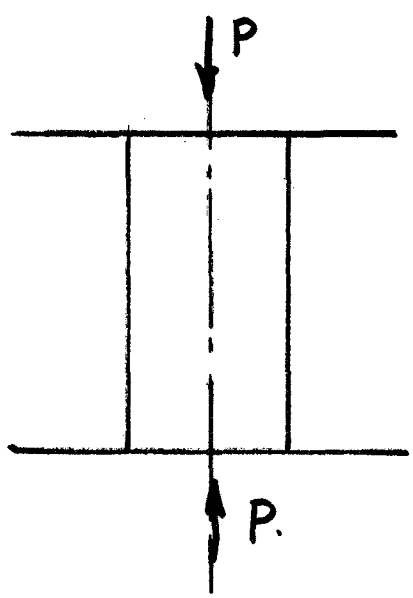


Figure 13. — Uniaxial compression test.

$\frac{h}{2a} \cong 10$, varying approximately as shown in figure 12 as $h/2a$ varies. As previously, Y = the uniaxial flow stress in a simple compression test such as that shown in figure 13.

Since the full constraint ($\overline{p}/Y = 3$) would probably not be developed when a central hole ($2b/D = 0.1$ is suggested) is present, the experiments should be repeated without a central hole.

Friction torque (and hence a mean coefficient of sliding friction) could be measured on one of the balls and the wear (progressive increase in dimension 2a) could be determined versus time.

Different lubricants should be investigated.

These experiments would yield data obtained under conditions of subsurface flow and when the constraint factor, $\overline{p}/Y$, on the rubbing surfaces varied from 1 to 3. These friction and wear results with gross subsurface plastic flow could be compared with those for conventional sliding (lightly loaded slider) by periodically decreasing the load p after first having run the apparatus under conditions to produce a spherical surface having $2a = 0.4D$.

The foregoing experiments should be repeated with heavy dc current flows in both directions (from ball to specimen and from specimen to ball). If one ball were insulated, the effect of the current flow on wear would be clearly evident by the difference in performance of the two balls.

The experiments described should employ different pairs of metals as follows:

1. Hard steel ball on soft steel specimen.
2. Hard steel ball on brass specimen.
3. Hard steel ball on 18-8 stainless steel.
4. 10% Co - WC ball on soft steel specimen.
5. 10% Co - WC + TiC ball on soft steel specimen.
6. Ceramic ball (nonconducting) on soft steel specimen.

It is felt that results of this sort would greatly improve our knowledge of the much neglect field of lubrication, friction,and wear under conditions involving gross subsurface flow.

Concluding Remarks

It is felt that an important area of the entire field of lubrication, friction,and wear has been identified — sliding under conditions of subsurface plastic flow. Conditions for this type of sliding differ significantly from the type of sliding ordinarily studied due primarily to the interaction of adjacent asperities which causes performance to deviate from Amonton's Law.

Studies of sliding under conditions of subsurface plastic flow are not only of importance for applications directly involving these conditions, but such studies are bound to lead to a better understanding of the performance of lightly loaded sliders by accentuating actions that are small but important under lightly loaded test conditions.

It is felt that the discussions that have taken place at this Workshop between people of entirely different background and experience represents an important contribution to a better understanding of the performance of heavily loaded sliders.

REFERENCES

1. Archard, J. F.: Wear. Interdisciplinary Approach to Friction and Wear. P. M. Ku, ed., NASA SP-181, 1968, pp. 267-333.

2. Burwell, J. T.; and Strang, C. D.: On the Empirical Law of Adhesive Wear. J. Appl. Phys., vol. 23, no. 1, Jan. 1952, pp. 18-28.

3. Shaw, M. C.: The Role of Friction in Deformation Processing. Wear, vol. 6, 1963, pp. 140-158.

4. Shaw, Milton C.; Ber, Abraham; and Mamin, Pierre A.: Friction Characteristics of Sliding Surfaces Undergoing Subsurface Plastic Flow. J. Basic Eng., vol. 82, no. 2, June 1960, pp. 342-346.

5. Williamson, J. B. P.: Topography of Solid Surfaces. Interdisciplinary Approach to Friction and Wear. P. M. Ku, ed., NASA SP-181, 1968, pp. 85-142.

6. Moore, A. J. W.: Deformation of Metals in Static and in Sliding Contact. Proc. Roy. Soc. (London), Ser. A, vol. 195, no. 1041, Dec. 7, 1948, pp. 231-244.

7. Shaw, M. C.; and De Salvo, G. J.: A New Approach to Plasticity and Its Application to Blunt Two-Dimensional Indenters. Paper 69-WA/PROD-11, ASME, Nov. 1969.
   Shaw, M. C.; and De Salvo, G. J.: On the Plastic Flow Beneath a Blunt Axisymmetric Indenter. Paper 69-WA/PROD-12, ASME, Nov. 1969.

8. Shaw, M. C.: Asperity Mechanics. To be published, 1970.

9. Williamson, J. B. P.: Behavior of Asperities. To be published, 1969.

10. Greenwood, J. A.; and Williamson, J. B. P.: Contact of Nominally Flat Surfaces. Proc. Roy. Soc. (London), Ser. A, vol. 295, no. 1442, Dec. 6, 1966, pp. 300-319.

11. Backer, W. R.; Marshall, E. R.; and Shaw, M. C.: The Size Effect in Metal Cutting. Trans. ASME, vol. 74, no. 1, Jan. 1952, pp. 61-72.

12. Shaw, Milton C.: A Yield Criterion for Ductile Metals Based Upon Atomic Structure. J. Franklin Inst., vol. 254, no. 2, Aug. 1952, pp. 109-126.

13. Shaw, Milton C.: Plastic Flow in the Cutting and Grinding of Materials. Proc. Nat. Acad. Sci., vol. 40, no. 6, June 15, 1954, pp. 393-401.

14. Walker, D. R.; and Shaw, M. C.: A Physical Explanation of the Empirical Laws of Comminution. Min. Eng., vol. 6, no. 3, Mar. 1954, pp. 313-320.

15. Osias, J. R.; and Tripp, J. H.: Mechanical Disruption of Surface Films on Metals. Wear, vol. 9, 1966, pp. 388-397.

16. Louthan, M. R., Jr.; and Marshall, R. R.: Control of Hydride Orientation in Zircaloy. J. Nucl. Mat., vol. 9, no. 2, July 1963, pp. 170-184.

17. Veerman, C. H. R.: On the Reproduction of Plastically Deformed Surfaces by Photoelectrons. Dissertation, Tech. Hoch. Delft, Stevin Laboratory, 1968.

18. Shaw, M. C.: Hydrosphere-New Hydrodynamic Bearing. J. Appl. Mech., vol. 15, no. 2, June 1948, pp. 137-145.

19. Opitz, H.; and Axer, A.: Beemflussung des Verchleissverbalters bei spanenden Werkzeugen durch flussige und gasformige Kuhlmittel und electrische Massnakmen. Forschungsber Wirt. Verkehrmin. Nordrhein-Westfalen, No. 271, 1956.

20. Opitz, Herwart; et al.: Einfluss oxydischer Einschlüsse auf die Bearbeitbarkeit von Stahl Ck 45 mit Hartmetall-Drehwerkzeugen. Arch. Eisenhütten., vol. 33, no. 12, Dec. 1962, pp. 841-851.

21. Trent, E. M.: Cutting Steel and Iron with Cemented Carbide Tools. Part III. The Influence of Metallurgical Factors in the Flow Zone. J. Iron Steel Inst., vol. 201, pt. 12, Dec. 1963, pp. 1001-1015.

22. Diederich, Nikolaus: Betrag zur Ermittlung der Ursachen fur das Auftreten von sulfidischen und oxidischen Schutzschichten an Hartmetalldiehwerkzeugen bei der Zerspannung von Stahlwerstoffen. Dissertation, Tech. Hoch. Aachen, 1968.

23. Koenig, W.; and Diederich, N.: Cutting Fluids Improve Tool Life of Carbide Tools by Chemical Reactions. Paper presented at CIRP Annual Meeting, Nottingham, 1968, to be published in Proceedings of CIRP, Pergamon Press, Oxford.

EXTREME-TEMPERATURE LUBRICATION

R. P. Shevchenko
Pratt and Whitney Aircraft
Division of United Aircraft Corporation
East Hartford, Connecticut

<u>Editors' Note:</u> This report from Working Group VI was transmitted by R. P. Shevchenko, Group Leader. Other members of the Group were L. S. Akin, S. Allen, H. H. Coe, S. Feuerstein, H. Gisser, F. A. Glassow, E. Kingsbury, W. R. Loomis, L. P. Ludwig, R. R. Nash, R. J. Parker, and E. V. Zaretsky.

The members of the Group represented seven different disciplines (chemistry, metallurgy, physics, aeronautical engineering, chemical engineering, electrical engineering, and mechanical engineering). This interaction of many disciplines resulted in a fruitful discussion of the problems ranging from fundamental concepts to practical design considerations.

The Group's assignment was as follows:

1. Lubricated friction and wear behavior at:
   a. Moderate temperature.
   b. High temperature.
   c. Cryogenic temperature.
2. Effect of environment on lubrication behavior.
3. Failure modes.
4. Fretting.

5. Design and lubrication considerations for mechanical components for extreme-temperature service, such as bearings, gears, and seals.

Due to limitations of time, some of the problems were considered at length while others were not discussed. Highlights of the discussions are given below.

Moderate-Temperature Lubrication

Key lubrication problems in the moderate temperature range (up to about 400°F) were considered to be dirt, bearing skidding, bearing life, high-speed problems, and poor lubrication practice.

Dirt. Dirt was recognized as a menace to system hardware, especially in modern jet engines for which the characteristically thin oil films would not permit even extremely fine dirt to pass through.

Dirt could come from assembly of dirty parts, seal air leakage, and wear. Many ideas for dirt control were discussed; but they generally fall into three classes: (a) dirt prevention and removal, (b) material selection, and (c) design.

The recommended courses of action were: (a) filtration of seal leakage air, (b) run-in and change oil, (c) agglomeration of dirt particles and filtration, (d) S-monel liner or aluminum hardcoat on rubbing parts, and (e) establishment of a sufficient oil-film thickness to allow particle passage (e. g., outerland riding cage, hydrostatically supported cage). It was noted that the suggested remedies were very close to the program carried out by engine manufacturers and users.

Bearing Skidding. The damaging effect of rolling-contact bearing skidding was recognized. Figure 1 shows an experimental "skidding map" for a fairly large thrust bearing. Typical data showing gross sliding of the cage and balls are illustrated in figure 2. The experimental peak point of the ratio of cage speed to shaft speed has been found to coincide with the calculated peak point at the minimum coefficient of friction required to keep the balls from slipping gyroscopically (fig. 3). The peak points are therefore calculable to develop the skidding-prone boundary for any new thrust bearing design as shown in figure 1.

Bearing Life. Rolling-contact fatigue life was discussed extensively. In general, it was felt that good life would require the consideration of: (a) side grain, (b) special steels (such as M50, M1, WD65, WB49), (c) hardness difference between balls and races (for example, balls harder than races by 1-2 Rockwell C unit with SAE 52100 steel), (d) thick elastohydrodynamic oil film, (e) better surface finish, (f) residual compressive stress in races, (g) multiple consumable vacuum remelt, (h) ausformed steel, (i) low residual trace elements, and (j) low austenite (dimensional stability).

Research needs in this area were: (a) surface characterization, (b) elimination of end grains in balls, (c) hollow or drilled balls, (d) hardness vs. life for new materials, (e) ball-to-race hardness difference vs. life for new materials, (f) fatigue initiation mechanism, and (g) crack propagation mechanism (surface and subsurface).

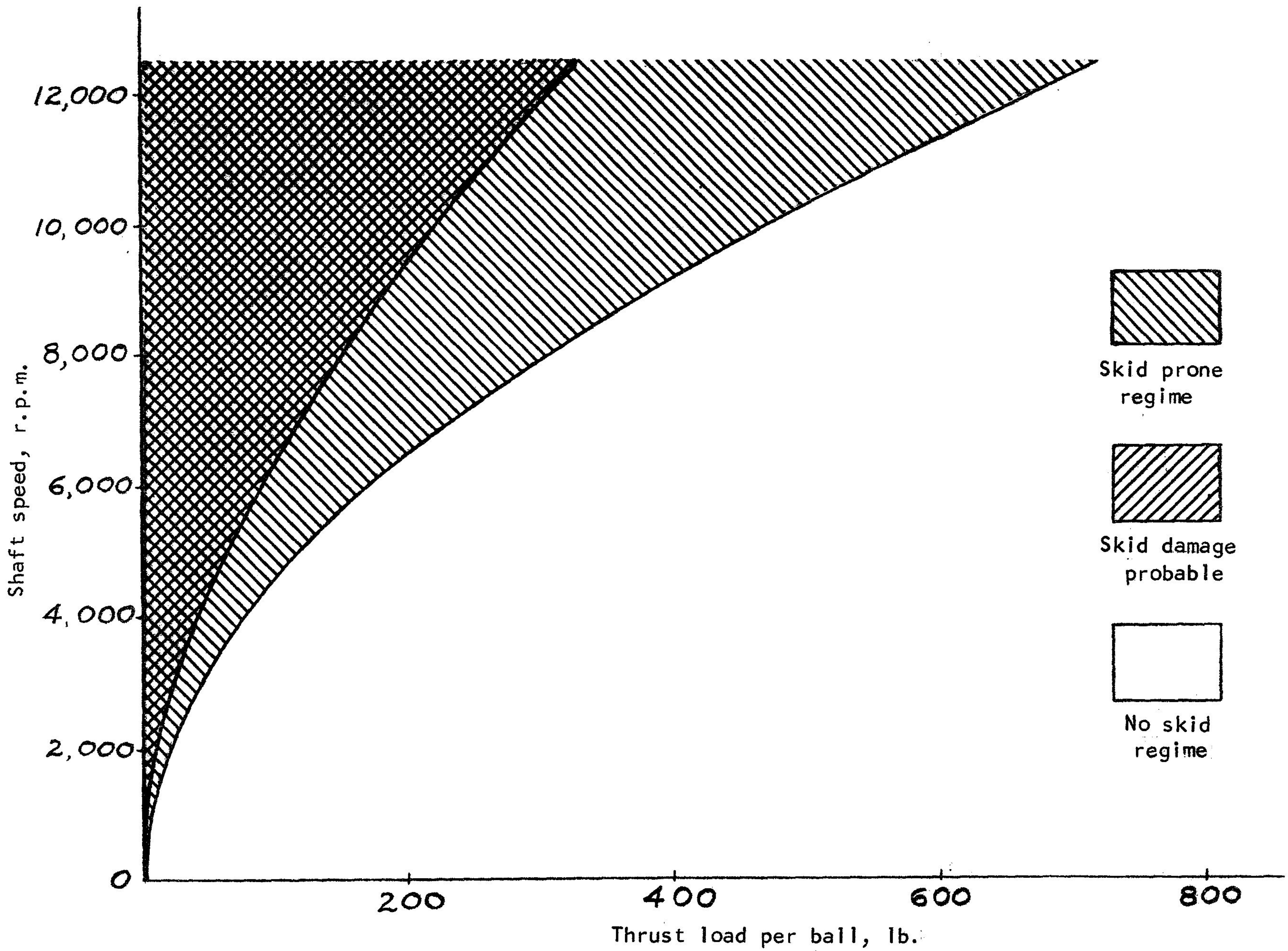


Figure 1 - Skidding map for a thrust bearing. 140-mm bore, 1.5-in. balls

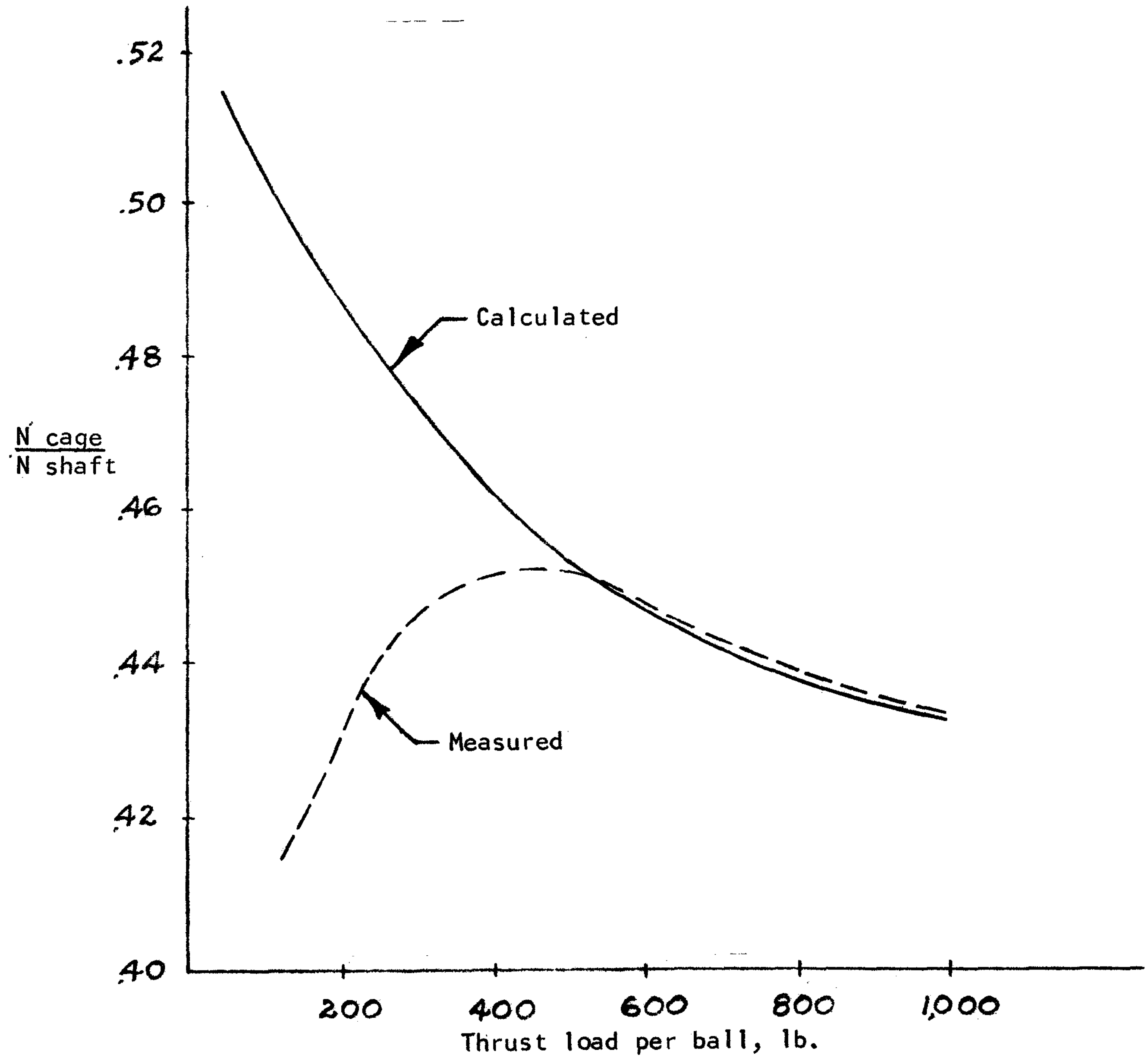


Figure 2 - Effect of load on cage speed. 140-mm bore, 1.5-in. balls, 10,000 rpm

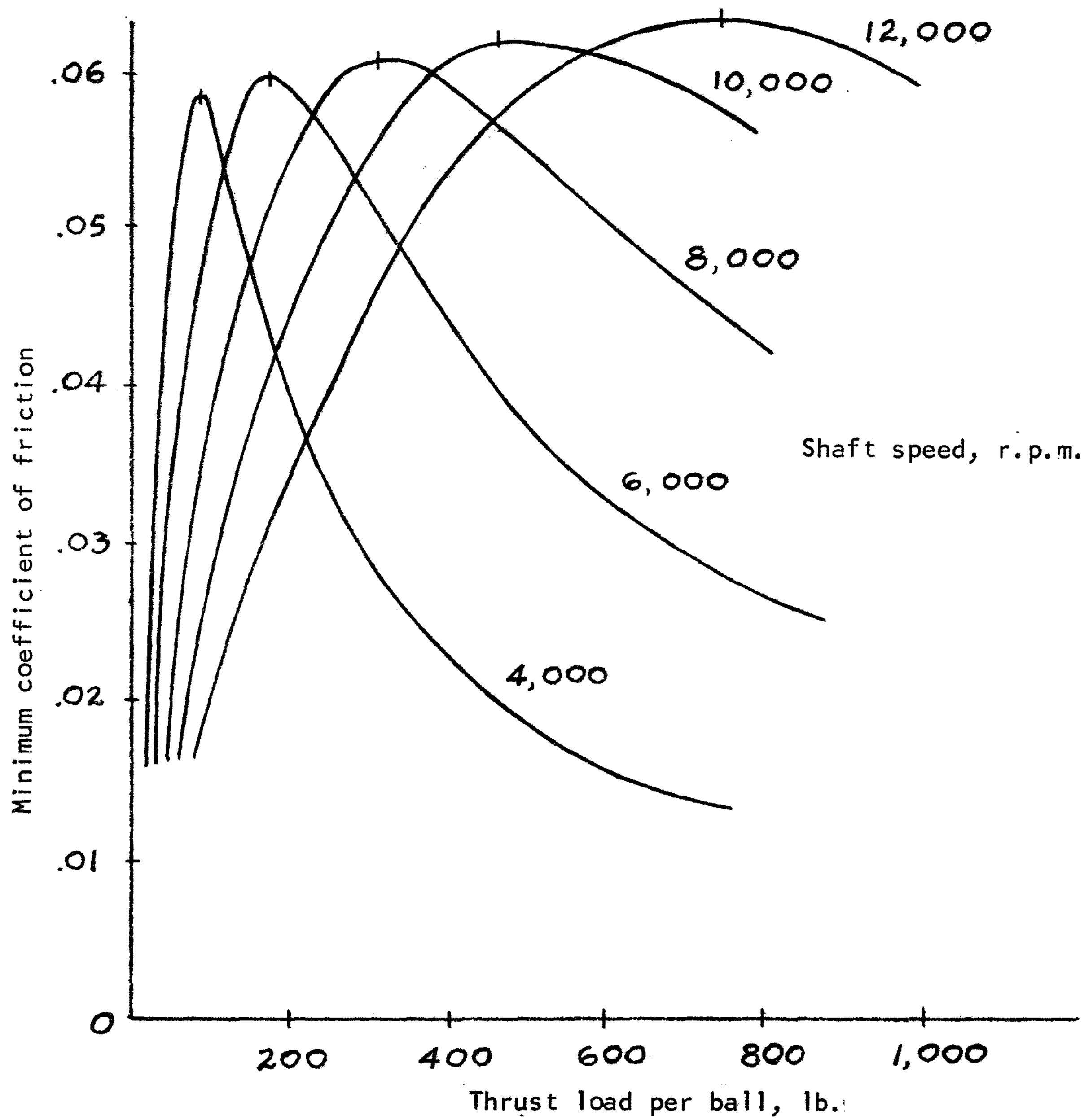


Figure 3 - Prediction of minimum coefficient of friction to prevent gyroscopic slip of balls. 140-mm bore, 1.5-in. balls

High-Temperature Lubrication

In the realm of high temperature, both liquid and solid lubrication were considered. However, emphasis was given to liquid lubricants which are limited in temperature capability (up to about 600°F) primarily by thermal degradation.

Thermal Degradation. It was observed that lubricant degradation at high temperature could be either oxidative or thermal. Thus, both oxidative stability and thermal stability were important.

Wettability. It was noted that certain high-temperature lubricants had application problems apparently related to their lack of sufficient "wettability". For example, a C-ether fluid has given rise to worn oil pump bushings and a polyphenol ether has caused cage wear until the fluid flow was substantially increased.

As applied to rolling-contact bearings, the Group suggested that the ratio of the minimum elastohydrodynamic film thickness to the composite surface roughness might be a pertinent parameter to consider. If this ratio is less than unity, there would be metal-to-metal contact and poor rolling fatigue life, and good wettability might be very important. If this ratio is between unity and 3, there would be light metal-to-metal contact and reasonably adequate rolling fatigue life, and good wettability might possibly be relevant. If this ratio is greater than 3, there would be no metallic contact and excellent rolling fatigue life, and good wettability may not be important.

The Group did not come up with a satisfactory definition of "wettability". It was merely noted that the most widely used parameter to study wetting by a liquid on a solid surface is the contact angle. Difficulties in contact angle measurements were discussed. Items recommended for research were: (a) the free energies involved, (b) a better understanding of the thermodynamics of the fluid-solid interface, (c) the rheological properties of the fluid, and (d) the effect of wettability on the elastohydrodynamic film thickness.

Effect of Environment

The effect of environment, particularly in the boundary lubrication regime, was recognized. The strong effect of environment, such as oxygen and water, on boundary lubrication and additive behavior has, in the Group's opinion, been amply demonstrated. However, the problem is most complex. The Group felt that much more study would be needed to relate the effects of environmental variables to boundary lubrication behavior.

Failure Mode Analysis

Failure mode analysis has received much attention in military procurement. An example of such an analysis is illustrated in table 1.

Fretting

The Group noted that no two surfaces in contact can be completely free of fretting. Examples in a jet engine are snaps, splines, shaft stack-ups, bolted faces, threads, and many others. To aid in design, knowledge of friction and energy dissipation with respect to relative motion would be required.

Table I. -- Failure Analysis for Rolling-Contact Bearing

Possible Causes	Effects and Consequences	Methods of Detection	Methods for Prevention	Remarks
		Spalling Damage		
1. Dirt inclusions 2. Microscopic cracks 3. Scratches 4. Forging laps 5. Grinding burns 6. Other manufacturing defects	Spall progresses in size and transfers to other rolling elements, eventually breaking cage and causing bearing seizure.	1. Visual inspection 2. Vibration monitoring 3. Chips in oil 4. Noise level detection	1. Inspect often (class 7 bearing quality) 2. Control specifications of: a) Heat treat b) Material composition c) Dimensions d) Forging practice 3. Production rig run in 4. Green run in engine 5. Inspect at vendor 6. Surveillance test each bearing lot 7. Use double sets of bearings in some locations	Spalling failures do not result in catastrophic engine failures because: 1. The rate of progression is slow, resulting in several hours of useful life. This allows time for detection, safe engine shutdown, and localization of damage to the bearing. 2. The bypass valve in main strainer prevents oil shut off to engine due to debris at strainer. 3. A second set of strainers in each oil line is used to prevent large pieces of debris from going through the bearings. 4. Redundant strainers are used when possible, and 5. Critical bearings are not mounted directly on the shaft between the compressor and the turbine. This prevents shaft failure due to over-temperaturing.
		Dirt Damage		
1. Improper oil storage or handling 2. Dirt carried into oil system by seal leakage 3. Introduction of dirt originally trapped in engine during assembly into oil system 4. Improper bearing cleaning, handling and installation	1. Dirt imbeds in soft cage plating and causes heavy wear on cage riding race. This additional debris causes additional bearing wear which ultimately can cause loss of rotor positioning. 2. Increased cage wear can eventually weaken cage and cause breakage (generally limited to riveted type cages. Riveted cages are not used on main shafts). 3. Eventual spalling (see spalling).	1. Visual inspection 2. Vibration monitoring 3. Chips in oil 4. Noise level detection	1. Minimize leakage of dirty air. This is best accomplished by rubbing contact seal, but an elaborate labyrinth seal system can also be used. 2. Carefully choose location for drawing off turbine cooling and pressurization air to minimize the amount of dirt passed through the seals. 3. Use strainers to clean oil. 4. Lubricate critical bearings with emphasis on inner race cooling. 5. Inspect often. 6. Green run in engine. 7. Use double sets of bearings in some locations.	Not a severe problem in rolling contact bearings. Failures are not catastrophic and leave plenty of time to be detected. This type of failure generally does not cause premature engine removal or inflight shutdown, but is found at overhaul by visual inspection.

Design and Lubrication Considerations

Table 2 illustrates an example of design and lubrication considerations for hydrodynamic and rolling-element bearings.

Table 2. -- Design Considerations for Bearing Choice

Note: Overall Advantage Designated by *

	Comments on Advantage or Deficiency	
	Hydrodynamic	Rolling Contact
A. Reliability for desired time between overhauls (TBO)	2000-3000 hrs TBO on piston engines, cavitation and wear problems	*10,000 hrs TBO on JT3D turbine engines, Rolling contact fatigue and skidding problems
1. Failure modes of bearings & consequences		
B. Engine Performance Penalty		
1. Oil flow required		*1/4 - 1/2 oil flow required
2. Heat generation		*1/4 - 1/2 overall friction loss
3. Effect of bearing on engine vibration	*Hydrodynamic bearings have inherent damping capacity	RC bearings go through critical speeds readily
4. Noise	Transmits little noise inherently	Noise made by aircraft quality bearings not detectable outside engine
C. MIL Lube Specification Compatibility		
1. Compatability with various chemical compositions	More susceptible to chemical attack	*Spalling fatigue affected by different fluids
2. Minus 65°F starting torque and operation	Possible but difficult because of high shearing forces	*Demonstrated with several type 1 fluids
3. Lubricant aeration	Aeration accelerates bearing cavitation	*No effect on RC fatigue
D. Oil Flow Restriction Effects		
1. Momentary oil shutoff	Fails in seconds	*Can accept repeated one minute oil shutoffs
2. Oil starvation		*More tolerant
3. Complete oil loss	Fails immediately	*Can operate up to several minutes
E. Environmental and Performance Demands		
1. Rapid acceleration to max power and deceleration to shutdown and violent maneuver		*Operates well over wide range of internal clearances & temperatures.
2. High speed	More care required to get through criticals, high heat generation	*Extensive successful experimental experience being obtained between 1.7 to 2.5 x 10^6 DN
3. Wide range temperature operation	Little high temperature work done at present	Only limitation is lubricant
4. Wide range load operation		*Preloaded bearings and thrust load control required but readily accomplished
5. Susceptibility to Dirt Damage	Dirt very deleterious to hydrodynamic bearing	More tolerance for dirt
F. Operational Demands		
1. Maintainability	Split bearings can be replaced in situ.	*Completely packaged bearings directly replaceable by following simple installation instructions
2. Ease of assembly and disassembly		See Item 1
3. Training requirements		See Item 2
G. Off-Design-Point Capability		
1. Misalignment	Increases end loading enormously, forces use of complicated self aligning designs	*Not desirable, but bearing in flexible mount more tolerant
2. Overspeed		*Considerable tolerance for short periods
3. Overload		*Considerable tolerance for short periods
H. Competitive Items		
1. Cost	Costs are higher	*
2. Weight	Weights are greater	*
3. Volume	Volumes are larger	*

CLOSING REMARKS

P. M. Ku
Southwest Research Institute
San Antonio, Texas

E. E. Bisson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

As mentioned in the Introduction, the Workshop was conducted in three parts. The first one-half day was a general session during which six Group Leaders introduced a number of key problems suggested by the Steering Committee for consideration by the Working Groups. During the following one and one-half days, the six Working Groups met separately to discuss these problems in depth. The final day was again a general session devoted to receiving the reports from the Groups and general discussions from the floor.

The reports from the six Working Groups, which appear in the preceding pages, speak for themselves. The writers need only comment here that, due to the complex nature of the problems, adequate record keeping of the proceedings of the working sessions was understandably most difficult. It was the writers' observation that all working sessions were conducted enthusiastically and constructively, and the Group reports reflected with all possible fidelity the majority opinions of the Groups.

The enthusiasm displayed by the participants was probably even more evident in the final general session, i.e., during the discussions that followed the presentation of the Group reports. We will now attempt to sketch the highlights of these discussions.

Interdisciplinary Approach. Three of the Group reports (those from Groups III, V, and VI) emphasized that the interaction of multidisciplinary talents produced fruitful results. Though not specifically so stated, the reports from the other three Groups (Groups I, II, and IV) also clearly evidenced the benefits of interdisciplinary cooperation.

During the final general session, G. Salomon expressed great enthusiasm in successfully bringing together specialists of many different backgrounds and interests to exchange ideas and viewpoints. He referred in particular to the communications gap that exists between research workers and design engineers. He suggested that, in the United States, there are many large industries which encompass within themselves strong research and design groups so that their communications problems may not be very acute. But even so, bringing representatives of many industries and research groups together in a single meeting is an exciting exercise. Referring to the European situation, where many small industries operate without internal research support, the problem of interdisciplinary cooperation is far more difficult. European scientists, he therefore concluded, have even greater responsibility to help the industry.

Salomon disagreed with G. S. Ansell who stated that advanced instrumental techniques are available and can readily be applied to lubrication studies. He emphasized that not all lubrication groups can afford such equipment, that considerable development work is still required to adapt such equipment to lubrication research, and that it is in this area that the basic scientists can make a notable contribution. Ansell's rejoinder was that the technical people should not perform experiments without adequate characterization, that it is the technical people's responsibility to decide consciously what to measure and what to leave out, and that the job itself must, in the last analysis, be done by the technical people themselves. However, the general concensus of the participants, who were overwhelmingly lubrication and design engineers to be sure, was that active participation of basic scientists was both desirable and necessary in the application of advanced instrumental techniques and in the interpretation of results.

R. Courtel stated that the Workshop was exceedingly challenging and he wished that a similar approach could be adopted in Europe. He further expressed the opinion that he would like to see friction and wear research actually conducted by small multidisciplinary teams, analogous to the Working Groups activated for this meeting. He added that the team leader should perhaps be a physicist for fundamental research projects and an engineer for applied research projects.

Friction and Wear Research. Courtel then went on to propose that in friction and wear research, the principal governing parameters are:

1. Load (and pressure).
2. Speed (and kinematics of motion).

3. Temperature (and thermal factors)

4. Nature of materials (and metallurgical structure).

5. State of the surfaces and of the superficial layers (geometric, physico-chemical, and structural).

6. Environment (including lubrication).

The principal effects to be observed are:

1. Frictional resistance (friction coefficient).

2. Thermal effects.

3. Damage (wear) and structural transformation.

4. Vibrations.

He suggested several friction and wear topics that might profitably be conducted by interdisciplinary teams (table 1).

Wetting. The importance of "wetting" to lubrication was emphasized by Groups IV and VI. In the final general discussion, J. K. Appeldoorn questioned the relevance of wetting, citing that a silicone fluid will displace a petroleum oil from a surface; but it is not a good lubricant. E. D. Brown countered that silicones are not all bad lubricants; besides, he asked what was meant by the term wetting. Salomon stated that wetting is a kinetic process and believed it to be useful in preventing wear.

Ansell emphasized that a scientific definition of "wetting" is required, which should relate the phenomenon to basic properties. In this sense, the contact angle measurement is not sufficient since it neglects the kinetic situation.

Table 1. — Preliminary Considerations of a Fundamental Study of Friction and Wear

			Interdisciplinary Aspects, Mechanics Plus Other Disciplines
1.	Mechanisms of Friction of Homogeneous Solids (single crystals)	Adhesion - Study on the Å scale, of electron arrangement and perturbations - Thermodynamic study of surface energy and its variation	Theoretical physics, quanta Thermodynamics of surfaces, physical chemistry
		Deformation - Study of μ scale of dislocation movements - Study of single contacts, geometrically defined (static) - Study of the continuum scale of friction, vibration (dynamic)	Physics of solids Elasticity, plasticity, viscoelasticity, rheology
2.	Taking Account of Hetrogeneity	Polycrystal Thin layers Defects Multiple phases	Metallurgy Elasticity, physics Metallurgy
3.	Mechanisms of Wear	Role of fatigue in sliding and rolling wear Statistical analysis of friction traces in multiple contacts Models of wear and theoretical calculations	Metallurgy Statistical analysis
4.	Thesaurus of Friction Data	Classification of friction parameters (see attached) Classification of effects of friction (see attached) Constitution of magnetic memory with multiple entires (especially case of high or low friction with low wear)	Physics Statistical analysis
5.	New Friction Materials	Friction compatibility of material pairs Mechanical properties of type of contact; influence of other factors Modes of application	Chemical physics Metallurgy

J. J. Bikerman called attention to a phenomenon known as the hysteresis of wetting, stating that one must consider advancing and receding contact angles. He emphasized that the science of wetting is very old, and means are available to calculate the rate of creep for Newtonian liquids. He also affirmed the importance of wetting to lubrication.

M. C. Shaw and E. A. Saibel suggested that wetting may be quite relevant in hydrodynamic and elastohydrodynamic lubrication. P. M. Ku called attention to the work of Deryagin on flow anomoly in the vicinity of solid surfaces, as well as the work of Naylor and others showing possible effects of adsorption even when operating in the EHD regime. R. L. Johnson added that wetting is important to the transport of lubricant in bearings and thus to cooling.

Elastohydrodynamic Lubrication. Referring to figure 1 in the report from Group III, R. S. Fein questioned the validity of representing hydrodynamic, elastohydrodynamic, mixed, and boundary lubrication regimes by a single curve on the f vs. ZN/P coordinates. He agreed with the single-curve representation for the hydrodynamic regime; but not with the others. W. J. Anderson, H. C. Cheng, E. V. Zaretsky, and R. P. Shevchenko all concurred with Fein. Ku suggested that the classical work of Crook and the more recent work on traction in EHD contacts by Naylor, K. L. Johnson and others all point to the fact that f in the EHD regime is not uniquely determined by ZN/P. As to mixed and boundary lubrication regimes, the fact that f is not uniquely determined by ZN/P is well known, for example, through the work of McKee and others.

Boundary Lubrication. The effect of lubricant-metal-atmosphere interaction on boundary lubrication was recognized in all Group discussions. The immense difficulties in performing controlled, critical experiments and in interpreting the results were also recognized.

Referring to the Group III report, Salomon mentioned the difficulty in controlling and measuring the oxygen content in experiments, and questioned how very low concentrations of oxygen were achieved. E. E. Klaus replied that the oxygen concentration referred to in figure 2 in the Group III report referred to that of the dissolved oxygen in the liquid; not that in the atmosphere.

Lubrication of Concentrated Contacts. Ku announced that a symposium on Interdisciplinary Approach to the Lubrication of Concentrated Contacts will be held in Troy, New York, on July 15-17, 1969, again under the sponsorship of NASA. He expected that many of the problems discussed here, such as elastohydrodynamic lubrication, rheological and chemical effects, etc, will be more thoroughly covered at that time.

LIST OF PARTICIPANTS

1. Adamczak, R. L., Air Force Materials Laboratory, Code MANL, Wright-Patterson Air Force Base, Ohio 45433

2. Akin, L. S., McDonnell Douglas Corporation, Dept. A-833, Group BBGO, 3000 Ocean Park Boulevard, Santa Monica, California 90406

3. Allen, G. P., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

4. Allen, S., MIT Instrumentation Laboratory, Mail Stop 29, 68 Albany Street, Cambridge, Massachusetts 02139

5. Anderson, W. J., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

6. Ansell, G. S., Materials Division, Rensselaer Polytechnic Institute, Troy, New York 12181

7. Antler, M., Research Division, Burndy Corporation, Richards Avenue, Norwalk, Connecticut 06852

8. Appeldoorn, J. K., Esso Research & Engineering Company, P. O. Box 51, Linden, New Jersey 07036

9. Babecki, A. J., NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

10. Bikerman, J. J., Horizons Inc., 2905 East 79th Street, Cleveland, Ohio 44104

11. Bisson, E. E., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

12. Bowen, P. H., Research Laboratory, Westinghouse Electric Corporation, Beulah Road, Churchill Borough, Pittsburgh, Pennsylvania 15235

13. Brainard, W. A., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

14. Brewe, D. E., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

15. Brown, E. D., Jr., Silicone Products Department, General Electric Corporation, Waterford, New York 12188

16. Buckley, D. H., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

17. Cheng, H. C., Northwestern University, Department of Mechanical Engineering, Evanston, Illinois 60201

18. Coe, H. H., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

19. Courtel, R., Centre National de la Recherche Scientifique, Laboratories de Bellevue, Bellevue, France

20. Davis, H. M., Metals and Ceramics Division, U. S. Army Research Office-Durham, Box CM, Duke Station, Durham, North Carolina 27706

21. Dawe, H. J., Acheson Industries, Inc., Michigan National Bank Building, Port Huron, Michigan 48060

22. Dayson, C., National Research Council of Canada, Building M9, Montreal Road, Ottawa 7, Ontario, Canada

23. Deutsch, G. C., Office of Advanced Research and Technology, NASA, 600 Independence Avenue, S. W., Washington, D. C. 20546

24. Evans, H. E., NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

25. Fein, R. S., Texaco Research Center, P. O. Box 8, Beacon, New York 12508

26. Feuerstein, S., Aerospace Corporation, Box 95085, Los Angeles, California 90045

27. Flom, D. G., G. E. Space Sciences Laboratory, Room No. M9132, P. O. Box 8555, Philadelphia, Pennsylvania 19101

28. Furaso, R. L., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

29. Gisser, H., Chemistry Research Laboratory, Frankford Arsenal, Pitman-Dunn Research Laboratories, Philadelphia, Pennsylvania 19137

30. Glassow, F. A., Electromechanical Department, Hughes Aircraft Company, P. O. Box 90919, Airport Station, Los Angeles, California 90009

31. Godfrey, D., Chevron Research Company, 576 Standard Avenue, Richmond, California 94802

32. Hady, W. F., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

33. Hammel, R. L., TRW Systems, R1-2211, 1 Space Park, Redondo Beach, California 90278

34. Hoffman, H. C., General Dynamics/Fort Worth, P. O. Box 748, Plant Mail Zone Y-28, Fort Worth, Texas 76101

35. Johnson, R. L., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

36. Jones, W. R., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

37. Keller, D. V., Jr., Syracuse University, Metallurgy Department, Collendale Campus, Syracuse, New York 13210

38. Kingsbury, E., MIT Instrumentation Laboratory, 68 Albany Street, Cambridge, Massachusetts 02139

39. Klaus, E. E., Chemical Engineering Department, The Pennsylvania State University, University Park, Pennsylvania 16802

40. Ku, P. M., Department of Fluids and Lubrication Technology, Southwest Research Institute, 8500 Culebra Road, San Antonio, Texas 78228

41. Lad, R. A., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

42. Lemanski, A. J., The Boeing Company, Boeing Center 3-28, P. O. Box 16858, Philadelphia, Pennsylvania 19142

43. Ling, F. F., Department of Mechanics, Rensselaer Polytechnic Institute, Troy, New York 12181

44. Littmann, W. E., Metallurgy Research, The Timken Roller Bearing Company, 1835 Dueber Avenue, S. W., Canton, Ohio 44706

45. Loomis, W. R., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

46. Ludema, K. C., Mechanical Engineering Department, University of Michigan, 2046 East Engineering Building, Ann Arbor, Michigan 48104

47. Ludwig, L. P., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

48. Male, A. T., Westinghouse Electric Company, Code MAMN, Building 51, Room 902, Wright-Patterson Air Force Base, Ohio 45433

49. Maltz, J., Office of Advanced Research and Technology, NASA, 600 Independence Avenue, S. W., Washington, D. C. 20546

50. McKannan, E. C., NASA Marshall Space Flight Center, Code R-P + VE-ME, Huntsville, Alabama 35812

51. Moyer, C. A., Engineering Research, The Timken Roller Bearing Company, 1835 Deuber Avenue, S. W., Canton, Ohio 44706

52. Nash, R. R., Office of Advanced Research and Technology, NASA, 600 Independence Avenue, S. W., Washington, D. C. 20546

53. Owens, R. S., Applied Surface Chemistry, General Electric Company, P. O. Box 8, Schenectady, New York 12301

54. Parker, R. J., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

55. Pentlicki, C. J., Comsat Laboratories, Spacecraft, 2100 L Street, N. W., Washington, D. C. 20037

56. Przybyszewski, J. S., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

57. Ramadanoff, D., Advanced Materials and Technology Inc., 4850 Delemere Avenue, Royal Oak, Michigan 48073

58. Rittenhouse, J. B., Materials Engineering D74-53, Building 170, Plant B-1, Lockheed California Company, P. O. Box 551, Burbank, California 91503

59. Rowe, C. N., Central Research Division, Mobil Research & Development Corporation, P. O. Box 1025, Princeton, New Jersey 08540

60. Saibel, E. A., Department of Mechanical Engineering, Carnegie-Mellon University, Schenley Park, Pittsburgh, Pennsylvania 15213

61. Salomon, G., Central Laboratory, T.N.O., P. O. Box 217, Delft, The Netherlands

62. Savage, C. H., Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91103

63. Schiefer, H. M., Dow Corning Corporation, Fluids and Lubricants Laboratory, Midland, Michigan 48640

64. Shaw, M. C., Department of Mechanical Engineering, Carnegie-Mellon University, Schenley Park, Pittsburgh, Pennsylvania 15213

65. Sherlock, J. J., Midwest Aero Industries Corporation, 4834 Delemere Avenue, Royal Oak, Michigan 48073

66. Shevchenko, R. P., Pratt and Whitney Aircraft, 400 South Main Street, East Hartford, Connecticut 06108

67. Shobert, E. I., II, Research Laboratory, Stackpole Carbon Company, St. Marys, Pennsylvania 15857

68. Sliney, H. E., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

69. Spalvins, T., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

70. Strom, T. N., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

71. Swikert, M. A., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

72. Teimer, W. H., The Bendix Corporation, Navigation and Control Division, Department 7511, Teterboro, New Jersey 07608

73. Waterhouse, R. B., Department of Metallurgy, University of Nottingham, Nottingham NG7 2RD, England

74. Wilde, R. A., Research Center, Eaton, Yale, and Towne, Inc., 26201 Northwestern Highway, Southfield, Michigan 48075

75. Williamson, J. B. P., Research Division, Burndy Corporation, Richards Avenue, Norwalk, Connecticut 06852

76. Wilmoth, R. G., Space Vacuum Laboratory, Mail Stop 187, NASA Langley Research Center, Langley Station, Hampton, Virginia 23365

77. Wisander, D. W., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

78. Zaretsky, E. V., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135

79. Zuk, J., NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135